Université Catholique de Louvain
Faculté d'Ingénierie Biologique, Agronomique et Environnementale
Département des Sciences du Milieu et de l'Aménagement du Territoire

Populations, Farming systems and Social transitions in Sahelian Niger: An Agent-based Modeling Approach

Mehdi SAQALLI

Juin 2008

Thèse présentée en vue de l'obtention
du grade de docteur en sciences agronomiques
et ingénierie biologique

Composition du jury:

Président : Prof. Joseph Dufey (UCL, Belgium)

Promoteurs : Prof. Pierre Defourny (UCL, Belgique)
Prof. Charles Bielders (UCL, Belgium)

Lecteurs : Dr François Bousquet (CIRAD, France)
Dr Bruno Gérard (ICRISAT - ILRI, Niger-Ethiopia)
Prof. Éric Lambin (UCL, Belgium)
Prof. Pierre-Joseph Laurent (UCL, Belgium)

REMERCIEMENTS

Il est d'usage de placer ici l'ensemble des personnes avec qui il m'a été possible de travailler. Je commencerais cependant par une dédicace : je dédie cette thèse à un grand Monsieur, qui a joué un rôle essentiel dans un moment difficile, et sans qui je n'aurais jamais suivi ce chemin qui m'a apporté autant. Merci, Monsieur Mazoyer !

Les citoyens des villages, jeunes et vieux, hommes et femmes, qui m'ont accueilli très souvent avec bienveillance et même amusement, je les salue avec respect. Pour les citer et entres autres, les habitants des villages de Guileyni, Wankama, Dantiandou, Banizoumbou, Kodeye, Zouzou Saney, Katanga et Fandou Beri dans le canton de Fakara. Pour la région de Gabi, le village de Gabi lui-même et ceux de Garin Tapki, de Takassaba et de Tokarawa. Enfin, à Zermou, les villages de Zermou, Tokarawa, Melawa, Kassama et Damagaram Takaya. J'en oublie sûrement et je m'en excuse.
Le travail de terrain n'aurait pas été possible sans des interprètes et collègues qui deviennent tout naturellement des amis. Je remercie ainsi Baki de Guileyni, Nouhou et Balkissa de Niamey. Enfin, Je salue et remercie Nouhou Hamidou, ingénieur CNEARC promis à un bel avenir.

Je salue et remercie volontiers mes promoteurs, Pr. Pierre Defourny et Pr. Charles Bielders (UCL), ainsi que le Dr Bruno Gérard, membre du jury coordonnateur du projet "Aide à la Décision" dans lequel s'est placé l'ensemble de la thèse. Débats et re-lectures ont rythmé ces années. Je salue et remercie mes co-doctorants Eduardo Marinho et Pierre Akponikpé. À ce titre, je salue également les deux institutions qui m'ont accueilli durant cette thèse, l'Université catholique de Louvain (UCL) et l'institut de recherche sur les cultures des tropiques semi-arides (ICRISAT), ainsi que la coopération au Développement de la Belgique (direction générale de la coopération au développement du Gouvernement belge, DGCD) qui a financé ce projet et ce travail. Je salue et remercie ainsi les autres membres du jury, Dr François Bousquet du CIRAD, Pr. Eric Lambin, professeur de Géographie, et Pr. Pierre-Joseph Laurent de l'UCL professeur d'Anthropologie pour leur lectures attentives.

De nombreux partenaires de ce projet furent d'une grande aide durant ce travail : je les citerais en partant de l'est vers l'ouest du Niger contrairement à l'usage et sans hiérarchie : A Zinder je pense en particulier aux agents de terrain d'AQUADEV, en particulier Omar Ango et Ali Issaka. À Maradi, à M. Abass Tidjani, chercheur de l'INRAN et grand amateur comme moi-même du Moringa, ainsi que les représentants de la FAO dont le travail réconcilierait tout le monde avec les institutions internationales. À Niamey et le Fakara enfin, l'ICRISAT où je salue M. Tahirou Saley, Laoualy, Ado Saley et aussi Ms. Ilah et Domingo, l'Agrhymet où je salue Djaby Bakary, Hubert N'djafa Ouaga et Issa Garba. Je remercie aussi M. Zarafi, M. Mohammed Abdoulaye et M. Tahirou Abdoulaye, membres ou anciens membres de l'INRAN pour leurs réflexions. Je salue enfin Ayouba Hassane, ancien de Mooriben. J'en oublie bien d'autres, dont la liste serait trop longue pour être placée ici. Qu'ils soient ici remerciés !

TABLE OF CONTENTS

REMERCIEMENTS / ACKNOWLEDGEMENTS………..……………i
CONTENTS……………………...……………………..…………..iii
LIST OF TABLES……………………...………………..…………ix
LIST OF FIGURES…………………...…………………………….xi
LIST OF ACRONYMS…………………...………………………..….xiii
MODEL PARAMETERS & VARIABLES…………………………xv
INSTITUTIONAL POSITION………………………..…………..…xvii

INTRODUCTION
1 Investigating the complexity of the Nigerien Sahel rural populations………..…………………………………..…………..… 1
2 Research objectives & challenges …..………..………………..3
3 Scientific tools and disciplines..…………..……..………………5
4. Outlines of the thesis…..………..……………………..…………6

CHAPTER 1: RURAL POPULATIONS & FARMING SYSTEMS OF NIGERIEN SAHEL
1 The Nigerien Sahel: living on the edge…..………..……………9
1.1 The Sahelian part of Niger 9
1.2 The Nigerien Sahel: A historical perspective 11
1.3 Economic production activities in Nigerien Sahel 15
1.3.1 Agriculture 16
1.3.2 Livestock keeping 17
1.3.3 Seasonal migration 19
1.3.4 Gardening 20
1.3.5 Other activities 21
1.3.6 Section conclusion 21
2 Family-based determinants of population evolutions……………22
2.1 A capacity of adaptation to acknowledge 22
2.2 Balancing decision powers: Family & individuals 23
2.2.1 The family as the relevant scale of study 23
2.2.2 Farmers & villagers: multiples activities & multiple finalities 24
2.2.3 The individual as the relevant decision level 26
2.3 The family criteria of social distribution 27
*2.3.1 Family rank*gender: the last hierarchy 27*
2.3.2 Reputation: a villagers' currency? 31
2.4 Family evolution modes 33
2.4.1 Family disintegration with declining economic hierarchy 34
2.4.2 Inheritance evolution with growing tenure constraints 37

2.5 Project actions: Fertilizers & warrantage 40
2.5.1 Fertilizers 41
2.5.2 Warrantage 42
2.6 Conclusion 42

CHAPTER 2: FIELD MATERIALS & METHODS

1 Characterization of the three study sites…..……………………..45
1.1 The study site selection 45
1.2 Description of the selected sites 47
1.2.1 The canton of Fakara 48
1.2.2 The canton of Gabi 49
1.2.3 The canton of Zermou 51

2 The overall methodology & assumptions…….…..……………..52

3 The ZADA: A local perception based regional mapping methodology & results for two study sites…………………………..55
3.1 Introduction 55
3.2 The ZADA Methodology 57
3.2.1 Preparing interviews 57
3.2.2 The ZADA map-making 58
3.2.3 Synthesizing & formalizing results 60
3.3 Results 60
3.3.1 A first classification based on environmental characteristics 60
3.3.2 The environmentally adapted economic activities 63
3.3.3 The intensification of practices: an urban influence 64
3.3.4 Access to basic infrastructure 66
3.4 Discussion 67
3.5 Conclusion 70

4 Individual interviews……….…..….……..…….…..……………..70
4.1 The village sampling of the three sites 70
4.2 The interviewed people & the interview methods 71
4.3 Assessing the implementation practice of development actions 73
4.4 Biases & limitations 74

CHAPTER 3: BUILDING THE AGENT-BASED MODEL

1 Simulating with Agent-based Models.……..…...…………………77
1.1 The necessary choice of a distributive model 77
1.2 The "cellular" models 79
1.3 The object-based models 80
1.4 What more do the Agents have? 81
1.5 Relevance of ABMs in social simulations on rural development problematic 82
1.6 The CORMAS platform 83

Table of contents

2 From field-originated questions to SimSahel building principles. 85

2.1 The population in its territory: an innovative subject for ABM modeling 85
2.2 A prior refusal of theorization 86
2.3 Multiple activities and multiple finalities 86
2.4 Hierarchizing the complexity of rationalities & processes 87
2.4.1 Keep it "sophisticatedly" simple 87
2.4.2 A stratified & empirical model: data for the framework, informations for the dynamic, theories for hypotheses 88
2.5 Spatialization & temporality 89

3 Entities and architecture of SimSahel……..……….………………...89

3.1 The model building methodology 89
3.2 Representation of the model 91
3.3 The model architecture 91
3.4 The Spatial entities 94
3.4.1 The Parcels 97
3.4.2 The Climate Blocks 99
3.5 The active & communicative entities: Agents & Objects………..99
3.5.1 The Livestock Objects 99
3.5.2 The Villager Agents 100
3.6 The passive entities as intermediate "work tools" 101
3.6.1 The Social status of individuals 101
3.6.2 The Families 104
3.6.3 The messages exchanged between Villagers 105

4 Building the relationships between SimSahel entities…………...105

4.1 Initialization: founding a village in SimSahel 105
4.2 The sequential schedule of the model 106
4.3 The spatial module of SimSahel 108
4.3.1 Rainfall 108
4.3.2 Vegetation & fertility 109
4.3.3 Pasture, manure & fertility 111
4.4 The social module of SimSahel 114
4.4.1 The Villager: Ageing & dying 115
4.4.2 The family structure: modes of inheritance & family organizations 116
4.4.3 The family functioning: marriage, births & food redistribution 118
4.4.4 The outside environment: price fluctuations & taxes 122
4.5 The Production module of SimSahel 123
4.5.1 Agriculture 123
4.5.2 Gardening 131
4.5.3 Seasonal migration or "exodus" 133
4.5.4 Livestock rearing 136

5 Assessing scenarios with SimSahel………..…..…..…………….140

5.1 Assessing scenarios on family organizations 140
5.2 Assessing scenarios on development actions 140
5.2.1 Warrantage 141
5.2.2 Inorganic fertilizers 142
5.3 Family evolutions with social pressures 143

5.3.1 Family disintegration with declining economic hierarchy. 143
5.3.2 Inheritance evolution with growing tenure constraints. 144

6 Validation & confidence building……….……….………..…………….144

6.1 The problem of empirical model validation 144
6.2 Testing the sensitivity of selected parameters 145
6.3 Confidence building 149
6.3.1 Comparing simulation outputs based on the two family organization types with external data 149
6.3.2 Comparing simulation outputs based on the two project actions with external data 151

CHAPTER 4: IMPACTS OF FAMILY ORGANIZATION IN SAHELIAN RURAL MULTI-ACTIVITY SYSTEMS: THE CASE OF FAKARA, NIGER

1 Abstract……….......……….…...….………...…...…………..……….153

2 Introduction……..…...…..……………..….………..…..…………….154

3 Results & discussion……..……..……….…….…….…………………156

3.1 Millet farming as a basis, others as necessary activities 156
3.2 More food for all, same quantity for each 159
3.2.1 Income & inequalities 159
3.2.2 Fertility & livestock 161
3.3 A hypothesis about a change in local social organization 161

4 Conclusion……..……...…………..…..……….……....….….…. 164

CHAPTER 5: BENCHMARKING HUMANITARIAN SUPPORT: MODELING DEVELOPMENT ACTIONS IN VILLAGES OF SAHELIAN NIGER

1 Abstract……….......……….…...….………...…...…………..……….167

2 Introduction……..…...…..……………..….………..…..…………….168

3 Results……..…...……………...….……….…..….……………………...171

3.1 Reputation: only a quicker wealth estimation factor 171
3.2 Comparing sites 172
3.2.1 Production assets: a structural geographic advantage 172
3.2.2 Activities distribution: site specific specialization 174
3.2.3 Inequality, sustainability: producing for how long & for whom? 176
3.3 Projects implementation: successes & failures 179
3.3.1 A low success mainly due to a poor saving capacity 179
3.3.2 Two development proposals targeting different population groups 180

4 Discussion & conclusion………..…..………..…..….……………182

CHAPTER 6: TESTING SOCIAL-DRIVEN FORCES ON THE EVOLUTION OF NIGERIEN RURAL FARMING SYSTEMS

1 Abstract……..187
2 Introduction……...188
3 Results……...190
3.1 The "No-Evolution" Scenario: a progressive degradation because of local constraints 190
3.1.1 Production, global sustainability & social inequity: a structural geographic advantage 191
3.1.2 Differentiation of economic activities: extra-local activities as a compensation for a local degradation 195
3.2 Introducing social evolutions: family shifts as accelerators of farming system evolutions 197
3.2.1 The family Evolution Scenario: same social rules but different contexts creating specific social stratifications. 197
3.2.2 Production & sustainability at the village level: new population robustness due to family decomposition & individualization. 201
3.2.3 Activities & livestock distribution: increasing the robustness through site-specific orientations 203
3.2.4 Production & sustainability at the family levels: differentiation of the social family types according to site history & environments 205
4. Conclusion……... 208

CONCLUSION & PERSPECTIVES

1 Summarizing the results……...211
2 Methodological contributions and limitations.........................215
2.1 Contributions related to the methodological objectives 216
2.1.1 Contributions of the field methodology 216
2.1.2 Contributions of the modeling methodology 217
2.2 Limitations of the methodology 218
3 Thematic contributions & limitations…….............................219
3.1 Contributions related to the thematic objectives 219
3.2 Practical relevance of the thematic results 221
3.3 Domain of validity of the thematic results 223
4 Perspectives……...223
4.1 Extending the research relevance of the model 223
4.2 Extending the practical relevance of the approach 224

PUBLICATIONS RELATED TO THE THESIS 227

REFERENCES 229

TITRES RÉCENTS DE LA COLLECTION 257

LIST OF TABLES

Table 1. Sources and uses of family incomes...........................25
Table 2. Factors of differentiation between the three sites...........................46
Table 3. Distribution of interviewees according to their professions...........................58
Table 4. Comparing methodological tools for land investigation in the context of Nigerien Sahel...........................68
Table 5. Available distributive software platforms for social Agent-based modeling...........................83
Table 6. The Universe Class: the external world...........................92
Table 7. Spatial distribution and land type fertility value of geomorphologic units in the SimSahel model for the three sites...........................95
Table 8. A Spatial elementary Class: The Parcel...........................97
Table 9. A spatial aggregated Class: The Climate block...........................99
Table 10. An active Object Class: The Livestock...........................100
Table 11. An active Agent Class: The Villager...........................101
Table 12. A passive Elementary Agent Class: The social status...........................101
Table 13. A passive Aggregated Class: The Family...........................104
Table 14. Implementing the rainfall module of the SimSahel model...........................108
Table 15. Implementing the fertility Fx module of the SimSahel model...........................110
Table 16. Human–managed fertilization processes on millet yield...........................113
Table 17. Parameters used for the socio-economic part of the model...........................114
Table 18. The simulated characteristics of the two analyzed family structures...........................118
Table 19. Impact functions of the pearl millet crop process on herbaceous and shrubs/trees growth on a parcel...........................127
Table 20. Periods of the millet cropping stages...........................128
Table 21. Migration periods, costs & risks for the three sites...........................134
Table 22. Average livestock mortality rate...........................138
Table 23. Livestock prices (in €)...........................139
Table 24. Comparison between the four Fakara scenario simulation outputs and external available data...........................152
Table 25. Simulated outputs for the two family structure scenarios showing part of each activity in villagers incomes...........................159
Table 26. Combination of scenarios and abbreviations...........................171
Table 27. Indicators and ratio comparison between project user families and the average population...........................181
Table 28. 100 years evolution of selected indicators for the three sites in a No-Evolution Scenario (fixed unitary family & customary inheritance system)...........................191
Table 29. 100 years evolution of selected indicators for the three sites in the Evolution scenario (family organizations & inheritance systems can change)...........................199
Table 30. Selected indicator mean values for the last quarter t=] 75-100] for the three sites for the "Evolution" scenario...........................206

LIST OF FIGURES

Figure 1. *Farming systems of Sahelian Niger……………….…….……….……..……10*
Figure 2. *The Nigerien territory around 1880……..………………………………..…..11*
Figure 3. *Land occupation in the Fakara at the beginning of the 20th century…..…13*
Figure 4. *Land occupation in the Fakara between 1920 & 1940……..……………...14*
Figure 5. *Land occupation in the Fakara between 1940 & 2000……..……………...15*
Figure 6. *Calendar of activities in Sahelian Niger……..………………………………16*
Figure 7. *Location of the research sites in southern Niger……..……………………..45*
Figure 8. *Field methodology used for the SimSahel building…..…………………….52*
Figure 9. *The different steps of the ZADA-mapping process…..…………………….59*
Figure 10. ZADA results of the biophysical organization of the two sites & IRD morphopedological map of Zarmaganda using the FAO soil classification……..…61
Figure 11. ZADA results for the dominant activities at the two sites………………….63
Figure 12. ZADA results on human occupancy dynamics and organization.………..66
Figure 13. ZADA results on dispensary access coverage……………………………..67
Figure 14. Global methodology of model building…..…………………………………..90
Figure 15. Unified Modeling Language architecture of the SimSahel model………..94
Figure 16. The spatial module of SimSahel………………….……………………..…..94
Figure 17. Schematic geomorphologic maps of the three sites…………………….…96
Figure 18. Relationships between Active entities in SimSahel………………………..99
Figure 19. The sequence diagram of one time step of the SimSahel model ………107
Figure 20. UML representation of the field expansion rule…………………………...125
Figure 21. UML figures for the three successive millet crop cycle steps which requires labor, each one representing a sequence of evaluation & action……………………128
Figure 22. Results of the sensitivity tests on several selected parameters…………146
Figure 23. Comparison of the annual growth rate of cultivated land for the two scenarios simulation outputs and interpolated data from Loireau-Delabre (1998)...150
Figure 24. Simulation outputs for the proportion of female Gardeners…………..…157
Figure 25. Simulation outputs for the proportion of male Migrants…………………..158
Figure 26. Simulation outputs for the unitary annual village production cycle scenario for the three simulated activities (year 50) ……………………………………….…..159
Figure 27. Total village income shares for the four gender / marital groups ……..…160
Figure 28. Simulation results for the mean coefficients of variation between Family sizes and repetitions.……………………………………………………………………..162
Figure 29. No project & no reputation simulation output means per capita for selected population characteristics in the three sites……………………………………………173
Figure 30. No project & no reputation simulation output means per capita for production activities in the three sites…………………………………………………..175
Figure 31. No project & no reputation simulation scenario output means for sustainability in the three sites ………………………………………………………..177

List of Figures

Figure 32. Comparison between the three sites of development action impact simulation output means in the no reputation scenario ……………………………….180
Figure 33. Proportion of species in the herds and proportion of the different activities in the village income of the three sites in the No-Evolution scenario……………..…194
Figure 34. Proportions of the four different family categories & the different activities in each site………………………………………………………………….…….…….….198
Figure 35. Proportion of species in the herds and proportion of the different activities in the village income of the three sites for the "Evolution" scenario…………………204

LIST OF ACRONYMS

ABM	Agent-Based Model
ACMAD	African Center of Meteorological Applications for Development
AGRHYMET	Centre Régional de Formation et d'Application en Agrométéorologie et Hydrologie Opérationnelle
AQUADEV	A Belgian NGO member of PAD
BAD-FAD	Banque africaine de Développement-Fonds africain de Développement
CEDEAO	Communauté Economique des Etats d'Afrique de l'Ouest
CIRAD	Centre International de Recherche en Agronomie pour le Développement (France)
CORMAS	Common Resources Management Agent-based System
CRESA	Centre Régional d'Enseignement Spécialisé en Agriculture (Niger)
DAP	Diammonium Phosphate
DGCD	Direction Générale de la Coopération et du Développement (Belgique)
FA	Farmers Association
FEC	Fakara Economy Control
FRC	Fakara Reputation Control
FEFW	Fakara Economy Fertilizer + Warrantage
FRFW	Fakara Reputation Fertilizer + Warrantage
FAO	Food and Agriculture Organization
FCFA	Franc Communauté Financière Africaine (1 kFCFA=1000 FCFA)
FEWS	Famine Early Warning Systems
FLU	Farming Labor Unit
FUMA GASKIYA	A Nigerien FA member of PAD
GIS	Geographic Information System
HDI	Human Development Index
ICRISAT	International Crops Research Institute for the Semi-Arid Tropics
IGNN	Institut Géographique National du Niger
ILRI	International Livestock Research Institute
INRAN	Institut National de Recherche Agronomique du Niger
IRD	Institut de Recherche pour le Développement (France)
MFI	Microfinance Institution
MOORIBEN	A Nigerien FA member of PAD
NCFCIS	Non-Cooperative Families with a Customary Inheritance System
NCFMIS	Non-Cooperative & "local Muslim" Inheritance System Families
NCFS	Non Cooperative Family Structure
NGO	Non governmental organization
NPK	Nitrogen, Phosphate and Potassium: The composition of many inorganic fertilizers

List of Acronyms

OSS-ROSELT	Observatoire du Sahara et du Sahel, Programme de Réseaux d'Observatoires de la Sécheresse et de l'Environnement à Long Terme
PAD	Projet Aide à la Décision (Improved Livelihoods in the Sahel through the development and implementation of household level bio-economic decision support systems
PRA	Participatory Research Assessment
RGP	Recensement Général de la Population
SAP	Système d'Alerte Précoce
SHU	Spatially Homogeneous Unit
SIMA	Information System on Agricultural Markets
SIMSAHEL	Agent-based SIMulation Model of SAHELian villages
TLU	Tropical Livestock Unit (Le Houérou & Hoste, 1977)
UFCIS	Unitary Families with a Customary Inheritance System
UFMIS	Unitary Family with the "local Muslim" Inheritance System
UFS	Unitary Family Structure
UML	Unified Modeling Language
UNDP	United Nations Development Program
WFP	World Food Program
ZADA	Zonage à Dires d'Acteurs

MODEL PARAMETERS & VARIABLES

Ax (t)	the weeds index
A_i (t)	the age of i at t
AS_i (t)	the value of sacrificed animals during ceremonies for i at t
AV_i (t)	the value of the animals sold for subsistence for i at t
B_i (t)	the livestock owned by i at t
B_{fi} (t)	the livestock owned by the family of i at t
ΣBov (i, t)	the number of cattle owned by i at t
ΣOth (i, t)	the number of caprines & ovines owned by i at t
C_i (t)	the number of children of I at t
CA_{di} (t)	the annual food consumption of the dependents di of i
di (t)	the number of family members of i relying on i at t
Dx	the distance from the village to the parcel x
D_i (t)	the gain of reputation by fulfilling social duties for i at t
D_{AC} i (t)	the dowry value for i to get married at t
DF_i (t)	the gifts not granted to beggars for i at t
DP_i (t)	the gain of reputation for i to get involved in development actions at t
DR_i (t)	the gifts not granted as a beggar
E	the impact of inorganic fertilizers per week
E_i (t-1)	the total value of the previous years with fertilizers;
EM_i (t)	the gain of reputation for economic characteristics of i at t
F	the impact of manure per week
$F_{drought}$	the drought factor on rainfalls
F_{site}	the site impact factor on rainfalls
Fi (t)	the members of the family of i at t
Fx (t)	the fertility level on a cell x at t
fer (t)	the fertilizing impact index on a vegetable's cycle
Frt_i (t)	the number of 80kg bags of inorganic fertilizers bought for i at t
g (t)	the average weekly gains for seasonal migration
G_i (t)	the gains of seasonal migration for an individual i at t
GF_i (t)	the gifts given to beggars for i at t
GR_i (t)	the gifts received as a beggar for i at t
Hx (t)	the herbaceous indicator on a cell x at t
I_0	the initial pearl millet constant
I_{weeds} (x, t)	the weed impact index of x at t
I_{price}	the drought impact on the following year millet price
ICx (t)	the millet cycle index on a cell x at t
ICMx (t)	the vegetables' cropping cycle index of x at t
IFx (t)	the manuring index on a cell x at t
IPx (t)	the millet potential production level index on a cell x at t
IPMx (t)	the potential vegetable yield index of x at t

Lf_i	the family lineage of i
Lx (t)	the shrubs indicator on a cell x at t
MH	the average human mortality rate
ML	the average livestock mortality rate
Mi (t)	the risk of human mortality of i at t
MLy (t)	the risk of mortality of a livestock head y
MO_i (t)	the manpower equivalent of i at t
MoF_i (t)	the i family manpower of i at t
$MoFe_i$ (t)	the available feminine manpower of i at t
N_i	the number of years of experience of the individual i
N_{CA}	the number of weeks needed for a maximum growth of weeds,
NEi (t-1)	the total value of the previous years without fertilizers
NF_i (t)	the inorganic fertilizers needs based on the property that had a better mean production with inorganic fertilizers than without.
NWi (t-1)	the total value of the previous years without warrantage
P_{dowry}	the price of two average oxen
P_i (t)	the size of the land property of i at t
Pf_i (t)	the size of the i family property at t
Pmil (t)	the price of one millet bundle
Pi / Pmax	Pi the human nutritional status of i; Pmax, the maximum value of Pi
PLy /PLmax	PLy the livestock nutritional status of y; PLmax, the maximum of PLy
PMh_i (t)	the volume of pearl millet harvested at t by i
PEX_i (t)	the part of the gains of an individual economic activity managed by i at t to be deposited in the common family pot
Rbb	the average number of millet bundles per millet bag
Rm	the average annual rainfall on the site (in mm)
R_i (t)	the individual Reputation of i at t
Rk_i (t)	the individual Rank of an individual in the family i at t
Rx (t)	the volume of rain on a cell x during t
S_i (t)	the individual Reputation from the social and economic means at t
SC_{fi} (t)	the cash stock of the family of i
SM_{fi} (t)	the millet stock of the family of i
$T_{noHarvest}$	the period of no harvesting millet
Tac (t)	the AntiClan tension index at t
Tf (t)	the land tenure tension at t
Vg_i (t)	the gain from vegetable gardening of i at t
WGC	the number of weeks needed for achieving a vegetables' cycle
VYx (t)	the harvested grain mass in millet bags to harvest on x at t
W_i (t-1)	the total value of the previous years with warrantage;
War_i (t)	the number of 80kg millet bags under "warrantage" for i at t
WC_i (t)	the weekly consumption of i at t
$Wives_i$ (t)	the number of spouses of i

THE INSTITUTIONAL POSITION: A PROJECT COMBINING DEVELOPMENT AND RESEARCH

The project entitled "Improved livelihoods in the Sahel through the development and implementation of household level bio-economic decision support systems" in which this work is institutionally included is coordinated by ICRISAT and funded by the Belgian general direction of cooperation & development (DGCD) for five years (Gérard, 2002). The objective of the project is to understand the functioning of local systems of activity and anticipates the attitudes of rural communities in a changing environment, in order to propose different decision-support tools to agricultural and economic development operators. This project seeks to combine research and development by enabling synergies between a dozen partners working in Niger: research institutions, NGO's and farmers' organizations. This project was assessed in three sites, the Fakara to the west of the country (department of Tillabéry), Gabi (department of Maradi on the border with Nigeria), and Zermou (district of Mirriah, department of Zinder, to the east of the country. Those three sites are chosen for their agro-ecological and socio-economic contrasting conditions but also for the relative abundance of existing data (reports, spatialized models and databases, remote sensing images). Each site research program is managed by two or three institutional partners: ICRISAT[1] and the farmers organization MOORIBEN[2] for the Fakara site, the FAO "Projet Intrants", INRAN[3] and the farmers' organization FUMA GUSKIYA for the Maradi site and the NGO AQUADEV[4] and INRAN for the Zinder site. This project combined three sections:

- An institutional support and the reinforcement of villages' capacities at the sites, through the support of different village councils and the support of one local radio station for each site.
- A technical support on farming practices via INRAN/ICRISAT common missions, combining demonstrations, farmer field schools, and diffusion of intensification-oriented practices and crop varieties.
- The research project through the construction of decision-support tools, in which three Ph.D. theses including this work are implemented as well as several M.Sc. theses.

[1] International Crop Research Center for the Semi-Arid Tropics
[2] Moore Aban: "stop the degradation!"
[3] National institution of agronomic research for Niger
[4] A Belgian NGO that works on microcredit.

INTRODUCTION

" Against the view of peasants as static actors and the agrarian systems as changed only by external factors, peasant logic is a product of a complex of physical, economic, and social rationality. In this sense the revival of a multidisciplinary, interactive, and institutional approach counteracts the notion of the rural world as both static and relatively isolated and shows how innovation, initiative, and transformation respond to a rational strategy by modern rural populations. (Gentili in Blanc-Pamard & Boutrais, 1997) "

1 Investigating the complexity of the Nigerien Sahel rural populations

The Sahel[5] since the great famines of the 70's and 80's (Alpha Gado, 1993) has been the focus and the stake of intense debates in terms of research and development policies. As described by Warren (2005) and Herrmann & Hutchinson (2005), only a multi-dimensional approach will allow to go beyond the shortcuts and simplifications that have been overused to describe this rapidly evolving environment. Actually, the main characteristic of the Sahelian part of West Africa is the intricate complexity of the social, environmental and economic dimensions that differentially affect the rural populations of this region.

Such an assertion may be applied to many rural societies in the world. However, in the Sahel, this complexity is enhanced by the extremely harsh environmental conditions on the one hand (Gentil *et al.*, 1993; Milleville & Serpantié, 1994; Hiernaux, 2001; Abdoulaye, 2002; Walther, 2004; Yamba, 2004; Fauquet, 2005) and by the tremendous effects that social relationships have on the evolution of the systems of activities and the related farming systems of the Sahelian villages (Balandier, 1955; Luxereau & Roussel, 1997; Olivier de Sardan *et al.*, 1995; Raynaut *et al.*, 1997). Even though the agro-ecological and economic constraints have been widely characterized, the ways in which they affect the rural population in practice still have to be

[5] The word " Sahel" in Arabic means the shore (the word "Swahili" has the same root), as the oekoumene limit vs. an alien environment like ocean or desert. It is appropriate for this meaning of boundaries and relationships between two banks: all the empires of this region were firstly commercial: Awdaghost for Ghana, Gao for the Songhay. Timbuktu and Agades were the southern desert ports that connected the two sides of Sahara.

determined. These ways are by all means social because it is the social organizations that locally determine how the Sahelian village populations provide access to natural resources and other wealth-producing assets (Bonnal *et al.*, 1997).

Therefore, addressing the complexity of this intrication between social, agro-ecological and economic dimensions is a necessary step towards a better understanding of how economic and biophysical conditions interact with social structures and behaviors to drive changes. Evaluating and estimating the nature and the relative importance of these dimensions and the ways in which they condition the evolution of the population implies investigating the pattern on which they are intricate at different levels: individuals, family, village and beyond. But the problem with such an approach is that a real dialogue between the related disciplines has yet to be built. We fully assume the citation from Raynaut (2007): "if one wants to understand the transformation processes already taking place in the Sahelo-Sudanese societies and even in all the rural societies in transition, [one has to] work with a complex model that rejects linear or univocal interpretations and that permits to describe how natural constraints, market pressures, technical practices and social and symbolic relationships are combined into a global system of interactions".

A further step beyond such a conceptual model as suggested by Raynaut is quantitative modeling. Actually, a modeling approach appears unavoidable if one wants to explore the differential consequences of these intricate relationships on local dynamics. Building such a model is a challenging task that cannot be achieved at the level of a single thesis. We therefore propose to restrain the study by focusing on the most prominent levels and factors that may condition this complex system and its evolutions and to focus the research on the economic activities and the different factors that affect them, because they define the differential living conditions of the population. This approach is facilitated by recent modeling tools, e.g. Agent-based models, which are designed to allow a dialogue between different scientific approaches (Rouchier & Requier-Desjardins, 1998).

For the Sahelian rural population, the village and its "terroir"[6], as well as the family are still the most important levels for the management of economic

[6] The French word "terroir" is defined both geographically (the set of space managed and exploited by a village community: Raison & Coniat, 1997) and socially (a socially defined territory containing a set of resources and associated rights to these resources: Bassett *et al.* 2007). It is therefore a geographically defined territory, but whose definition is social: it is the geographical framework of life of a rural society. For Sahelian West Africa, this spatial unit should be considered as the most

activities. However, strong centrifuge forces affect these levels (Olivier de Sardan, 2003b; Yamba, 2004), implying that the individual is also a relevant scale for the study of these societies. Therefore, we develop an approach that combines the three scales, i.e. villages made of families and individuals who have differing access to economic assets.

Such a model may encounter many inconsistencies especially between social and anthropological sources if its fundamental structure is only based on literature. A game-theory approach leads to omit the problem of the intrication of the concerned relationships and dimensions. Therefore, we stand on a field-based approach where field results support the local consistency of the model and guide the selection among the concepts, informations and data from the literature. Such an approach provides more confidence on the practical relevance of the results but also helps to favor the dialogue between the different concerned dimensions. To extend the geographical domain of application of the model, the research is carried out on three study sites that constitute contrasted situations of the Sahel. Logistic, temporal and institutional contingencies impose the selection of the three sites within the Sahelian region of the Republic of Niger.

2 Research objectives and challenges

The overall aim of the thesis is to better understand the socio-economic dynamics of the rural societies of the Nigerien Sahel by developing a modeling approach addressing the complexity of the relationships between the population and the factors that affect it, i.e. the economic and biophysical environment, the social structure and external interventions. Most specifically, the research focuses on the differentiation factors that discriminates the components of the population facing environmental and social constaints. The main contribution of this thesis is to consider that these factors occur at the family level, yet assuming that decisions are taken at the individual level. The key-steps are thereby to decode the components of this social space, to formalize them through a dynamic model that can explore the complexity of the Nigerien villages' situations and to provide insights to research and development issues.

1. Consequently, the first specific objective is the building of this multidisciplinary methodology, with an ABM model as the main medium (Amblard & Phan, 2006). We then propose to test this methodology by applying it on several research issues that have strong implications for the development in this region, thereby fulfilling the

pertinent for farming system analysis (Bonin *et al.* 2001). It corresponds to the notion of "finage" used in Europe, i.e. a legal spatial unit designating the territory possessed and used by the inhabitants of a village (Landais & Deffontaines, 1987).

mandate of the research and development program that hosted us. These research issues are as follow:

2. It is well known in the research community working on Sahelian Niger that the everyday access of the villagers to production assets in the Sahelian Niger is controlled by social factors (Raynaut, 1988; Luxereau & Roussel, 1997; Rain, 1999; Olivier de Sardan, 2003b; Yamba, 2004). But the relative influence of such elements still has to be investigated. Our second specific objective is therefore to simulate and estimate the impacts of several social differentiation factors on the dynamics of individuals, families and the population and on the distribution of production activities. The impact of the biophysical environment on this evolution is assessed by applying the model to three contrasted areas of Sahelian Niger.
3. Our third specific objective is thereafter to use the model to analyze the villagers' responses to development interventions according to the specific agro-ecological and socio-economic characteristics of the study sites. These two development incentives are inorganic fertilizers availability and inventory credit. They have been selected for analysis because they are emblematic of development strategies in the country and are even considered as the most promising development techniques by many institutional development operators. Moreover, they are the most prominent proposals the institutions associated in the project try to promote in the different investigated sites.
4. Finally, we propose to confront our hypotheses on a longer time perspective. Raynaut (2007) presents the changes that affect Sahelian societies as a consequence of modifications of farming systems[7]. The origin of such modifications is seen as external, namely demographic growth and economic globalization. However, Sahelian societies quickly evolve and social evolutions have to be considered. We hypothesize that social changes may be the catalytic factor and the medium through which these farming system transitions operate. Our fourth and last specific objective is therefore to estimate the impacts of transitions in family structure on the evolutions of the populations, their systems of activities and the related farming systems.

To reach the objectives, two connected challenges have to be dealt with:

[7] A farming system, in the enlarged definition of the term by including other extra-agricultural activities, is the organization mode adopted by a rural society in order to exploit its territory and manage its resources. It is also the result of the history of relationships between a rural society and its environment, a history in which the countryside was shaped and technical, economic and social rules were conceived to manage and use the environment (Jouve & Tallec, 1994)

- A field challenge: The challenge is to decode the complexity of the relationships that condition the access to economic and production assets among villagers (Lavigne-Delville, 1999). Indeed, we assume as a working hypothesis that social relationships have a strong impact on individual, family and village evolutions. People are not only producers, but their production activity is part of a system conditioned by social relationships. This implies characterizing the heterogeneity and identifying the discrimination factors between villagers in their access to production means and the use of the related income.
- A methodological challenge: it is about building a behavioral model for several contrasting villages of the Nigerien Sahel that is capable of combining information from different disciplines. Agent-based modeling is an efficient and flexible approach for integrating different types of information and data[8] coming from various sources and for simulating the interaction between different aspects of a complex reality in a dynamic way.

3 Scientific tools and disciplines

As noticed in the preceding section, there is no *a priori* restriction on the disciplines called upon in this study as far as they concern the same object, the rural populations socially and spatially living on a regular basis in the terroir[9]. Four concepts and tools are used:

- The "farming system" systemic approach as described by Mazoyer & Roudart (1997) is a way to apprehend a "terroir" and the related society as a dynamic system. It thereby allows apprehending farm strategies, the resources management and improvement logics that are used by the different groups of a society. This tool also helps to rebuild the historical evolution of a farming system.
- The "development anthropology" as described by Olivier de Sardan (2003a) proposes field investigation methods that allow understanding the present-time social organizations and fractures in a society viewed not as a stable and stabilized system but on the contrary as an arena as suggested by Lavigne-Delville (1999), i.e. a social space where individual and/or collective interests may create conflicts. Farming system and development anthropology approaches are tools that, when

[8]Informations (expert-based, local interviews, direct observations, etc.) allow getting relationships and dynamics while data (maps, demography, etc.) can parameterize these relationships (OSS-ROSELT-Niger, 2006).

[9] We do not therefore include traders, officials, politicians and transporters in that group. A second restriction concerns semi-nomadic and transhumant livestock herders in the work.

combined, allow comparing local strategies in the same "terroir" (Faure, 1997).

- A geographical zonation appraisal at meso-scale (Caron, 2001) based on the villagers' perception of their territory (ZADA[10]), contributes to the understanding of the differentiation and interaction processes, common drivers and specificities that characterize and discriminate the different parts of a regional territory. Combined with the two previous disciplines, it helps build a conceptual model of such rural societies.
- The modeling of the villagers' relationships by agent-based distributive simulations. Agent-based models (ABM) permit to represent social systems based upon interactions between entities that are called agents (Rouchier, 2000; Feuillette, 2001). The three above-mentioned tools (farming systems, development anthropology, ZADA) provide information and data for this spatialized ABM. The advantage of ABMs is that they allow redefining the driving factors for each of the entities in a weighted and discriminated manner.

4 Outlines of the thesis

This thesis is structured in six sections.
The first chapter groups all the elements that concern the studied field and the associated problematic. We first present a global description of the Sahelian Niger characteristics and evolutions. In particular, we present the main production and economic activities that are practiced in this part of the country. We reposition this description along its historical pathway, together with a brief historical reconstitution of the farming systems and the related social and family relationships. All these sections provide the elements needed to build the different concepts and hypotheses we used and developed in this thesis.

The second chapter concerns the field materials and methods. The three sites we investigated are presented here. We then present the field investigation tools we used from which we derived the variables used for conceptualizing these rural societies and for building the rules that support their functioning. It is followed by the results of the perception-based zonation carried out in two of the three sites.

Chapter 3 is dedicated to the modeling choices and concepts. The implementation of the SimSahel Agent-based model, which resulted from these choices, observations and hypotheses, is then presented. We first justify our choice of the Agent-based model as the most relevant model type

[10] French Acronym for “Zonage A Dires d’Acteurs”, i.e. local perception-based zoning.

for such societies and problematics. We then present the way in which we use the ABM tool, by establishing the different assumptions, hypotheses and concepts that are necessary for such a model. The model implementation is thereafter presented. Finally, we present several results concerning a sensitivity test on several selected parameters and a confidence building exercise to test the model validity and robustness for further uses.
The subsequent steps address the three earlier-mentioned research questions that are central to this thesis[11]. These questions are elaborated according to investigation results and have been translated into scenarios implemented in the SimSahel model.

Chapter 4 concerns the impact of family organization on the access to production assets and the sustainability of the rural population. Two scenarios are considered, one corresponding to the patriarchal family archetype, the other one being a model of a mononuclear family. This present-day version of the social dimension allows exploring a hypothesis regarding the historical dimension of social family evolutions.

Chapter 5 introduces development interventions through two emblematic actions proposed to a present-day village. These two actions are on the one hand support to inorganic fertilizers, a tool that mainly seeks to maximize crop productivity, and on the other hand an inventory credit called "warrantage" as a potential food-security enhancement tool. The concept of reputation is introduced in the model and several scenarios are proposed and analyzed.

In the sixth and last chapter, we consider a longer-term perspective by analyzing the effects of family transition processes on farming system evolutions. This is based on the hypothesis that family organization changes may be the transmission belt of these transitions of systems of activity and thereby of farming systems. It allows reinvestigating both social and geographical dialectics that are discussed in the previous chapters from a more historical perspective, as suggested in chapter 3.

Note: *As specified at the beginning of some chapters, the thesis is based on adapted versions of manuscripts that are published, submitted or about to be submitted to peer review scientific journals or conferences.*

---

[11] Impacts of social differentiation factors on individuals, families and population, villagers' responses to development interventions, family structure transitions and their impact on sahelian societies.

CHAPTER I: RURAL POPULATIONS AND FARMING SYSTEMS OF NIGERIEN SAHEL

Note: Sections of this chapter are adapted from a text presented at the 23rd" "Journées du Développement de l'Association Tiers-Monde" (may 2007) and accepted for publication in VertigO 8: 2 "Le désert & la désertification : impacts, adaptation et politiques" (Saqalli, M. "Le pouvoir des savoirs: enjeux des conceptions sur le développement rural pour le Sahel Nigérien").

This chapter is a presentation of the context and stakes of the study. We present the conditions and constraints of the Nigerien Sahel and a brief history of the farming systems along the 20th century that conditions the present-time systems of activities in this region. This presentation supports the description of the concepts to test in the following chapters:

1. The impacts of factors determining the intra-family structure: the family rank*gender*age matrix, the reputation.
2. The impact of factors that conditions the intra-family evolutions: the inheritance system and the family organization
3. The impact of development interventions on the village populations.

1 The Nigerien Sahel: living on the edge.

1.1 The Sahelian part of Niger

Niger is a vast and landlocked country of West Africa (1,227,000 km²) covered by the Sahel in the south of the country and the Sahara in the north. It is bordered to the west by Burkina Faso and Mali. Libya and Algeria are at its northern boundaries while Chad is its eastern neighbor. The south of the country is bordered by Benin and Nigeria. There is a strong north-south rainfall gradient with less than 50 mm annual rainfall in the north and 800 mm in the southern tip (Figure 1).

One single rainy season occurs from May to October[12]. The 300 km wide southern fringe can be divided in two zones. In the northern one, the climate is Saharo-Sahelian; agriculture is almost absent[13] and very uncertain and transhumant and/or nomad livestock keeping is dominant (Graef & Haigis, 2001; Sicot, 1989). The southern part of the country belongs to the Sahelo-Sudanese environment and covers 15% of the national territory, around 200,000 to 300,000 km². This southern Sahelian Niger allows rainfed agriculture and carries approximately 90% of the population (12 to 14 millions inhabitants in 2007), of which 85 % live in its rural part. We called this latter area the Nigerien Sahel or rainfed Niger, characterized by the possibility of cultivation thanks to rain. This area constitutes our area of study. It is designated thereafter "Nigerien Sahel", as we assume that this attribute is restrictive. The usual meaning of Sahel covers the whole pastoral zone as well (Raynaut *et al.*, 1997).

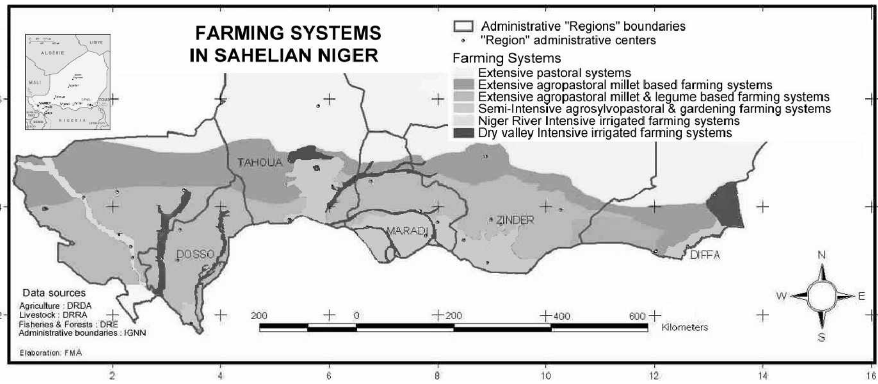


Figure 1. Farming systems of Sahelian Niger (AGRHYMET Publication, 2004)

This Sahelian zone is mainly occupied by three important ethnic groups: The Zarma-Songhay in the west (3 to 4 millions) along the Niger River, the Hausa in the center (6 to 7 millions) and the Kanuri (1 million) in the east right up to lake Chad (Tandia, 1991). One should add around a million Fulanis, initially semi-nomad, transhumant or nomad herders and slowly becoming sedentary, spread across this zone and the pastoral northern zone.
The Nigerien population combines the highest fecundity rate in the world (7.1 children per woman[14]), the lowest UNDP rank for human development index (HDI), and one of the lowest levels of income per capita ($900 purchasing power parity) (UNDP, 2005).

[12] Except some rare "mango rains" at the end of the cold season, i.e. in March
[13] Except the irrigated fields in the oasis
[14] 7.46 in 2007

1.2 The Nigerien Sahel: A historical perspective

Niger presents the singular characteristic of very prestigious but multiple historical influences. Each major human group of this country is linked to strong Empires or powerful organizations (Songhay empire, Hausa city states, Kanuri empire of Kanem-Bornu, Fulani empire of Sokoto, large trading, enslaving and combating Tuareg clans), giving pride and legitimacy to each one as a reminiscence of a prosperous past.

The main source of wealth came from the transsahelian West-East trade and the transsaharian north-south one. The collapse of the Songhay Empire in 1591 was followed by a period of decline and the beginning of all the subsequent troubles from the 17th to the 19th century. Several poles of power appeared and fought against each other, resulting in broad frontiers or fuzzy fighting fronts crossed by slavery raids, and where insecurity reigned. The Figure 2 shows these poles as at the end of the 19th century right before the French colonization:

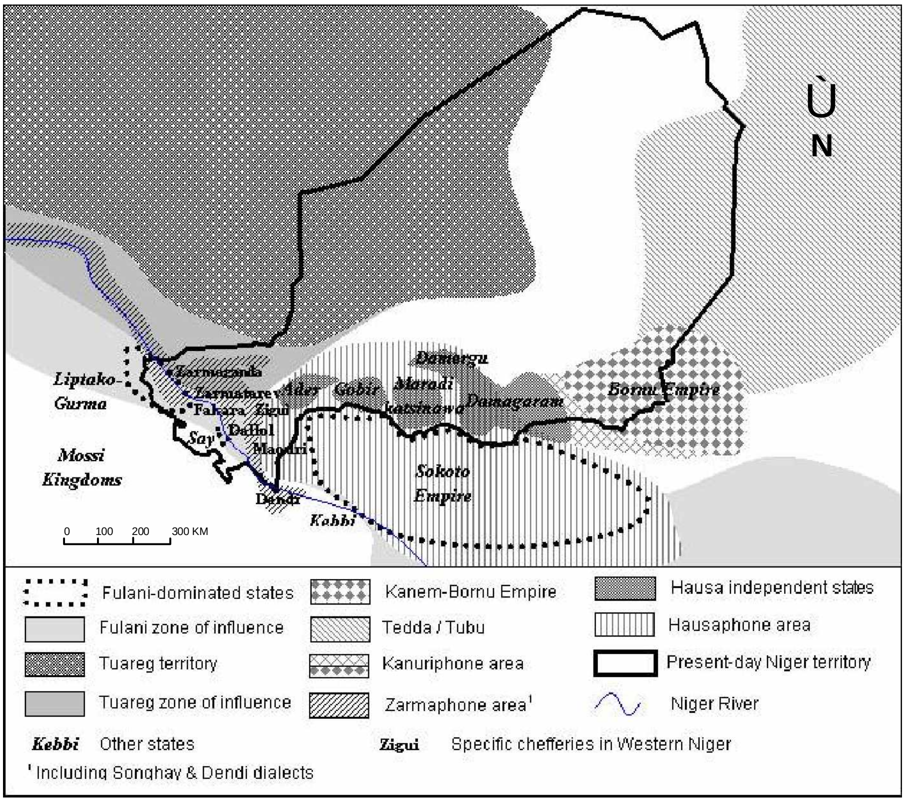


Figure 2. The Nigerien territory around 1880, based on Ki-Zerbo (1972), Poncet (1973), Coquery-Vidrovitch & Moniot (1974), Alpha Gado (1993), Olivier de Sardan (2003c) and M'Bokolo (2004).

These poles could be briefly described as follows:

- Several Tuareg clans, expanding mainly on the zarmaphone zone, dominated the territory to the north and the west without settling in it.
- To the south, the new Fulani empire of Sokoto: originated from the jihad of Osman Dan Fodio, this empire was occupying most of the Hausa-populated part of present-day Nigeria. By distributing banners to various newly constituted emirates, it supported some sorts of "joint-ventures" all over the Sahel: the Fulani-ruled Liptako-Gourma on the "Gurma" bank of the Niger river in the territory of present-time Niger, the empire of el-Hajj Omar in the neighboring Mali, the religious city of Say, etc. Some non-state-ruled territories were also under Fulani control, such as the Boboye. A large part of the zarmaphone territory was also under control of several Fulani-originated aristocracies.
- The remaining Hausa sultanates, struggling against the Sokoto conquest: the refounded Katsina sultanate with the new town of Maradi, Ader, Gobir, and Damagaram/Damergou with Zinder as capital city.
- The eastern kanuriphone Kanem-Bornu Empire, slowly declining, facing mainly the rising Hausa-ruled Damagaram.

As an example of these "frontier" spaces, the Fakara in the western part of the country may have been under the domination of a "chefferie"[15], but under the permanent threat of slavery raids. Consequently, villages could not spread out by expanding fields and creating new villages and stayed locked on or close to the plateaus or other defensive sites, as shown in Figure 3.

The Gabi "chefferie" south of Maradi was also at a border between the Sokoto Empire and the refounded sultanate of Katsina. The region of Zermou northeast of Zinder was a kanuriphone zone under the domination of the Hausa sultanate of Zinder, as a march against the Kanem-Bornu Empire. Thus, as described by Raynaut *et al.* (1997), the present-time population distribution in the Nigerien Sahel is a result of both biophysical and historical factors. "It is history that explains the strength of the biophysical factor in the population evolution " Raison & Coniat (1997).

[15]The French word "chefferie" was the colonial administrative term for a small fief ruled by an aristocrat family. This word was then used by the colonial power and is still used in Niger.

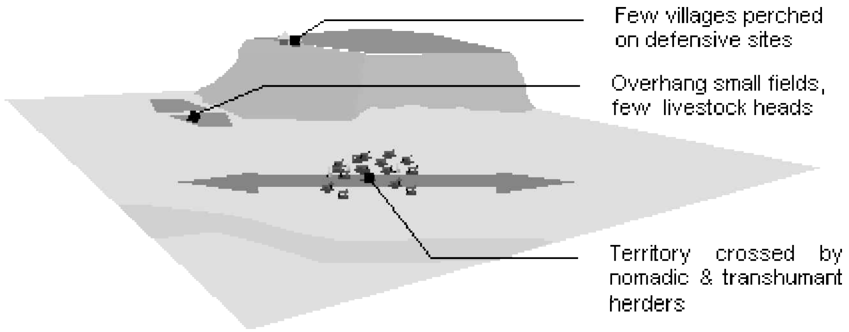


Figure 3. Land occupation in the Fakara at the beginning of the 20th century

The French penetrated the Niger territory at the very end of the 19th century leading to a series of famines, epizooties and massacres that strongly affected the population Alpha Gado 1993)[16]. According to several authors, we can consider that between 1850 and 1910, livestock decreased by 90% and the population by 30% in West Africa (Coquery-Vidrovitch & Moniot, 1974). However, the conquest allowed the *pax Francia* to be politically and militarily imposed and settled[17]. It allowed the population of Nigerien Sahel to go out and conquer its own national rural "frontier", i.e. its own potential cultivable land, by spreading out fields and new villages, as shown in Figure 4. The forced labor, the new taxes and military service also contributed to this scattering by pushing the concerned population (mainly the young men) to escape such enrolments. Consequently, nine villages out of ten in present-day Nigerien Sahel are less than 150 years old (Raynaut *et al.,* 1997; Vanderlinden, 1998). This has implications for the initialization of the model as described in chapter 3, because it implies that we can create "realistic" villages of Nigerien Sahel by simulating population dynamics over a limited period of time (50 – 100 years). Moreover, such colonial practices favors the seasonal migration of these young men for the English-ruled colonies, Golden Coast (present-day Ghana) and Nigeria in particular. This seasonal migration increased thereafter with the expansion of the transportation systems. The migration has thereby to be implemented in a model.

---

[16] Let us recall the awful crossing of the Voulet-Chanoine expedition all along the Nigérien Sahel (at least 20 to 40,000 assassinated persons, reminded as the "Sar-Sar" in Hausa), which lead to a great famine by burning the storehouses.

[17] Let us however recall that peace and security were fully established all over the present-day Niger in the 16th century, when the Songhay Empire, the Hausa city-states and the Kanem-Bornu Empire were at their heights.

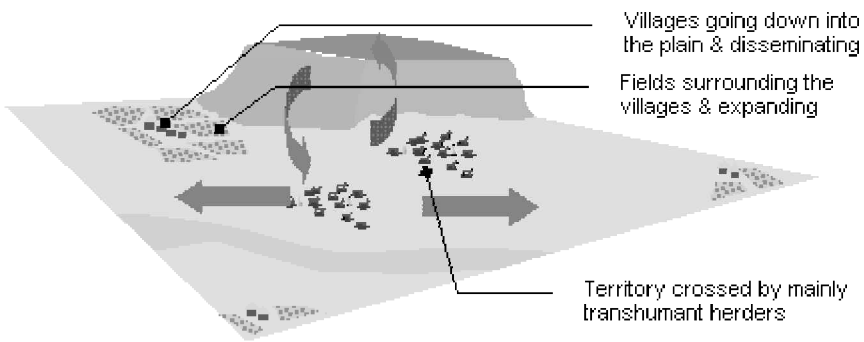


Figure 4. Land occupation in the Fakara between 1920 & 1940.

As a consequence, farming systems have evolved during the last century towards the generalization of an extensive land-clearing mode, with a dissemination of the combined cropping/ livestock keeping multi-activity (Jouve, 2004). In 1950, only about 10% of arable surfaces in the Sahelian zone were actually cultivated but the number of villages had increased tenfold during this first half of the 20th century (Loireau-Delabre 1998).

With the subsequent demographic explosion, mainly after the 1960 independence, the number of inhabitants has increased from 3 to 12 million in 2002[18] (Guenguant *et al.*, 2002), which has accelerated the land conquest during the last fifty years. The increase of the number of new village settlements slowed down but this has lead to "fill the gaps" between villages and semi-nomad encampments. As illustrated in Figure 5, the extension seems to have reached its end, with a progressive saturation of the arable land as highlighted by the reduction of pluriannual fallows (Banoin & Guenguant, 1999) and the decrease of long-distance transhumances (Augusseau *et al.*, 2006).

[18] And maybe 14 millions in 2007

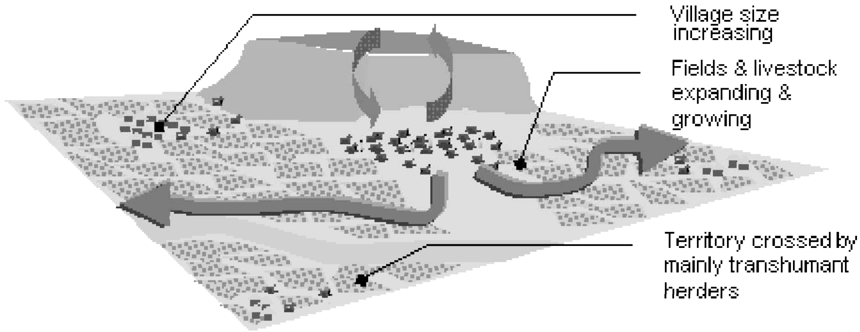


Figure 5. Land occupation in the Fakara between 1940 & 2000

However, the extent of this conquest is variable depending on the regions of Niger: In southern regions of the country, at the border with Nigeria, and in particular the central southwestern part of Nigerien Sahel (Region of Maradi), the territory is entirely occupied (up to 200 inhab. per km^2) (Mortimore *et al.,* 2001), whereas the field extension still proceeds in the north of the region of Zinder (central South-east), particularly towards the eastern direction, but this field settlement movement seems to be slowing down in the region of Niamey (south-west)(Mounkaïla, 2003). If one includes short-term fallows in the cropped area, this zone is almost already cultivated up to 90%, of arable land but manpower begins to lack (own observations 2004-2005).

Therefore, the present situation is far from being stable and these driving forces, and particularly the demographic one, still play the main role in the evolution of farming systems. Modeling such farming systems implies to reject the conception of a stable equilibrium between natural resources and population as a relevant scenario.

1.3 Economic production activities in Nigerien Sahel

Here we present the different activities that are carried out in the Sahelian villages. Some activities concern only a specific social group, such as men for seasonal migration. Meanwhile, people are not specialized towards one activity and pluriactivity is generalized. A simplified calendar of the activities, the livestock movements and the main social annual events for the Sahelian Nigerien regions is shown in Figure 6.

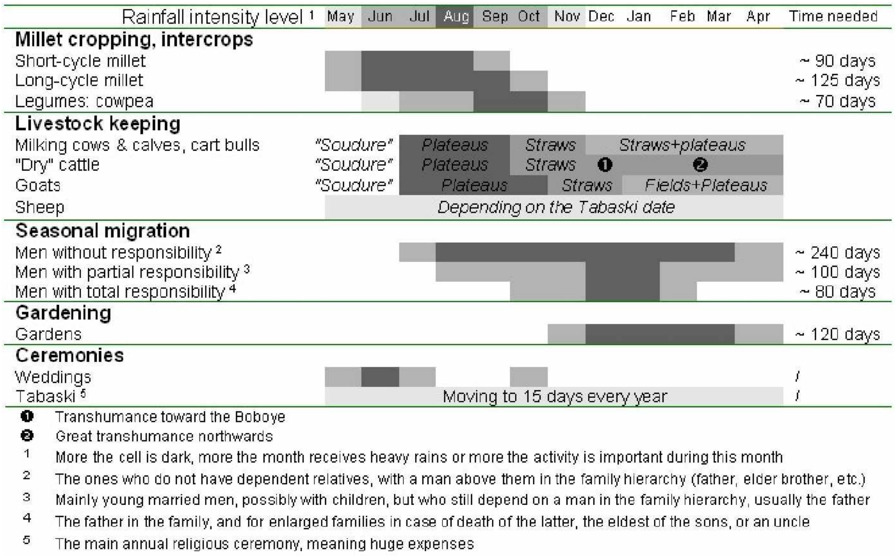


Figure 6. Calendar of activities in Sahelian Niger (Loireau-Delabre, 1998; own data 2004-2005)

1.3.1 Agriculture

In Sahelian Niger, rainfed agriculture is the main activity in terms of land and manpower requirement, but only during the short rainy season (Abdoulaye & Lowenberg-DeBoer, 2000; Abdoulaye, 2002). It is considered as a strong norm that men should be the farm managers[19], using their dependants as manpower. The main cereal is pearl millet (*Pennisetum glaucum L. Br.*) and sorghum (*Sorghum bicolor L. Moench*) in the south of the country, both often associated with cowpea as legume (*Vigna ungiculata L. Walp*) (Ada & Rockström, 1993). Agriculture is presently managed in an extensive and anti-risk approach. Given the very low inherent fertility of the soils and the high spatial and temporal intra-annual and inter-annual rainfall variability (Sangaré *et al.*, 2001; Gérard & Buerkert, 2001), farmers tend to clear and sow more surface than they can manage and harvest for food security and tenure purposes (Loireau-Delabre, 1998; Graef & Haigis, 2001). The farmers' parcels are scattered in the "terroir" according to the distance to the village and soil quality mainly, and even sometimes on several "terroirs" (Loireau-Delabre, 1998; Abdoulaye, 2002). This spatial dispersion of fields helps to mitigate the effects of the rainfall spatial variability on crop yield (Seybou, 1993; Minet, 2007). All the cereals are sown after the first rains, in

[19] And most often also the family managers

May or June[20]. Indeed, sowings can often fail and villagers have to repeat them several times in a parcel, up to five times a year (Loireau-Delabre, 1998). The main manpower peak occurs during weedings in July[21]. The main part of the cereals are harvested in September-October but some short-cycle varieties can be harvested in August but need more manpower and better soils.

1.3.2 Livestock keeping

Livestock represents the second "traditional" activity of the Nigerien Sahel, as it is described as a key component of the farming systems of this region for centuries (Ki-Zerbo 1972; Boulier & Jouve 1990; Jouve 1991).
Considering the harsh conditions and the variability of the rainfall, the livestock keeping system in the Sahelian part of Niger was in the past almost totally transhumant and nomadic (Milleville, 1989; Sicot, 1989). Herders in this part of the country were mainly Fulanis[22]. Their livestock were largely composed of cattle and some goats, these lasts usually belonging to the Fulani women. Every year during the rainy season, they were moving to the grazing areas of the North such as Azawagh of Mali and Niger, Toukounous, Damergou, etc. (Hammel, 2000). After the livestock "cure salée" ("*mbagoriire"*) in October[23] and the millet harvests in the South, they were coming back to graze the post-harvest straws and remains in the bushes during the whole dry season (Bernus, 1994)[24].

Meanwhile, some herders were pasturing on a lower scale, using some close environmentally contrasted sites. For instance, transhumant Fulani herders were transhuming from the dallols of the western part of the country to the bordering plateaus[25] (Boutrais, 2007). No transhumance to the south was

[20] The main variability of the rain cycle is the delay of the first rains, that may fall from May to even July, which is very important because the sowings are realized only after these first rains and the cereal cycle may thereby not be achieved at the end of the rainy season.

[21] Usually, farmers have to weed once, more probably twice and sometimes thrice in case of heavy rains and good soils.

[22] The livestock keeping Tuaregs were controlling the northern part of the country.

[23]At the end of the rainy season, the soil evaporation let the mineral salts (NaCl, KCl) to cover some specific clayish camps (ponds, dry valleys). The "cure salée" is a herders' meeting who bring their herds onto such places during specific times for sanitation purposes.

[24] Some herders were moving thereafter their herds until the Niger River to graze the semi-aquatic burgu grass (*Echinochloa* spp.)

[25] For instance, transhumant herders were leaving the dallol Bosso at the beginning of the rainy season for the western plateau of the Fakara or the eastern plateau of Zigui. They were coming back in the Dallol at the end of the rainy season and just

possible because of the trypanosomes (tsetse flies). However, such systems need large grazing areas for the dry season pastures. Actually, the sedentary populations were having only small herds and were leaving the few cattle they owned to be kept by the Fulanis. Finally, the complementarity between the two juxtaposed but separated systems was realized through manure contracts: a herder keeps his herd upon a field to manure it. In exchange, the field owner gives millet or cash.

The expansion of farmers on the territory has reduced the grazing areas during the 20th century (Barbier & Hazell, 2000). The droughts of 1973 and 1984 have been the catalytic shocks that have transformed the Nigerien Sahel livestock systems (Thébaud, 1996):

- The sedentary farmers have increased their own livestock, which now constitutes one of the key foraging/manuring components for the sustainability of their mixed farming systems (La Rovere, 2001). Manure contracts have almost disappeared (Turner, 1999) because of the lack of grazing camps around the fields (Banoin & Achard, 1998). Meanwhile, the proportion of the small livestock in the herds increased for both sedentary farmers and herders. The latters slowly evolve towards a shepherd status for the sedentary farmers (Hamidou, 2005). The ownership distribution of such animals is more "democratic", i.e. the proportion of women and young men owning goats and/or sheep has increased (Shiawoya, 2006). However, the purchase of cattle is still unofficially restricted to men[26]. Finally, the disappearance of the grazing areas let the conflicts between farmers and herders to rise all over the Nigerien Sahel (Lycklama, 2000; Thébaud & Batterbury, 2001; Turner *et al.*, 2005).
- Transhumance routes and practices have changed. The survival movements of the herders during the great droughts have opened new routes to the south (Boutrais, 2007). Thanks to new veterinary techniques, the Fulani cattle races are now able to stay several months in the southern countries (Benin and Nigeria). Moreover, grazing areas of the north become insecure (rebel movements, theft, custom officers between Mali and Niger). Therefore, a dry season transhumance appeared oriented towards the south and became dominant, to the detriment of the north-oriented rainy season transhumance (Peyre de Fabrègues, 2001; Augusseau *et al.*, 2006). The latter still continues but on a smaller scale and limited to some Fulanis (Boutrais, 2007). The

after the harvest to assess their own "cure salée" (*hurfaare*) in the ponds of the fossil valley.

[26] Malicious gossips are generated if a woman shows enough money to buy cattle, and even more if she is not married…

main stake is now to put away the sedentary-owned livestock from the too small grazing areas during the dry season, with Fulanis as livestock keepers (Hammel, 2000).

1.3.3 Seasonal Migration

Most men migrate each dry season, from October to May[27], to try to find work in the main employment and business centers of the countries bordering the gulf of Guinea (Reardon, 1994; Timera, 2001; Mounkaïla, 2003), usually as small traders, "chaïmen" (tea sellers)[28] and other small commercial activities. This activity is ancient (Franqueville, 1973) and rapidly growing: one can estimate that more than 1 million men migrate every year (Guenguant *et al.*, 2002; Mounkaïla, 2003), i.e. around 30 to 80% of men in working age migrate depending on the areas in Niger (Reardon, 1994). According to our investigations in 10 western Niger villages, the percentage of adult men who migrate in the gulf of Guinea varies from 70 to 90% depending on the local opportunities for extra-agricultural income generation, which reduce the need for migration (presence of a market or of dry season activities), but also the age. The migrants are rather young, between 20 and 40 years old[29]. In the entire Zarma-Songhay zone, this migration is mainly orientated towards Ghana and Côte d'Ivoire (Mounkaïla, 2003). In the Hausa zone, the flux is almost entirely directed towards the also Hausa-populated Nigerian neighbor (Rain, 1999).

Seasonal migration allows reducing the number of people feeding on the millet stock, leaving more food for those who stay home. Moreover, the financial transfers of these migrants, including clothing for the whole family, represent an important contribution to families staying in the village, around 8 to 30 € per inhabitant per year (290 € per family per year) (Ada & Rockström, 1993; Luxereau & Roussel, 1997; Loireau-Delabre, 1998; Abdoulaye, 2002; Mounkaïla, 2003; Harragin, 2006; Van Dyck, 2007; own surveys 2004-2005).

These funds do not seem to transform the local economic structure yet, according to our observations and analyses by other scholars. They are mainly used to fulfill food requirements that are chronically not covered by agriculture (OSS-ROSELT-Niger, 2001), but also the various expenses for

[27] The Hausa word for this activity is "*Cin Rani*": eating the dry season (Rain, 1999).
[28] A Hausa metaphor for migration in the Damagaram is "tea-making" (own investigations, 2004-2005).
[29] This slice constitutes a very important proportion of the population: in 1999, it constitutes 34.5 % of adult men of Nigerien Sahel (less than 70 years old) (RGP, 2001).

social purposes and ceremonies (marriages and religious rituals[30]) and for male ostentation purposes such as cigarettes or sunglasses. Once back from migration to the village, migrants also buy small ruminants, thereby saving some money from the requests of the enlarged family, and allowing them to pay the next migration travel expenses. Departure time is normally after crop harvest in October/November[31] but many young bachelors frequently leave earlier, arguing that there is still a married male in charge remaining at home to handle crop harvest (own surveys 2004-2005).

1.3.4 Gardening

Dry season vegetable gardening is practiced during the dry season only in places where wells, marshes and valleys give access to shallow groundwater in talweg fields. Two types of valleys are observed in Sahelian Niger: the Dallols in the western part of the country[32] and the Goulbis in the eastern part [33]. Social access to gardening varies according to the region: it is actually restricted in the Zarma areas to married and respectable women with family manpower (daughter-in-laws and/or unmarried daughters). By owing obedience, they free the elder from heavy domestic chores and give time for gardening. These women can borrow some land in the talwegs after the millet harvest. This activity provides annually between 20 and 70 kFCFA (30 to 105 €) per gardener (Hamidou, 2005; Van Dyck, 2007; own surveys 2004-2005).

---

[30] Based on our own investigations, each marriage costs about 1 150 € excluding the dowry the man should give to the bride's family (a sum equivalent to two bulls, i.e. almost 300 €). Several studied villages have seen some earnest meetings to get collective agreements to lower the marriage cost inflation. Tabaski or Aïd-el-kebir is the main annual Muslim feast, where a sheep should be traditionally sacrificed, is a time when sheep prices reach 5 to 6 times the usual price, reaching 135 € against 30 € "off-season".

[31] 2004 & 2005 have seen a delay in the departure due to the temporal proximity of the Tabaski ceremony.

[32] Dallol is a vernacular Fulani word for the large north-south–oriented fossil valleys (more than 20 km in width) connected with the Niger River basin in the western part of the country. Water never run in it even during rainy seasons but shallow water is one meter deep. Soils are globally very sandy and even salty in the center of the valley, and consequently not arable. Therefore, irrigated fields are mainly on the borders of such valleys. The Boboye is a former political unit ruled by the Fulanis in the Dallol Bosso.

[33] The Goulbi is a Hausa term designating fossil valleys in the central Hausaphone zone. These goulbis are however smaller (less than 5 km in width) than in Dallols and without salty emissions. Water is easily accessible and even run after heavy rains during rainy seasons. The soils are generally more clay and globally better than that of the dallols. They constitute thus a privileged site for irrigated cultivations.

In the Hausa areas, mainly men are the garden managers. The profitability of these gardens depends largely on the local characteristics, access to irrigation, extension of the irrigable fields, access to markets and transportation, etc. Such characteristics are highly variable (Raynaut 1989; Waziri Mato, 2000; Bouzou 2000; Mortimore *et al.*, 2001; Phillips, 2007).

1.3.5 Other activities

Gardening, seasonal migration and livestock keeping are practiced all over the Nigerien Sahel. Handicraft, livestock trading, trading in general (small village shops, market traders) but also the "maraboutage"[34], the "fonctionnaire"[35] are also common activities one may observe in a village. However, these are not practiced by every family in the village and have little impact according to our own investigations (2004-2005) and literature (Tandia, 1991; Seybou, 1993; Ada & Rockström, 1993; Reardon, 1994; Luxereau & Roussel, 1997; Loireau-Delabre 1998; La Rovere, 2001; Timera, 2001; Mounkaïla, 2003; Hamidou, 2005; Phillips, 2007).

1.3.6 Section conclusion

One may notice that the Nigerien Sahel is strongly ecologically constrained: the search of satisfaction of agricultural needs comes up against poor and fragile resources (Breman *et al.*, 2001; Osbahr & Allan, 2003) and a very spatially and temporally variable and limited volume of rainfall (Sicot, 1989) (Mainguet & Da Silva, 1998). Farming systems in Niger are nowadays disrupted by extraneously strong factors (unprecedented demographic growth, repeated droughts). This situation induced or will probably inducea transition toward another ways of resource uses depending on the characteristics of the regions of Niger (Jouve, 2006). Therefore, we consider the present time distribution of the population and the organization of the farming systems as the result of the combination of the natural resources and the historical evolution due to political factors (end of insecurity, colonization and independence) and not only a simple adaptation to agro-ecological constraints. The Sahelian rural society still evolves. The drivers of this evolution are mainly family-determined: economic activities are more and more individually managed. Whereas several social elements still condition the hierarchy at the family and the village level (family rank, age,

[34] This Franco-Senegalese word (from the Arabic word corresponding to "religious retreat") means both the people that teach the Coranic precepts and verses to "talibé" children (the main education system in the Sahelian Niger) and the people who propose/sale magical/religious rituals to the population.

[35] Unfortunately for all the literate population of Niger, the major part of the salaried jobs belongs to government because the private sector is quite absent.

gender, reputation), two drivers are transforming the functioning of the families themselves. Finally, such elements have a considerable influence on the impact of development interventions. The following sections deal with these social factors that we consider as having a crucial influence on farming system transitions.

2 Family-based determinants of population evolutions

2.1 An adaptation capacity to acknowledge

On a geographic point of view and to cite what Bradley wrote in his preface of "Sahels, diversity and dynamics of the relations between societies & nature" (Raynaut *et al.*, 1997), there is not "one single Sahelian agriculture but a large panel of agricultures, each one positioned in the Sahelian region", each one being a constrained and circumstantial combination of social organization (power centralization level, social stratification, modes of circulation and distribution of goods more than the ethnic origin), of the resource management practices (distribution of functions between land and labor) and of the state/dynamic of resources themselves. The human density distribution map shown in Raynaut's book does not coincide with the soil potentialities, but a lot more with historical contingencies. The densest places of the Sahel are on the whole the places that had to suffer the least from wars and raids. We cannot consider a simple determinism between the natural environment and the society.

On a historical point of view, before the explosion of villages that preceded the demographic explosion, village production systems in Sahelian Niger were land-intensive, as people could not permit themselves to go far away from the villages for fear of the slavery raids and wars (Olivier de Sardan, 2003c). We can conclude that past local populations were able to manage their own intensive system.

Moreover, considering that extensive farming systems are defective comes to neglect the advantages of this extensification, that anyhow was the easiest way to feed (more or less) the ten million supplementary people that have lived in Niger over a century (Raynaut *et al.*, 1997; Phillips, 2007). Meanwhile on a regional level, a large part of the decrease of the average rate of field fertility as repeatedly noticed by many scholars does not mean the decrease of the medium fertility rate of all the fields: As farmers first settled their fields on the best lands, their extension obviously included marginal lands, i.e. *de facto* worse land, thus lowering the average, without any significance in terms of fertility management (Jouve, 2004; Yamba

2005). Moreover, fertility does not always decline with demographic pressure and can even sometimes improve under particular conditions (Mortimore *et al.*, 2001; Koning & Smaling, 2005). In consequence, farming systems reacted well to the demographic explosion through optimizing the most constrained factors and in particular labor (Saqalli, 2002). The populations are well able to modify and adapt their farming systems.

Therefore, assuming that populations have adapted to their social and environmental conditions and still have this capacity, one may question the medium through which such evolutions occur. Our hypothesis is that changes of family structures are the means that are *de facto* selected by the rural populations of the Sahelian Niger to support their adaptation to exogenous and endogen shocks and constraints that affect them. This adaption is ssessed through a higher adoption of coping strategies (diversification, decentralization of the decisions).

2.2 Balancing decision powers: Family & individuals

2.2.1 The family as the relevant scale of study

Transition processes may occur for the social level through shifts in social organizations. However, the powers of the family, the village and the "chefferie" levels have not been affected by the colonial and independence powers with the same intensity:

- The "chefferie" level, which groups several villages, has been almost washed away by the "collaboration" with the French power during the colonization era, especially in the Zarma part of the country. The independence did not help much and the different traditional powers maintain their legitimacy only through their role of protectors and guardians of the traditional values (Abba, 1985). However, they still have a strong power through the capacity to perturb and influence village chiefs' nominations and other elections (Vanderlinden, 1998).
- The village chief legitimacy was also affected by the tax collector function they have since the beginning of the colonization. As described by Olivier de Sardan, 2006c pp. 244-249), their functions depend on the origin (e.g. land or war aristocracy) and are variously applied according to villages. For instance, they had in the past the function of unused land manager, to lend fields to newcomers. But, as many village territories are actually already cropped, this function does not make sense any longer. Their tax-collecting and conflict-managing role is now competing with the new mayoral system established by the decentralization process.

- The village community strength is highly variable from a village to another. But, if one focus on economic activities, solidarity between villagers is low, because the major steps of the cereal and vegetable cropping cycles occur for all households at the same time. We never observed a common herder for the whole village or for a group of quarters[36] for instance. Actually, Migration is the only activity that benefits from the village and/or ethnicity solidarity between one migrant and his fellow migrants who speak the same language (Olivier de Sardan & Dagobi, 2000).
- Anyhow, the family level has become the last level where roles and functions are still under control of a family chief. But this control varies depending on the family organization. We define the family as distinct from the household defintion that concerns only spatial and economic aspects. We consider the family as a social group connecting relatives through links of permanent mutual responsability and where an obedience/insubordination dialectic may occur between family members and the family head. In many families, this family head control decreases facing the physical and economic dispersion of the family members until the level where the family has lost its position as the first level of decision and management regarding the distribution of the access to economic assets and income. Actually, the situation is very contrasting between families. We thereby consider that the family remains anyhow the level where the individual interests are discussed and balanced. It is at this very level that social-based constraints may be transformed. We thereby consider that the family is the relevant level of the analysis of the production and economic activities but also the key level in which the crucial social evolutions may occur.

2.2.2 Farmers and villagers: multiples activities and multiple finalities

The first principle in development and farming system sciences is the postulate that farmers are rational (Mazoyer & Roudart, 1997). One can consider that this rationality can be seen by the consistency of all the decisions of the farmer about its production system. The latter is the result of a trade-off between the objectives of the farmer and its family on the one hand and the production factors on the other hand, given the perception that the farmer has on his/her social-economic environment.

[36] Village quarters are groups of houses slightly disconnected between them. Quarters are historically, socially, and sometimes ethnically defined. For instance in the Fakara, a lot of villages have a quite apart quarter where lives only the descendants of the former *horso* (family servants) or *banniya* (captives or slaves).

However, considering that decisions are made according to the production system characteristics sends back to the particular situation of motorized production systems where single occupation farmers find themselves at the head of a so-called "farm plant". In this case, the concept of a system of agricultural production applies itself to the level of the farm, but this conception loses its relevancy in particular in Niger. Milleville (1989a) noticed that for the whole Sahel, "production systems do only constitute parts of strategies for rural villagers. These strategies are far beyond the sole agricultural activity but also beyond the local sphere". Actually, pluriactivity is a structural constant of Sahelian societies, and not a way for villagers to avoid the impacts of a global crisis (globalization, social upheaval, ecological constraints). It is an intrinsic characteristic of the rural societies in Niger (Franqueville, 1973; Paul *et al.*, 2003).

The farming activities, including livestock keeping, are part of a large panel of activities spread out along the year, practiced either in or outside the village level and strictly gender-discriminated (Mazzucato & Niemeijer, 2001). Therefore, the production system logics and especially the distribution of family resources to farm activities (labor, land, cash & tools) cannot be understood without referring to a larger system of activity, which includes agricultural productions and other productive activities of the family (Perrot & Landais, 1993; Jouve & Tallec 1994; Paul *et al.*, 2003).

This system of activity is the real domain of coherence of the choices and the practices of the farmer and his family. Agricultural work is just one of the ways using the labor factor.

Also, family-level strategies can only be understood at a larger level of rationality. The decision-making domain of coherence is not necessarily based on an agro-economic reasoning. For instance, Harragin (2006) presented the results from his field investigation in the Hausaphone central Niger during his 2005 famine diagnosis, as shown in Table 1: with such an importance given to social relationships, restricting the analysis of family strategies to the sole economic activities is clearly insufficient.

Table 1. Sources and uses of family incomes (Harragin, 2006)

Food sources		Expenses % (Kilani & Waziri Mato, 2001)	
Agriculture	67 %	Food	48 %
Gifts	21 %	Marriages and religious feasts[37]	41 %
Loans	10 %	Farm inputs	5 %
Handicraft	2 %	Clothing	3 %
		Taxes	2 %
		Health expenses	1 %

[37] First the Tabaski also named Aïd-el-kebir.

At this stage, we can conclude that multiples activities and multiple finalities are inherent elements of the families in the Nigerien Sahel. Understanding and modeling the related farming systems must thereby include both concepts. The challenge is to build a relevant unit that can integrate these two dimensions.

2.2.3 The individual as the relevant decision level

Agro-economic investigations are often the first stage of a development action process. They usually take the family as the relevant economic unit, i.e. the household that optimizes, maximizes or secures its production (Gastellu 1980; Blaizeau & Dubois, 1990; Vaugelade, 1997; Meignel, 1997; de Janvry & Sadoulet, 2003; Radja, 2003; Basu, 2004). This implies a tacit hypothesis: the family has its own coherence. However, some contradictions may appear between the production system potentialities and the objectives of the different members of the family. All the activities are not accessible to all the families or individuals in a village, or to all the adult members of a family, for different social and/or economic reasons[38]. Production assets are not always collectively managed[39]. Moreover, considering the family as one unit implies some social rules for internal control that are not necessarily effective. The notion of dynamics and tensions among different logics has to be considered for the family level. For the sake of simplicity, it is usually tackled out in many development projects, especially the ones working on a large scale[40].

It means choosing the most efficient unit for research and action. In all cases, the unit should constitute an *ad hoc* structure that succeeds to explain observed phenomena or organizations[41]. Several propositions, based on various criteria (geography, consumption and commensality, management, food distribution, decision power) were used to define a unit that can combine the characteristics of an exploitation unit, a decision unit and the management unit. These units come up against the plurality of decision

---

[38] For instance, because of the local social pressure at the village level, women cannot leave the village for seasonal migration (Timera, 2001).

[39] The father in the family has theoretically no right of ownership or use on his wife/wives livestock;

[40] For instance, Turner (1999a) underlined the omission of important factors in village studies along regional approaches: the small livestock owned by women is often neglected in regional approaches while it has a bigger impact on natural resources and fertility than the declining transhumant herds.

[41] The unit should be seen as nothing but a purpose-built and explicative framework, adapted for researchers and development operators. It is not a reality but a model of it.

scales (chief and members in the family for the field management), of management levels (a family member looks after the common livestock, but it is the whole family that benefits from the different types of revenue) and also of the plurality of activities (all the farm activities but also extra-agricultural activities) and of different objectives within the family. Considering the actual activity diversity, whatever the chosen unit, it will come up against exceptions and contradictions facing the distribution of activities, decisions and tasks to be undertaken between family members. Gastellu (1980) underlines this aspect in his article entitled: "Where are the economic units that our friends are looking for in Africa"?

Therefore, we consider the sole individual as the best unit to work with, as long as he/she is maintained in his/her socio-economic and biophysical environment. The links this individual has with his/her social environment can then be used to characterize and define the individual. It allows considering the family not as a single finality level but more as an arena of negotiations between individuals. These negotiations are defined upon the interests of each member of the family and the rules that condition the relationships between the members, assuming that such rules may evolve as well. It means thereby that individuals within the family are not necessarily antagonist either, as hierarchy and solidarity ties connect them.

2.3 The family criteria of social distribution

Since the individual is recognized as the most efficient elementary unit, the different types and levels of relationships between individuals must be investigated in details. Several structural elements defines the position, the personal status of one individual that conditions the ways these relationships are built. These elements are personal or defined by the family level. We present in the following sections these elements at both levels:

2.3.1 Family rank*gender*age: the last hierarchy

The family rank can be defined as the rank of a family member within the hierarchy of his/her family. With the gender, rank is the main factor of differentiation in families and villages of Nigerien Sahel, because it affects the access to social activities (marriages, land ownerships, redistribution of food & money) and economic activities, both locally (millet culture for men, access to gardening and livestock keeping for women or men) and outside the "terroir" (seasonal migration, transhumance) (Turner 1999; Basu 2004). Our own investigations (2004-2005), together with literature, showed how strong are the social limitations to the various economic activities. Such constraints are described for different regions of the Nigerien Sahel, i.e. mainly Luxereau & Roussel (1997), Rain (1999) & Yamba (2005) for the region of Maradi, Hill (1972) and Waziri Mato (2000) for the region of Zinder, Olivier de Sardan (2003) for the Zarma population and Hama Beïdi (1993) for the Fulanis in the Zarma-speaking areas.

However, the most common description of the systems of activities omits this discrimination as an important factor and maybe the most important one towards the development of income-generating activities in rural areas of the Sahelian part of the country. This omission is noticed for West Africa by several scholars (Stone *et al.*, 1995; Yépez del Castillo *et al.*, 2001).

Actually, three other adult groups have to be added to male family heads, completing the social "family rank * gender *age" hierarchy: single men, single women and married women. The last two groups, i.e. women are the ones that Boserup underlined as the development driving forces of at least the whole West Africa (Boserup, 1989). This author has put herself into the frame of the "terroir" and demonstrates that, in a northern Hausa-speaking Nigerian context similar to the Hausa Niger, women, usually having less production assets than men, orientate themselves towards either less land-demanding, either land-independent activities.

Finally, the rank plays also a role for each of these groups within the family. It can then be considered as a combination of the gender, the age order, the order of succession and the marital status (Stone *et al.*, 1995; Basu, 2004). One should understand that such hierarchies are not precisely established and may vary depending on the family. Meanwhile, field investigations have shown that some "rules" are more official than others. As a trial of classification, we separate the discrimination processes based on the family rank* gender* age hierarchy in two categories: the first one groups all the "rules" that are justified locally upon an official right[42]. The second one groups the unofficial and tacit rules but also practical consequences of several principles that are an indirect way for these discriminations to be reinforced:

1. The "official social code" discriminates the village population into groups of different rights according to gender, marital status, age hierarchy and the nature of activity.
    a. Gender determines the access to seasonal migration: Adult men of all categories have access to seasonal migration while it is forbidden to women (Stone *et al.* 1995; Aide & Action 2003; Mounkaïla 2003; Phillips, 2007)

[42] A right is here defined as not restricting the practice of the activity, but the right to management and to the related benefits.

b. Marital status determines the access to local activities: actually, marriage defines the access to a "real" majority whatever the gender. Therefore, only married individuals of all genders may have access to the management power on any asset[43] (Rain, 1999). However, this splits along gender: Only married men can manage millet cropping, stopping single men from having access to available land and manpower in the family[44] (Olivier de Sardan, 2003). Differences are still fundamental between married and single women: Single women have no access to the management of economic assets[45]. Gardening rights vary according to the region: it is restricted to married women for Zarmaphone areas (Hamidou, 2005) while it is usually restricted to men in the Hausaphone part of the country (Raynaut, 1989). The marital status plays its role whatever the effective situation of the individual: a widow has a higher status than a bachelor. Thereby, in the Zarma areas, she can garden while the bachelor may encounter difficulties and gossips
c. Age hierarchy is important as well:
    - Between two generations, once a son remains in the house of his father, it is commonly accepted that he should obey to his father. For instance, he cannot leave for the seasonal migration without his father's authorization (Rain, 1999). The same dependence appears for the gardening activity in the Zarma area: only one woman per family may actually start a garden, while her daughters should work in her garden by pouring regularly water on gardens with buckets (Hamidou, 2005).
    - This age hierarchy can be applied between members of the same generation and of the same gender[46]. For instance for the

[43] The married status implies some social access rights to economic activities (gardening in western Niger, small ruminants for the whole Sahelian Niger) but also to manpower (children, young brothers & sisters, lower-rank co-wives, daughters-in-law) and possibly small pieces of land to manage (only borrowed lands limited in surface by access to wells for irrigation).

[44] Meanwhile, exceptions exist and numbers of families adopts ways to avoid such a strict obedience that youngsters may not accept. For instance, a common practice is to let parts of the common family field to some of their unmarried sons uses and benefits, to train themselves, get some money for marriage and migration tickets.

[45] These constraints apply less intensely on widows that benefit from the status of “respectability” but more intensely on divorcees, always guilty in the eyes of opinion.

[46] As described above, production activities are so sexually discriminated that hierarchy between family members of different genders have little impact. However, one should consider this differentiation as strictly limited to production activities as

gardening activity, the hierarchy between sisters is as strong as the hierarchy between a mother and her daughters as described above. Meanwhile, we have observed in many families that this hierarchy means also more duties for the elders, who are theoretically the potential heirs and thereby the "ones in charge": for instance, the eldest son has to stay and help the father to finish the harvest while the cadet may leave for migration earlier (own observations 2004-2005).

2. The second right is tacit but has great effects, through the obedience hierarchy allowing access to manpower and reducing public reprobation or disregard. Those who control the necessary capital to get access to an activity are de facto rulers of this activity. For instance, in some families where the patriarchal family archetype is still active, the gains the son may have obtained from the preceding migration campaign have been given to the father, meaning that the son still depends on the father's will for paying the required transportation ticket for the next migration campaign[47] but also the cash needed for starting business during the campaign. This last factor conditions his gains[48] and thereby marriage and thereby his right on land and village citizenship (Kilani & Waziri Mato, 2001; Mortimore *et al.*, 2001).

Therefore, an individual-based analysis of the accesses to economic assets within families should include the importance of the gender, but also the marital status of each individual. Meanwhile, such an analysis should consider that, even if the hierarchy between family members is observed in all the families according to the same principles (married father > married son > unmarried son > daughter-in-law > unmarried daughter, to combine with the age effect), the consequences of this hierarchy are varying depending on the families. Such a difference is described and analyzed in the following sections.

---

we listed them (livestock, agriculture, gardening, migration). Social relationships (marriage, inheritance, etc.) mean the mutual implication of genders: Married men have theoretically the full power of decision, while women may have their unofficial "*veto*".

[47] As noticed above, exceptions do exist.

[48] The main activity during migration is trade or "tea-making" that needs some cash to begin the season. The amount one can bring back depends on the cash loan he may receive from compatriots. However, this loan amount is strictly depending on the experience. It means that more one postpone his first departure, more it will take time to get enough money to pay the dowry and get married.

2.3.2 Reputation: a villagers' currency?

Social capital plays a strong role among rural Nigeriens. For instance, the position of a villager within the village determines the possibility to get support from other villagers or to build strong matrimonial relationships with wealthy families. Apart from anthropological or game theory researches (Pujol *et al.,* 2005), the integration of social factors in the analysis of development stakes in the Sahel is often restricted to the ethnicity, the position in the family, i.e. the rank, and in some cases the lineage, while the latter is difficult to estimate because of the complexity of the family situations and thereby the necessary time to "desintricate" the related social networks (Sirven, 2003). Several scholars have acknowledged the power of the social capital that may influence for instance marriages (Small, 1999; White, 1999), reproduction (Read, 2003), social networks (Alam Shah *et al.*, 2005) or even commercial transactions (Greif, 1989), which all can be found in a Sahelian village[49].

Therefore, once we acknowledge the importance of reputation, it is necessary to characterize it. Firstly, we strictly differentiate the family rank notion, which is used only within the family arena to hierarchize its members, and the village reputation, which may include the family rank but should be considered as defining the position of one villager within the village arena. Secondly, two conceptions may be envisaged to represent such a reputation concept:

- Reputation is not a common and objective value. Each person may build his/her own opinion on another villager. It means that the value for a village composed of n habitants should be defined for each relation within the village, i.e. n^2 values to consider. Beyond the complexity of such a representation that can be however overcome by integrating the memory of the events that have affected each mutual relationship, one may notice that, at the village level, people talk. Sharing the opinion about somebody is probably the main medium by which it is transmitted and the common values are shared[50].
- A second conception of the reputation is quite similar to that of Requier-Desjardins (2000) and implemented and modeled in Rouchier *et al.* (2001): Our observations let to consider the local reputation of one

[49] Reputation is here defined following Rouchier *et al.* (2001) as equivalent to a social capital value for each villager. Therefore, social capital and reputation are exchangeable in the text.

[50] All fables & tales have to group two characteristics: remind and share the common values and link them to the related present, past or symbolic examples. The importance of the "griots" as the main reputation medium throughout families and history should be underlined here.

> individual is a value that fluctuates according to the relationships between this individual and the rest of the poulation, evolving according to events which are (or are not) fulfilled by a villager. Reputation can be here defined as the esteem one villager is considered with among the other villagers. It is therefore a conjunctural combination of the family social value, which is usually quite stable (lineage, family wealth and relationship network, etc.), and the individual position (personal wealth, family rank, etc.) that may vary more. Reputation is gained by fulfilling social duties: having large progeny, answering relatives demands, sacrificing livestock during religious and domestic feasts are examples of necessary actions to maintain a good stature within the village and the family arena. However, the greater the welfare, the higher the social pressure; villagers have to balance between reputation gains and their wealth capacity. Unlike Rouchier *et al.* (2001), we explicitly integrate the wealth as a reputation-building factor[51], but we do not consider the effect of such a reputation on one villager's self-esteem as we focus on his access to economic activities and thereby his/her relationship with the other villagers.

As the latter definition includes one villager's wealth as a part of his reputation among the other villagers, we assume that this reputation can be considered as the main “currency” used within the village, on which each villager may evaluate, calculate and balance costs and advantages of an action and/or a decision.

As a conclusion for this section, it is thereby interesting to test a hypothesis on the validity of the reputation as a better "currency" at the village level. We consider a first testing step on a short-term basis to see if such a reputation "currency" does have an effect in the decision process of the villagers. Actually, field observations suggested that the project-village relationship is strongly affected by reputation effects. More globally, social and political power in a village can influence the impact of any development action, particularly if these action types are *de facto* targeting a certain category of the population (Gentil *et al.,* 1993; Laurent, 2000; Olivier de Sardan & Dagobi, 2000)[52]. It is also obvious that this has an effect on

[51] As an anecdote, it is easy to count the number of "griots" that are present during the funeral of a rich villager, compared to a poorer one. More important, one griot may find more qualities to promote for the rich than for the poor villager!

[52] Gender discrimination in access to project interventions is at least equally strong. One may have only to observe collective meetings during PRAs or farmer's organization groups: once one man of the village is present, all women usually stay silent. Therefore, many projects focus their actions onto different gender-defined groups to avoid or at least limit the influence of the main powers in the village.

relationships between villagers apart from project interventions (Stone & Downum, 1999).

As one of our objectives is to analyze the village-project relationship, we propose to combine this "currency" test with the analysis of the tests on the impact of the two development interventions we planned (inorganic fertilizers' availability and inventory credit), as a good way to analyze the distribution of the strategies of the villagers. A future stage may be to test if such a "currency" difference has an effect on the village long-term demography and sustainability. This stage has not been implemented for this thesis.

This section §2.3 presented the structural elements that condition the hierarchy of the individuals within their families and their village. The following section deals with family-level factors that transform the impacts of the preceding structural factors.

2.4 Family evolution modes

We have seen in § 2.2.1 that the family is the relevant level for the analysis of the economic activities but also the key level in which social evolutions may occur. Chapter 1§2.2.3 has acknowledged that the family is more an arena of negotiations between individual family members upon their respective interests and the family hierarchizing and functioning rules, assuming that such rules may evolve as well. Finally, chapter 1§2.3.1, we noticed that the hierarchy effects are different between families.

As described above, economic activities and related gains are fully or partially restricted to a part of the population, usually male family heads. This part of the population has social advantages in the present-time social organization that permit them to maintain their status. This means that there is little chance that they may will to modify the *statu quo*. However, this control does restrict access to local production activities to near three quarters of the adult population (50% of women, around 25% of unmarried or depending men, own investigations 2004-2005), reducing by then the effective manpower that remains the principal factor limiting Sahelian farming system developments. More globally, because individuals are not fully under control of a single strategy for the whole family, namely and more precisely the one of the head of family, we make the hypothesis that the least favored groups in the social organization are those that will be more inclined to develop alternative activities. Such activities may be in and out of the "terroir" since they have no social access to activities nor decision rights nor gain on them in the present-time actual situation (Crozier & Friedberg, 1977 pp. 240-241). Therefore, they are theoretically the main forces for diversification and development other than pearl millet agriculture as far as they can gain some access to the related activities. Extending the reasoning of Boserup, (1989), one may consider that such social groups either orientate themselves towards more open access activities either push towards an evolution of the family structures.

Several scholars acknowledged the population capacity to adapt the rules of access to production assets and thereby the organization of the systems of activities they use. In particular, the link between demography, social structure and resources has been documented as far back as 1956 (Davis & Blake, 1956).

These anticipating adaptation processes are already taking place in Nigerien Sahel: inheritance, family organization, land tenure, social and symbolic references are evolving, because of economic pressures on individuals, families, and communities. Milleville & Serpantié (1994), Ehrlich & Luib (1997), Mathieu (1998), Lambin *et al.* (2001), Reenberg (2001), Mazzucato & Niemeijer (2001), Jouve (2004), ; Ouédraogo (2005), Raynaut (2007) and Tappan & McGahuey (2007) among others have all highlighted the major importance of social factors in farming system evolution analyses. Grégoire (1986), Luxereau & Roussel (id.), Olivier de Sardan (2003), all of them referring to the Sahelian part of Niger, have suggested two major, village-level social factors to consider as the main pathways for local farming system evolutions:

1. An evolution of the family organization, based on the tension between the family head and his relatives who bring him income from their activities.
2. An evolution of the inheritance system, based on the tension within the family due to the land scarcity

2.4.1 Family disintegration with declining economic hierarchy

All the investigated literature that concerns local family evolutions[53] described the average family at the end of the 19th century, as enlarged and

[53] Among others, for the Nigerien Sahel in general, Abba (1985), Alpha Gado (1993); for the Hausa in Maradi, Grégoire (1986), Luxereau & Roussel (1997), Yamba (2004); for the Hausa in Zinder, Hill (1972), Waziri Mato (2000); for the Zarmas, Hama (1967), Olivier de Sardan (2003c) Abdoulaye p. 23 (2002); for all the Fulanis, Bernus (1994); for the Fulanis of the Boboye, Hama Beïdi (1993); for the whole West Africa, Balandier (1955), Franqueville (1973), Coquery-Vidrovitch (1974), Gastellu (1980) Raynaut *et al.* (1997).

quite strictly hierarchized[54]: The father was ruling the whole family, including servants and slaves, as one single consistent exploitation, management and decision unit. Such families may be defined as enlarged (because they group several generations that are not allowed to leave the family unit) and unitary (because members should obey one decision unit, i.e. the family head). This family concept is close to the Mediterranean family based upon the *Pater familias* omnipotence. Actually, this unit was not fully independent: insecurity was forcing enlarged families to act as a group against foreigners, usually under the rule of the old aristocracy or the rising warlords[55].

Meanwhile and as described in § 1.2, we have seen that the *pax Francia* opened both the access to land in the Nigerien Sahel and to external jobs in the Gulf of Guinea. Migrations and more individualistic behaviors trajectories multiply (Timera, 2001). The generalization of multi-activity, with the end of the insecurity that was forcing people to group under one rule, undermined the hierarchy foundations and rendered more and more difficult the justification of wealth and asset concentration in the hands of a single person, the head of the enlarged household.

We therefore hypothesize that this led to a fragmentation of the family organization that favor decision-making and income diversification (Saqalli, 2002), as theorized by Boserup (id. pp. 316-346). Such dismantlement of the family structure is actually described by an extensive literature regarding various sites in Nigerien Sahel or the neighboring countries[56]. We position this hypothesis in the economics debate between unitary structures and collective non-cooperative ones (Radja, 2003; Donni, 2004). The latter corresponds to a multi-decision family organization where there is a collective organization but not based on a cooperation efficiency as defined by Pareto (Sen, 1983 in Meignel, 1997)[57].

---

[54] Several scholars, including Ki-Zerbo (1972) and Olivier de Sardan (2003c) underlined that the previous family model prior to the Muslim implantation was matrilineal and much more complex in its organization. Meanwhile, and as described also by Olivier de Sardan, the disintegration of the enlarged family was noticed as far as 1914 for the Zarmaganda (ibid. p. 246)!

[55] *Amirou* (in Hausa from Arabic), *wankoye* (in Zarma), which both mean etymologically "warlords".

[56] Luxereau & Roussel (id.), Hambally (1999), Turner (1999a & b), Mortimore et al. (Id.), Mounkaïla (2003), Yamba (id.), Fauquet (2005) and La Rovere et al. (2007) for the Nigerien Sahel case, Raynaut et al. (id.), Milleville (1989b) and Mortimore & Adams (2001) for the whole West Africa.

[57] For instance elders and males are typically favored in Nigerien Sahel families.

Practically, heads of such mononuclear families have more often a very important role of representation towards the outside, a role of balance between family members and a function of guarantee of the durability of the group. But their “absolute" authorities do exert themselves only in certain "extreme" conditions ("soudure"[58], famine…), and are limited in periods without emergency. Finally, in some areas, particularly the Zarma-populated territories, some more risky functions are not only "left on the side" by the elders but are quite officially reserved for women and youngsters, each one with his/her own objectives (a monetary function for women, a role of social affirmation for youngsters through the marriage) and his/her own strategies (gardening; migration & trade).

Actually, such a shift is described by literature[59] but we observe that the two types of family are still both present in the villages. Our census in three sites of the Nigerien Sahel reports the presence of both types but in different proportions depending on the site[60]. It means that such a shift was not absolute but variable depending on site characteristics, but also that this shift has occurred in all the Nigerien Sahel. Such family evolutions in less than one century implies to question the conception of the Sahelian family: for the majority of them, they are not a "traditional" unit and they do not constitute "households" allowing development operators to deal only with family heads as unique representatives of the family.
It means also to develop two research questions:

1. What are the consequences these two family types have on the related villages and "terroirs"? The impact of both family structures should then be compared:
    - A collective non-cooperative and mononuclear family and referred to as the Non Cooperative Family Structure (NCFS).
    - A unitary concept of the enlarged family, corresponding to the main concept of African families as used by development agencies, hereafter referred to as the Unitary Family Structure (UFS).
2. What are the causes explaining such a shift? We have supposed above that the disintegration of the enlarged family is due to the generalization

[58] The French term "soudure" means the annual period before the harvest, during the rainy season, when storehouses are emptying and food shortages may appear.

[59] Meanwhile, one may easily observe how this issue is not integrated in Terms of reference of development projects or institutions: the enlarged household archetype is still described as the main family unit: CARE (2002), UNDP (2005), BAD-FAD (2006), FAO (2006).

[60] 76% of our sample in the Fakara site (Tillabery region, southwestern Niger) belongs to the non-cooperative mononuclear type, 59% for the Gabi site (Maradi region, south central Niger), 69% for the Zermou site (Zinder region, southeastern Niger) (see chap. 2 §1.2).

of multi-activity that has undermined the hierarchy foundations and reduced the justification of wealth concentration in the hands of the family head. Therefore, such a process should be implemented as a tension growing with the increase of the proportion of income coming from other sources than the head of the family, eventually leading to a shift in the family organization.

2.4.2 Inheritance evolution with growing tenure constraints

The question of the inheritance system is extremely complex, among others because of the enormous gap between formal and official rules on the one hand and the tacit practices on the other hand. Actually, the question remains paradoxically more sensitive than the family organization one[61], because the gap implies a religious offense. All the population of Nigerien Sahel considers itself as Muslim. A straight question on inheritance will imply therefore the norm as the answer: the Muslim laws are followed. Theoretically, such inheritance laws are based on the equity between generations and among genders but inequality between genders. The heritage is equally divided between generations (half for the brothers and sisters of the dead person, half for his/her offspring). Among a generation, all parts are shared in order to provide one part for each sister and two parts for each brother.

However, even if this mode implies gender inequity, applying literally such a system for land in a patrilocal society means that a lineage can see crumbling and disappearing large parts of its land property when daughters get married, "carrying away" parcels into another family when they leave the family home for their husband's. In the 19th century and because of the need for powerful and enlarged families facing insecurity at this time, practices were oriented to maintain the power of the lineage more than equity. The legitimacy was then based on the "custom"[62]. Therefore, the so-called "customary" inheritance mode was based on the entire transfer of all the land and assets of the father to his eldest son. It is considered to have been the major inheritance system throughout the Sahelian part of the country up to

[61] It is a paradox because the family organization gap between the enlarged archetype and the mononuclear type can be observed in the everyday life and concerns the wealth during all the life, while the inheritance gap can be seen only at death.

[62] Islam values were less strong in Niger at the beginning of the 20th century and many anthropological works have shown the resilience of animist values, references & ceremonies (for instance the *bori* or possession by djinns) that however are presently declining.

the beginning of the 20th century (Raynaut *et al.*, 1997). It remains dominant in large parts of Nigerien Sahel, mostly in northern and less densely populated zones and where land pressure is still low (Vanderlinden, 1998).

At the present time, the tension concerns the need of all the children to get access to land on his/her own and the need for the family head and the potential heir to keep unbroken the family property. If the Muslim system imposes the equity between brothers, a transformation of these laws is usually observed. Either this transformation is formally recognized as the official inheritance rule based on custom, either it constitutes the tacit shape of an interwoven system that claims to belong to the Muslim system. For this last case, the official and designated heirs do not correspond to the managers, as Muslim laws are too much respected for being violated in such a blatant manner. The heir is therefore considered as its official manager, its regent for the account of a "minor" (woman, sick man & child). Consequently, the values of "shame" and non- ostentation being very strong, none of his younger brothers, and even less the sisters, will dare to protest thereafter for a more equal sharing. The usual tactic is therefore to leave "rotting" the situation, up to the presumptive heirs abandoning their prerogatives on the land property. One note that the gap seems equivalent to what has been described in the Maghreb: in her book "The harem and the cousins", G. Tillion (1982) described this difference as a consequence of the family desire for keeping lands.

Population has exploded during the 20th century. The cadets who have to leave the families and settle somewhere else found less and less new empty places, due to the decrease in available land. As described by Luxereau & Roussel (id.), Mortimore *et al.* (2001) or Yamba (id.), this customary inheritance mode seems to have been less and less adapted to the situation, and thereby to have been toppled over during the last decades in several densely populated and land-saturated areas of Niger, such as Maradi, towards a local version of the Muslim land tenure code[63]. In this last system, land and livestock are equally shared between direct descendent heirs but gender specifically (i.e. female-owned livestock is shared between female heirs and male-owned livestock and land between male heirs), collateral relatives receiving a share only if there are no living adult children[64]. We

[63] Religion can be considered as the sole value that can play the role of a counter-power when confronting the tradition for permitting whatever change of these eminently strategic rules. One must consider it as an argumentative "weapon" used by the beneficiaries of this new system.

[64] One should notice that the main difference between the written and official Muslim law and reality is that almost all women do not officially own fields, largely due to the tricks men use to avoid female land inheritance. It can happen that some

suppose that some hidden and complex mechanisms of coercive compensation are put into place in order to avoid the same problem as noticed above. As a result, at least family heads favors endogamic marriages.

We make a strong anthropological hypothesis, as a generalization of observations and hypotheses from G. Tillion in the Maghreb and the Tuareg world (Tillion, 1982): facing the scarcity of available lands, families orientate themselves towards a *de facto* endogamy, where daughters are married with their cousins by cloistering them more and more. It may explain the heavy habit witnessed in investigated villages in the region of Maradi and of Zinder where land is rare. The elders and experts we met consider this process as recent: it first aims to prevent women to work, to trade and to have an independent social activity. Therefore, as women do not practically owned land[65], land remains within male heirs. This adaptation can be considered as a means that families have put in place to adjust to farming system evolutions as a catalyst pathway for farming systems transition because of its lowering effect on the average arable surface per family, without blatantly confronting the Muslim official principles that are stronger in the present time than in the beginning of the 20th century. One should underline the effects of such an evolution: a reduction of the average arable surface per family by including the cadets into the land allocation system means thereby that families are more rapidly forced to choose whether to involve more in the agriculture production or to diversify into external activities. It can be considered as a strong incentive for either intensification along a Boserupian process or a disintensification one as described by Conelly (1994).

We took our own results as a basis with the available literature: Ada & Rockström (1993), Seybou (1993), Loireau-Delabre (1998), Abdoulaye (2002) for the Fakara site (region of Tillabery); Luxereau & Roussel (1997), Rain (1999), Tiffen (2001), Mortimore *et al.* (2001), Yamba (2005) for the site of Gabi (region of Maradi); Hill (1972), Waziri Mato (2000) for the site of Zermou (region of Zinder). The Fakara site was selected as the first archetype representative for the modeling. Several major books are used as reference, as Olivier de Sardan (2003) for the Zarma population and Hama Beïdi (1993) for the population of the Fulanis of the Dallol Bosso and the surrounding plateaus. As Hama Beïdi noticed, all the population of

---

women officially inherit some pieces of land, but the social pressure forces them anyway to "delegate" the management to some brothers. This phenomenon is actually widespread in all of Muslim Africa. Cf. "the harem and the cousins" by Tillion (1982)

[65] Except some exceptions for widows without heirs, we mean here that they cannot manage and keep the benefits from it.

Zarmaganda, and by extension, the one of all Nigerien Sahel, is well informed of the Muslim inheritance laws, but does not put these rules fully in application.
Analyzing such evolutions means several hypotheses describing the different social steps[66] that are similar in the conception to the "multiphase response" of families in the society of Davis (1990), thereby opposed to a Rostow-like unilateral process. We thereby propose to focus on one transition process, the one that is presently occurring at different levels throughout Nigerien Sahel, i.e. the transition between the "customary" inheritance system and the "local Muslim" one, as an illustration of a non-obvious phenomenon with important impacts. The question is therefore which one of the ways (the local version of the Muslim system or the customary system) each family has chosen to "arrange" the formal rules. The proportions of the inheritance modes (see chap.2§1.2) are actually different between the three investigated sites[67]. This transition will be implemented in our model and analyzed, together with the transition between family organizations.

The last analysis concerns the relationship between development project interventions and villages, as they may constitute a strong catalyst effect on the evolution of the village. Actually, facing the present-time financial difficulties of the Niger government, development projects are often the sole institutional actor that can influence the evolution of a village.

2.5 Project actions: Fertilizers and warrantage

The two selected development interventions we propose to analyze are emblematic of development strategies in the country and are even considered as the most promising development techniques by many development institutional operators (Buresh *et al.*, 1997; Nederlof & Dangbégnon, 2006; Quin'ones *et al.*, 1997; FAO & CEDEAO, 2006). The inventory credit locally named "warrantage" can be viewed as a securizing strategy while inorganic fertilizer availability at market prices corresponds mainly to a maximizing strategy on agriculture and gardening. They are thereby representative of two development policies that have been applied in Niger in a juxtaposed and sometimes opposed manner. Moreover, they are the most prominent proposals the consortium of institutions we belong promote in the different investigated sites. Our purpose is therefore to compare both

[66] In our case, a first matrilineal family, evolving towards a patrilineal "customary" system, then to a local version of the Muslim system.
[67] 82% of our sample in the Fakara site (Tillabery region, southwestern Niger) belongs to the "customary" mode, 88% for the Zermou site (Zinder region, southeastern Niger), but only 29% for the Gabi site (Maradi region, south central Niger) (see chap. 2 §1.2).

interventions in terms of impact on the population under different local environments, based on our hypotheses regarding local villager logics and behavior.
Actually, such interventions may be implemented on the field along numerous ways[68]. Analyzing the different procedures they can be implemented along relies on game theory research and implies to build numerous scenarios. Even if it have been noticed for decades that the ways they are implemented may have effects on the success of such proposals, it seems more relevant to analyze the effects of such proposals along the ways they are actually implemented on the field and as we have observed them thanks to our involvement in the consortium.

2.5.1 Fertilizers

Niger having one of the lowest fertilizer use rates (0.27 $kg.ha^{-1}$) (World Bank, 1997), fertilizers are considered by many development operators as the bottleneck for farming system intensification and income increase in Niger (Van Keulen *et al.,* 2001; de Rouw & Rajot, 2004; Ouédraogo, 2005) and even for all Africa (Quin'ones *et al.,* 1997; Breman *et al.,* 2001).

A huge debate, mainly originated from the Malthus/Boserup controversy (Boserup, 1965; Mathieu, 1998; Jouve 2006) is actually opposing fertilizers supporters, arguing that this is the main solution to compensate mineral nutrient constant losses in Sahelian soils (Yamoah *et al.,* 2002; Schlect & Buerkert, 2004; Abdoulaye & Sanders, 2006; Bationo *et al.,* 1998) and opponents, who noticed that fertilizers and other off-farm inputs use reduce the household economic viability (Mazzucato & Niemeijer, 2001; de Rouw 2004), are economically less interesting than crop residues, livestock or household-originated organic manure (de Ridder *et al.,* 2004) and even for some of them, increase the risk of a poor yield (Affholder, 1997; Koning & Smaling, 2005). The purpose of these operators is to support farmers to use fertilizers again[69] in food crop fields and vegetable gardens through farmers' organizations, by increasing the availability of fertilizers at the village-level and the knowledge on their use, with an emphasis on the microdose technology (Abdoulaye & Sanders, 2005; Gérard *et al.,* 2007), thereby

[68] One project office or many; farming groups stratified along gender, age, etc. or not; with or without incentives or formation sessions, with or without membership, etc.
[69] One should not forget that Nigérien farmers have used around 30,000 tons of inorganic fertilizers per year during the 70's, when the price was subsidized thanks to the Uranium boom. It means that farmers are usually aware of fertilizers, both their advantages and limitations.

reducing fertilizers waste and the weed impact (Muehlig-Versen *et al.*, 2003).

2.5.2 Warrantage

Warrantage, also named inventory credit, is a credit technique based on the use of farmers goods set down as a guarantee in a warehouse. Even if this technique was actually applied for a long time in Niger under various names (Gentil *et al.*, 1993), it is presently reconsidered as relevant for rural development issues for this country. Meanwhile, its modalities vary depending on the site, the Microfinance Institution (MFI) and the Farmers Association (FA) involved (Fraslin *et al.*, 2005; Ali Zene, 2006).

We have mainly observed the following option: at the time farmers have stocks (typically pearl millet after harvest), stocking in a reliable warehouse owned by a MFI partner, for instance a FA, is a guarantee for the MFI to provide credit equivalent to 100% of the value of the stock at the time of the deal[70]. The farmer can reimburse the credit by buying back the stored millet and sell it on the market because the stock price usually increases along the year. The benefit due to price increase during the storage period belongs to the farmer, with 10% of the initial stock value for the FA as storage and fee costs. The objective of the method is to provide better access of smallholder farmers to financial resources (Badamassi, 2006) but also for rural income securization, as it should compensate millet price fluctuations (Pender *et al.*, 2006). In the absence of warrantage, millet is mainly sold just after harvest, at its lowest price (around 750 FCFA ~ 1.13 € per sheaf) because people need cash to fulfill economic and social needs (taxes, clothes, etc.) that cannot be postponed. Usually, the rural populations buy millet during the cropping cycle at the "soudure" period, i.e. just before the next harvest because they do not have millet anymore. Therefore, the price they pay the millet is at its highest (around 1500 FCFA ~ 2.3 to 3 € per sheaf).

2.6 Conclusion

We have seen that farming systems and rural populations of the Nigerien Sahel are conditioned by a combination of agro-ecological and socio-economic constraints. The latters have evolved and still evolve quickly while agro-ecological constraints remain. If the socio-economical context is also changing (for instance, the transportation system for the countries of the Gulf of Guinea), the decline of the "chefferie" and the village levels have highlighted the importance of the changes at the family level, particularly

[70] It means that the credit value is the yield portion the farmer let in the warehouse, upon the price at the harvest, usually around 100 FCFA/kg (0.15 €/ kg).

regarding the family hierarchies that condition the access to economic assets. The challenge is to estimate the impacts of such transition processes that are thresholds for rural development as they appeared during investigations.

As social processes are non-linear, evaluating such transition processes in a systematic manner is unfortunately impossible. Moreover, both temporal and social scales do matter: more one goes "down" in the village, more different phenomena are detected that can have a crucial effect on the village population evolution. More one enlarges the temporal scale of the village evolutions, the more the conceptions on local strategies that condition the present-time situation are irrelevant. Therefore and reconsidering the preceding sections, it may be interesting to select the process that appears to be the most determining on the present-time situation but also as the necessary first steps for the analysis of the impacts of social phenomena that have affected this part of the country. We select thereby three processes to analyze:

1. The effect of the two family organizations on the evolution on farming systems and populations of one selected village archetype of the Nigerien Sahel, as a first test of the importance of the family organization impact.
2. The effect of the village social organizations and characteristics as observed on the field on their responses to development proposals and their impacts on farming systems and populations of these village archetypes, as an analysis of the development strategies that corresponds to each proposal and the weight such proposals may have in the evolution of such villages. We test these proposals with two different "currencies": the income or the reputation as proposed in §2.3.2.
3. The effects of family structure transition processes on farming systems and populations of these village archetypes, on a long-term basis, also as a test of such processes' weight in the evolution of such villages.

For such research questions and as proposed in the introduction of this thesis, we propose to model several village archetypes as representative of different sites of the Nigerien Sahel as we have observed and investigated them. The next two chapters present thereby the methodologies we followed on the field and during the model building process. The last three chapters present the results of the model simulations that are related to the preceding questions.

CHAPTER II:FIELD MATERIALS AND METHODS

Note: The second section of this chapter was submitted for publication in Applied Geography in 2007 and is still under review (Saqalli, M., Defourny P., Caron P., Issaka A. "A fast and low-cost indigenous perception-based regional mapping methodology in support of rural development: analysis of an experience in Niger").

1 Characterization of the three study sites

1.1 The study site selection

The program that supported our research was hosted and managed by a consortium that associates several institutions working in Niger (Research institutions, national farmers' associations, UN institutions (FAO) and a Belgian NGO). The operators of the consortium possessed extensive literature and data sets resulting from 20 years of agricultural research and are implementing several development actions, including warrantage and inorganic fertilizers' availability, in three sites of the Sahelian part of Niger.
The research locations were therefore selected because they are benchmark sites for one or more of the consortium members and because of data and literature availability. As shown in Figure 7, the three sites are Zermou in the region of Zinder, Gabi in the region of Maradi and Fakara in the region of Tillabery.

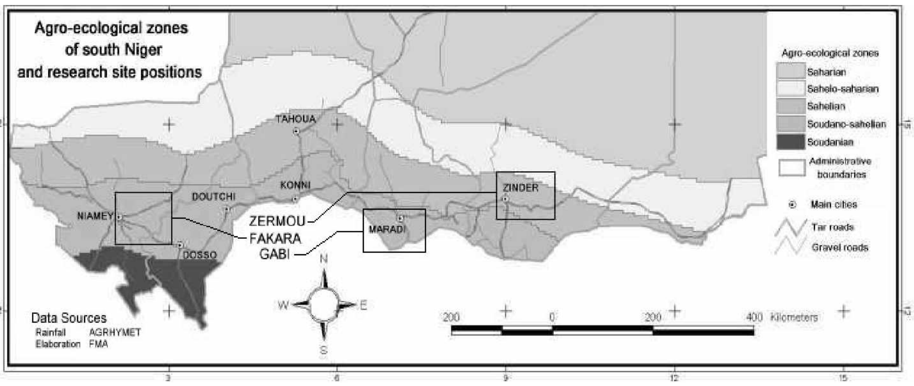


Figure 7. Location of the research sites in southern Niger

The differences between the sites are summarized in Table 2:

Table 2. Factors of differentiation between the three sites

	Zermou			Fakara			Gabi		
Location	Zinder Region, Eastern Niger			Tillabery Region, Western Niger			Maradi Region, Central Niger		
Annual rainfall	Mean: 350 mm Range: [70-525 mm]			Mean: 450 mm Range: [180-675 mm]			Mean: 550 mm Range: [275-775 mm]		
Initial soil fertility	Poor on average			Average on average			Good on average		
Soil arability	Valley (good)	Plain (average)	Stony hills (unsuitable)	Valley (good)	Plain (average)	Plateaus (unsuitable)	Valley (good)	Plain (average)	Hills (poor)
proportion (%°)	0.1	69.9	30.0	3.9	79.6	16.5	18.1	60.0	21.9
Urban pole	Zinder			Niamey			Maradi		
Migration destination & impact on other activities	Nigeria: Gardening incompatible with migration			Ghana & Côte d'Ivoire No competition between gardening & migration because of the gender differentiation			Bordering Nigeria: Gardening compatible with migration		
Migration constraints	Transport costs: 45 kFCFA Racket risks: 2%			Transport costs: 30 kFCFA Racket risks: 1%			Transport costs: 5 kFCFA Racket risks: 0,5%		
Main ethnicity	Hausa			Zarma			Hausa		
Women activity	Sheep raising			Sheep raising & gardening			Sheep raising		
Men activity	Farming, migration & gardening			Farming & migration			Farming, migration & gardening		
Present time dominant family type[71]	Mononuclear			Mononuclear			Mononuclear		
Present time inheritance system[72]	Local customary			Local customary			Local Muslim		
Sources	(Waziri Mato, 2000; Kilani & Waziri Mato, 2001; Lund, 2001; Aide & Action, 2003; AQUADEV, 2006; Phillips, 2007)			(Seybou, 1993; Hama Beïdi, 1993; Loireau-Delabre, 1998; Hiernaux 1998; Abdoulaye, 2002; Mounkaïla, 2003; Olivier de Sardan, 2003c; Hamidou, 2005)			(Hill, 1972; Luxereau & Roussel, 1997; Rain, 1999; Mortimore *et al.*, 2001; Tiffen, 2001; Jouve, 2003; Yamba, 2005)		

[71] See chapter 1 for the description of the impact of the two family organization types and chapter 3 for their implementation in the SimSahel model; the main difference is the control by household heads of the activity of their family members; for instance, youngsters are not allowed to leave for migration until the family harvest is achieved.

[72] See chapter 1 for the description of the impact of the two inheritance modes and chapter 3 for their implementation in the SimSahel model; the main difference is that the so-called traditional mode favors one single male heir, usually the elder, by giving him all the assets, excluding small livestock heads. In the local version of the Muslim inheritance mode, the assets are shared between all the male heirs.

They represent 3 contrasted situations of the Sahelian agro-pastoral zone of Niger. These regions are: (i) located in areas with rainfed agriculture (10% of the Nigerien territory), (ii) close to a regional urban pole, and (iii) linked to the main farming ethnic groups of the country (Zarma in the Fakara site close to Niamey, Hausa in Gabi, close to the city of Maradi, and Hausa / Hausa-speaking Kanuri in Zermou, close to the city of Zinder). The sites we chose in these three regions: (iv) are considered as poorly resource-endowed and (v) are sites of both active scientific research and development support by operators (Gérard, 2002). Each site covers an area of about 2000 km². The site of the Fakara was the main location where we elaborated our social hypotheses, which were then extended to the two other sites with the support of the available literature (Luxereau and Roussel, 1997; Waziri, 2000; Mortimore *et al.*, 2001; Jouve, 2003; Yamba, 2005).

1.2 Description of the selected sites

The three sites present an interesting diversity from a climatic, pedological and human point of view. They follow a rainfall gradient but also a social and economic pattern of differentiation. However, certain characteristics remain common and justify our choice to consider them as modalities of the same space.

Climate is tropical semi-arid with rains distributed in one single rainy season from May to October. The Sahelian Niger presents a rainfall gradient from north to south: the Zermou site is the driest, with an average of 350 mm rainfall per year. The site of Fakara presents an average annual rainfall of 500 mm whereas the Gabi site has a higher average rainfall around 550 mm per year. Annual rainfall is everywhere very variable in time and in space but this variability increases from south to north.

Soils are all strongly leached and weathered. They are mainly of sedimentary origin with recent eolian alluvions. On the hills and plateaus, the soil is usually stony and rocky. Sand dominates on the slopes and the plains and clay concentrates itself in valleys (goulbis & koris), ponds and shallow depressions. Overall, their water and cation holding capacities are very low (Graef & Haigis, 2001). Mainly sandy and stony, their structure is weakly developed. The low levels of calcium reinforce this characteristic. The organic matter content is very low. Manure is the main fertilization method in the whole Sahelian Niger, but it is not available in quantities large enough to meet demand (La Rovere, 2001) while at the same time inorganic fertilizers are still expensive.

All the three sites correspond grossly to a "canton"[73]. Around forty villages are grouped under the rule of one "chef de canton", each one located 10 to 20 kilometers apart from each other (around 10 km in the most favored site of Gabi along the valley, around 20 for the least-favored site of Zermou). Villages should therefore be differentiated between the "chef-lieu de canton", i.e. the capital of the canton, the common villages and the "hamlets", i.e. smaller villages, still depending on one village for the tax payment and not far from it and usually more recent[74]. These three cantons belong to supra-political entities as presented in chapter 1: the Fakara belongs to the Zarmaganda, the territory of the Zarmas, the site of Zermou was a "march" of the 19th century sultanate of Damagaram, and Gabi was a border between the Sokoto empire and the remnant part of the sultanate of Katsina that was refounded in Maradi.

1.2.1 The canton of Fakara

The commune of Dantiandou also named the canton of Fakara is situated 70 km northeast of the capital, Niamey[75] and the well-populated valley of the Niger River (see Figure 7). It is bordered to the east by the also well-populated dallol Bosso[76], also called the Boboye in its central part. The territory is crossed by a network of dry and thin talwegs (less than 4% of total surface) where dry season irrigated gardens can be cultivated (Ada & Rockström, 1993; Hamidou 2005). The local toposequence spreads out from the talwegs into wide sandy plains (80% of the zone) that constitute the

[73] Since independence, the smallest administrative unit beyond the village level in the rainfed part of Niger is the canton. It is an administrative level created by the French on the basis of former "chefferies" or created *ex nihilo*, grouping the territory of around forty villages and officially ruled by a "chef de canton". This chief should belong to one of the reigning families, according to each canton rules. Its legitimacy is by then historical, both colonial and precolonial. Actually, its main function was to collect taxes for the ruling power, with a portion for himself. Mediation between villagers and administrative authorities and arbitrage between villagers are also part of his duties. Since the decentralization of 2004, these cantons have become "communes" ruled by an elected mayor and a council. One of the main future political stakes at local levels will be the tax sharing between the State, the "chef de canton" and the commune (Tiffen, 1999). "Commune" and "canton" are hereafter used without distinction.

[74] Such villages are usually originated from a conflict or at least a dispute between villagers from the first village. For instance, the loser in a village chefferie succession left the village with many of his partisans and founded a new hamlet. It means that the tax payment is thereafter very difficult and conflictual.

[75] Officially 707 000 inhabitants (RGP 2001), more probably around 1 million inhabitants.

[76] 56.36 inhab. per km² (RGP 2001).

major part of cultivated spaces (Hiernaux, 1998; Loireau-Delabre, 2000; OSS-ROSELT-Niger, 2001). Finally, the remaining 16% are hardened lateritic plateaus[77], used for pasture and wood gathering (Loireau-Delabre, 1998). They are stony and have low herbaceous cover, except on some small old sand dune spots.

The area groups approximately forty villages, hamlets and herder camps. The dominant ethnical group is the Zarma, mainly farmers with a growing livestock-keeping activity in their farming system. Seasonal migrants mainly belong to Zarma well-established land-owning families. There is also an important minority of semi-nomadic Fulanis[78], originally coming from the Boboye and slowly becoming sedentary in the area (Tandia, 1991; Boutrais, 2007)[79]. A priori, the Fakara area presented two severe limitations regarding its representativeness. First, the proximity of the capital city of Niamey may potentially have resulted in a shift towards extra-agricultural activities. Secondly, again due to the proximity of Niamey, numerous research and/or development projects have been working in the area for years and consequently they may have changed some local patterns, and in particular the relationships between the "traditional" village authorities and villagers as well as between the villagers themselves. The mental map we performed and which is presented in §3 revealed that this potential bias was not very strong.

The Fakara local land inheritance system is largely based on the so-called "customary" mode (82% of the sample interviewed on this aspect). The family organization is mainly oriented towards mononuclear families (76% of our sample), to the detriment of the patriarchal ones.

1.2.2 The canton of Gabi

The canton of Gabi is situated 40 km to the south of Maradi, the second major town of the country[80] and is less than 30 km away from the border with Nigeria[81]. Devoid of hardened plateaus or stony hills, it is crossed by a dry valley (called the Goulbi of Gabi) oriented south-north, that joins the Madarounfa lake and a second eastern and parallel goulbi named the goulbi of Madarounfa at the northern border of the canton. Including the several

[77] "Fakara" means a hardened zone in Zarma.
[78] Between 10 to 25% depending on the authors.
[79] We do not consider this population, as we did not interview enough Fulani groups on their access to production means. Transhumant and nomadic Fulani are considered to have a significantly different system, particularly for the Woodabe sub-group, with a stronger focus on livestock keeping.
[80] 300,000 inhab. (RGP 2001)
[81] 80 km from Katsina (1 million inhab.) and 200 km from Kano (3 millions inhab.)

small talwegs that are related to the goulbi, this valley space has amongst the most fertile soils of the country and covers about 20% of the territory. A plain similar to the two other sites but less sandy occupies 60% of the territory. Higher plains with harder soils situated to the west of the territory, constitutes the remaining 20% of the total surface. This space is covered by a dry forest and is officially protected thanks to the Baba'n'Rafi forest reserve (Mahamane, 2001).

The Gabi site is mainly populated by Hausaphones, with a minority of Fulanis and Bellas (or Bouzous[82]) becoming sedentary. Gabi has been the subject of many studies on farming system transitions from a Boserupian point of view (Mortimore *et al.*, 2001; Tiffen, 2001). Natural resources (soils & vegetation mainly) seem to have been reconsidered by large parts of the rural population as a crucial stake for local development (Bouzou, 2000). The data for the *Département* of Madarounfa that include the canton of Gabi show a more or less constant area planted to millet and a positive trend in its yield (though annual yields varied with rainfall) (Mortimore & Harris, 2005). Nevertheless, because of the demographic growth, vegetation is still largely declining (Luxereau & Roussel, 1997; Mahamane, 2001).

Gabi also largely benefits from its border with Nigeria: the bootlegging/trade constitutes a large and informal part of the income of the families (Grégoire, 1986). The traditional migration activity is also advantaged: thanks to many relatives on the other side of the border, social networks for trading/business are easy to build and Gabi people have only to cross the border and reach Katsina, Kano or even closer cities in Nigeria (and even the city of Maradi itself) to carry out their migration business (Hill, 1972; Raynaut *et al.*, 1988; Rain 1999; Phillips, 2007).

The Gabi land inheritance system largely corresponds to the local version of the Muslim mode (71% of the sample interviewed on this aspect). We made in chapter 1 the hypothesis of a transition process from the former customary inheritance system to a local version of the Muslim one, because of land pressure factors that are more intense in densely populated sites such as Gabi (Raynaut, 1989). The family organization is, like in the Fakara, mainly oriented towards mononuclear families (59% of our sample).

Finally, because of a better access to markets and to the migration activity, a larger acreage suitable for irrigation and therefore a better profitability but also a social evolution pushing away women from fields because of the rise

[82] Descendants of Tuareg captives and freed during the colonization. They still keep large elements of the Tuareg culture (importance of livestock).

of "Islamic" values, Gabi has seen a shift in the gardening activity from a female driven traditional mode to a pure male activity (Yamba, 2005). The site of Zermou has seen the same social shift but, unlike Gabi, has access to only a very small suitable acreage.

1.2.3 The canton of Zermou

The canton or commune of Zermou is situated 40 km northwest of Zinder, the third town of the country[83]. It is characterized by countryside of rocky inselbergs and stony granite or metamorphic hills. They constitute, depending on the villages, around 30% of the territory of the "terroir". They cannot be cropped and are used as grazing camps. The rest of the territory is almost entirely covered by a sandy plain, constituting the major part of millet cropped areas and more sandy than in the Fakara. The presence of sand favors drainage but in case of low rains increases the risk of poor yields (AQUADEV, 2006). The territory is sprinkled with very few ponds in the valley bottoms, where small gardens, brick production centers and wells are found. Actually, the area is "comprised" between more southern areas, which have access to better rainfalls and better access to shallow water but with a low acreage par capita, and a northern zone, that compensates the lack of rainfalls and the absence of irrigated areas by a very high acreage per capita (Waziri Mato, 2000; Kilani & Waziri Mato 2001; own investigations 2004-2005). Because of these combined constraints, the area has not been structurally autonomous in terms of food production for at least three generations (own investigations 2004-2005) and has suffered from many famines (Aide & Action, 2003), the last one having occurred as close as 2005.

The site of Zermou is Hausaphone, with a mixed origin of Kanuri/Hausa. As for the other two sites, many Fulani transhumant or nomadic herder groups cross the territory. Despite the common Hausa language, Zermou migrants have no real access to jobs/trade in Hausa-speaking cities of Nigeria. They have to reach Yoruba cities in the south of this country, which explains the high transportation costs, including "gifts" for customs officers (Phillips, 2007; own investigations 2004-2005).

The Zermou land inheritance system largely remains within the "customary" mode (88% of the sample interviewed on this aspect). The family organization is, like in the Fakara, mainly oriented towards mononuclear families (69% of our sample).

[83] 250,000 inhab. (RGP 2001). The city is also called Damagaram.

2 Methodology assumptions and tools

This section deals with the overall field and modeling methodology because the overall research methodology followed an iterative process between field investigations, discussions with local experts, confrontations with literature and modeling, as illustrated in Figure 8. This section presents thereby the field methodology in connection with the modeling objectives we have. The main purpose of the field methodology is to collect information and data for building and parameterizing the ABM. This field method is similar to that conceptualized by Bogdan & Taylor (1975) and used by Rouchier & Requier-Desjardins (1998).

The methodology is based on the dichotomy between the macro level, i.e. all the social organizations that one can observe in a village (the family level, the village level, social group levels) and the micro level, i.e. the individual (Verhagen & Smit, 2003). Since individual interviews provide more reliable information that what can be derived from a collective approach because of lower social control during field investigations, we used individual interviews as bases to build individual-centered rules and relationships between factors in the ABM. The individual level is then the one on which rules are built.

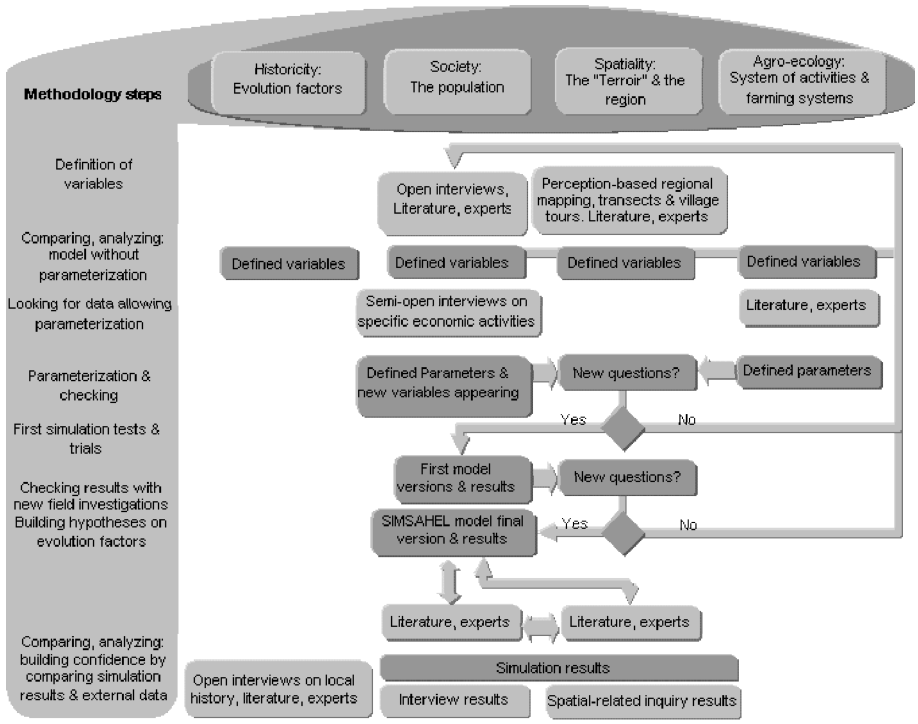


Figure 8. Field methodology used for the SimSahel building

The environmental part of the macro level is well described by literature and experts: for instance, one can find information describing the functioning of the Sahelian production systems and data providing figures on the performance of such systems. Therefore, we relied on literature for this environmental part. On social aspects, the literature provides various data or information but the hierarchy of social and economic values and criteria are difficult to derive from it. This is why we used a macro tool providing social informations on the social aspect at the collective level, to link and compare with simulation outputs from individual rules based on individual interviews. The information derived from macro tools (ZADA, PRAs, village tours, experts and literature) are then used to calibrate the model and for the first model verification step. The macro level is therefore the level at which the results and the outputs of the rules are checked, compared with literature and calibrated.

The first principle of the methodology is that one should differentiate variables and data. Variables allow getting relationships and dynamics while data parameterize these relationships (OSS-ROSELT-Niger, 2006). Variables have to be identified and hierarchized according to a paradigm or a principle that legitimizes their selection to the detriment of other variables. In our case, we base their selection on the following assumption: there is a consistency between the perceptions of the villagers and the behavior rules they have. Therefore, individual rules and the context of their application were based on the number of times information was repeated by villagers during the interviews and through crosschecking between interviews. They are then compared to behavior descriptions and rules we found in the available literature. If a contradiction appeared between literature and decision criteria derived from interviews, we selected the latter, considering that the decisions taken by villagers are consistent with the perception they have of their environment and not always with the environment as perceived and described by the literature.

Both biophysical and socio-economic variables were defined through villagers' interviews at the micro level and checked at the macro level by means of more collective tools (ZADA, PRAs). Data describing biophysical variables are determined through the literature. Data related to socio-economic variables that do not concern social relationships come from literature as far as interview results do not provide them.

We consider that taking into account the components of a farming system (including the related society and the environmental and socio-economic context) and simplifying them is more relevant than neglecting some activities by focusing on the one which seems to be the most important. Therefore, as we focus on production and economic activities, the interviews are semi-open to integrate all the factors interviewees consider as relevant for describing their constraints and practices of their production activities.

Several socio-anthropological tools were used at different levels:

- At the global level: at the village level, several PRAs were realized following the principles and the recommendations from several scholars (Chambers, 1994; Dunn, 1994; Loader & Amartiya, 1999; Sontheimer *et al.*, 1999; Lavigne-Delville *et al.*, 2001). At a more regional level, we used the ZADA[84] (Bonin *et al.*, 2001; Caron, 2001; Caron, 2001). This tool is a regional perception-based mapping process that helps identify and even hierarchize the main criteria that differentiate and characterize the environment.
- At the individual level: open and semi-open interviews were used following Lavigne-Delville (2001) and Olivier de Sardan (2003b). The main difference between them is that open interviews are a first "reconnaissance" step to identify the context and the way people describe their environments while semi-open interviews are more specific and connected to an interview guide, including quantitative data.
- The field investigation and participatory observation period took about two years between 2003 and 2005, regarding both the groups of villages in the three investigated sites and the organizations acting in these villages. This time was required to define the local context, the main differentiation factors between villagers and a villager-based typology of access to economic activities from the "inside".

As PRAs are well described in the literature, we focus in the following part the presentation of the collective tools on the methodology and the results of the two ZADA that were carried out in the Fakara and Zermou:

[84] French Acronym for "Zonage A Dires d'Acteurs", i.e. local perception-based zoning.

3 A new collective tool: The ZADA: A local perception based regional mapping methodology and results for two study sites

3.1 Introduction

Since the 80's, mental geography has been revived by the development of the humanitarian sector in developing countries: Participatory Rural Appraisals (PRAs) are one of the main tools used by NGOs in their development approach (Loader & Amartiya 1999; Olivier de Sardan, 2003b). PRAs are a combination of community-based tools including mental spatial representation through village territory and resource maps. PRAs are easy to integrate in a first-contact and programming methodology, are not expensive to adopt, and are well-suited for the spatial scales at which development NGOs intervene, which are usually quite small (Chambers, 1994).

However, because PRAs are focused on the village scale, they do not capture regional scale spatial organization. This factor increases the time needed for a regional assessment and reduces the low-cost advantage of the method (Jackson, 1993). Moreover, the PRA assessments focus on local context and resources as the main influencing factor, neglecting the position of the local site in the regional distribution of opportunities. Furthermore, complementary tools are required to bring a more dynamic point of view in the understanding of the local situation (McCarthy *et al.*, 2004). Finally, the inherent variability of the local judicial definition of a village territory can reveal large ambiguities and cause political problems within the villages NGOs want to support (McCall, 2002).

Moreover, from a geographical point of view, the regional level is the scale of the development program concept, slowly replacing in Niger the local rural projects concept. There is room for a regional-scale tool between nation-level tools largely relying on economic and geomatics-based analyses[85], and village-level based tools such as the PRA, largely relying on socio-anthropology[86].

---

[85] Considered as the most relevant, mainly due to the fact they rely on analyses based on external sources.

[86] Usually considered as the most interesting discipline to acknowledge the multiple rationality and the complexity of a local society.

Two points are crucial for building such a regional scale mapping tool based on local perceptions:

- No real ex ante standard evaluation methodology exists to define the local main determinants on which rural development projects should focus on (Moss & Edmonds, 2005): External data are too rapidly defined as the variables, i.e. the factors that really determine the evolution of the area while they are only the most easily acquired and analyzed. Therefore they usually constitute the pattern in which the local perception is inserted as data, reinforcing the dominance of external point of view upon local ones in the determination of research variables to investigate (Campo, 2003; Crosetto *et al.*, 2006). Actually, facing the large number of unknown local factors and variables to investigate, the large amount of time and money to be dedicated and the lack of reliable and continuous local data provided by either the local Government or other development institutions (Mettrick, 1994), many rural development operators tend to rely on external data sources which give the impression of reliability and are updated frequently. However, these sources do not necessarily provide relevant information, especially regarding social and economic issues at the relevant scale, i.e. the regional level at which development agencies are usually working. In addition, since few institutions have the expertise, the dedication of assets and the time to generate information[87], the number of information sources is limited. Moreover, the fund raising system is based on short-term contracts, which do not allow allocating a lot of funds and assets for evaluation purposes. Finally, many development agencies develop their own hierarchy of criteria and reduce their support for indigenous evaluation in order to ensure that evaluation criteria match their own goals and domains of expertise (Bonnal *et al.*, 1997; Audinet & Haralambous, 2005; Watkins & von Braun, 2004). The previous point is strongly linked with the discipline sectorial gap: one can observe the lack of dialogue between social and "hard" sciences in the field of development. A tool combining these disciplines, building its legitimacy on the local perception of development factors and constraints, can facilitate the gap filling.
- Combining the outcome of a mental map with geographical positioning information in an attempt to integrate social and environmental information is not obvious (McNamara, 1992; Halfacree 1993; Bailly, 2006). With no geographical reference, the information is conceptual and qualitative, and therefore cannot be expressed in a quantitative manner to estimate and compare situations, without prior knowledge of the local organization. A standardized methodology has yet to be

[87] From field statistical surveys or high-resolution satellite image analyses

defined for combining computer-based Geographic Information Systems (GIS) and mental cartography approaches. Such combinations have been tried, for instance by Touré *et al.* (2004), by including qualitative mental maps into a GIS but this sequence implies a lot of time to reposition the perception-based elements. Moreover, the method requires about half a year's work because it needs self-impregnation, information collection and formalization in order to adapt the qualitative information to a GIS system

Therefore, transforming a local perception-based map into a GIS-based data system means to specify, ex-ante, a system of coordinates and references to host qualitative geographical information, without an ex-ante definition of the descriptive variables.

All these factors make the proposition of a low-cost, local perception-based regional map-making methodology (ZADA) relevant. Caron (1998; 2001) and Bonin *et al.* (2001) proposed a methodology to collect local perceptions at a regional scale, replacing a particular site in its agro-ecologic and socio-economic context. The main objective was the establishment of a dialogue between development agents and villagers through the map-making action: sites are described through separate spatial units defined on the basis of various criteria identified by the interviewed people themselves. Each entity should be a spatially homogeneous unit (SHU) in view of analyzing the dynamic processes and fluxes between the units. We chose to use this method as it has both a geographic reference and a perception-based approach, but adapted it by making the different dimensions of each SHU more explicit.

The two ZADAs were carried out in the sites of the Fakara and Zermou. The ZADA of Gabi was not carried out for logistical and budgetary reasons.

3.2 The ZADA Methodology

3.2.1 Preparing interviews

The ZADA needs a legible geographical support on which mapping has to be done. Both for Zermou and the Fakara, we used a 1/200,000-recomposed map from the National Geographical institute of Niger (IGNN) as background for the drawings. Each map was centered on its site and approximately six times its size, covering about 3600 km².

Each site was split into a number of parts equal to the number of days available (6 days in the present case). Each sub-area has to be mapped in a single day. In our case, six villages were chosen for each site, one per sub-area. Large rural market-based centers, as scattered as possible, were selected, in order to adequately cover the zone and to have access to a large variety of people. In each of these villages, through the support of local resource-persons (teachers, association representatives, local chief representatives, etc.), interview candidates were contacted during market days, when the widest variety of people was available with the widest possible backgrounds and the best knowledge. This step took at least a week per site because it required a lot of time for preparatory contacts. The easiest way is to send one member of the team to contact interview candidates in a village while the rest of the team is carrying out the ZADA in another village. Table 3 shows the distribution of professions and functions of interviewees for our survey in the two sites.

Table 3. Distribution of interviewees according to their professions

% Type	Government officers [A]	Farmers & gardeners	Herders	Traders	Men	Women
Zarmaganda	27,1	27,1	20,8	25	68,75	31,25
Damagaram	25	37,5	14,6	22,9	62,50	37,50

[A] (teachers, nurses, chief representatives, agriculture officers, etc.), over-represented for accessibility and diplomacy reasons.

3.2.2 The ZADA map-making

Map-making was performed outside market days, when interviewees were more free from other activities. Research teams are composed of two interviewers and two interviewees. One interviewer is writing down information while the second is asking questions and initiating the discussion. Two such teams worked concurrently. Each team made one interview including one map per half-day and per market-based village, which means four maps are made per day, for a total of twenty-four maps and forty-eight people interviewed for each site.

The principle is to interview simultaneously two people with different knowledge domains and social standings, and if possible, who do not know each other in order to limit pre-eminence conflicts or domination based on gender, age or other social issues. The results depend very strongly on the spatial coverage and the accuracy of the interviewees' knowledge[88] and their will to participate in the discussion[89], as well as the interviewers capacity to limit the influence of social statute between themselves and interviewees and between the interviewees. The method is summarized in Figure 9.

[88] For instance, a female gardener has a precise knowledge of a very spatially-limited area while a Fulani semi-nomadic herder has a wide knowledge on natural resources but no precise information about village specificities.

[89] For instance, a trader disapprouved the fact that we were considering the female co-interviewee as an equivalent source of information as himself and stayed quiet…

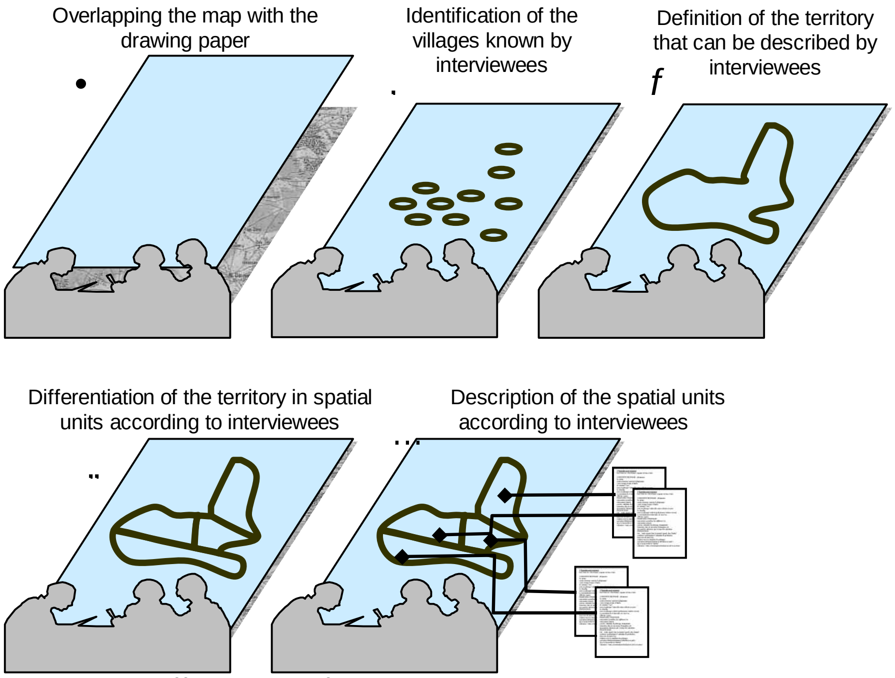


Figure 9. The different steps of the ZADA-mapping process

The interview begins by putting a tracing paper on the 1/200,000 map (• on Figure 9) and giving pencils to the two interviewees. The first stage is the identification of the interviewees' spatial domain of knowledge, by surrounding the villages he/she recognizes (‚ on Figure 9), i.e. the territory the villager can describe based on his/her domain of activity (ƒ on Figure 9).

The second stage consists of dividing the drawn territory into homogeneous units. These units can combine different agro-ecological environments (plateaus and plains for instance), but this combination has to be a homogeneous system of use and knowledge (Lewis & Sheppard, 2005). Only the interviewees define the criteria of differentiation, without any suggestion on the part of the interviewer [90]. The origin of these criteria must be recorded[91], in addition to the discussions and reactions between the interviewees („ on Figure 9). In the third and last stage, the interviewers

[90] Here the biggest mistakes often appeared: facing hesitation and embarrassment from interviewees, the interviewer had to stop him/herself from "helping" people with suggestions.

[91] Who had proposed the criteria? Was it after a long hesitation or a long discussion between the interviewees? On the contrary was it quickly defined?

have to question the interviewees for each identified SHU through a framework of questions about local infrastructure (commercial, religious, sanitary and education), population, main productions and trade (… on Figure 9). The order and the way in which these criteria appear during the map-making process provide information on the local hierarchy of factors.

3.2.3 Synthesizing and formalizing results

The final step for each site is to combine the twenty-four maps. The task is to get a map with a limited number of well-described and relevant units. The factors chosen to discriminate ambiguous cases and combine the maps are the repetition of a criterion throughout interviews, the accuracy of an interviewee about that criterion and its consistency by crosschecking with literature and secondary data. For instance, if the majority of the interviewees described a zone as agriculturally and ecologically homogeneous, it is relevant to add an economic criterion coming from even only one interviewee in order to have a better discrimination of the zone. Once the final map is obtained, the SHU are discriminated in different information layers to make more explicit the different dimensions of each SHU. The objective is their incorporation into GIS software for a further combination with other data.

3.3 Results

Criteria for spatial differentiation are defined locally. Therefore the grids and legends for the cartographic units are obviously not similar across sites. Here we present the results of the definitive maps of the two sites.

3.3.1 A first classification based on environmental characteristics

For all the interviewees in the site of Zarmaganda, the territory was first described as being organized according to biophysical criteria, as shown in Figure 10 (a).

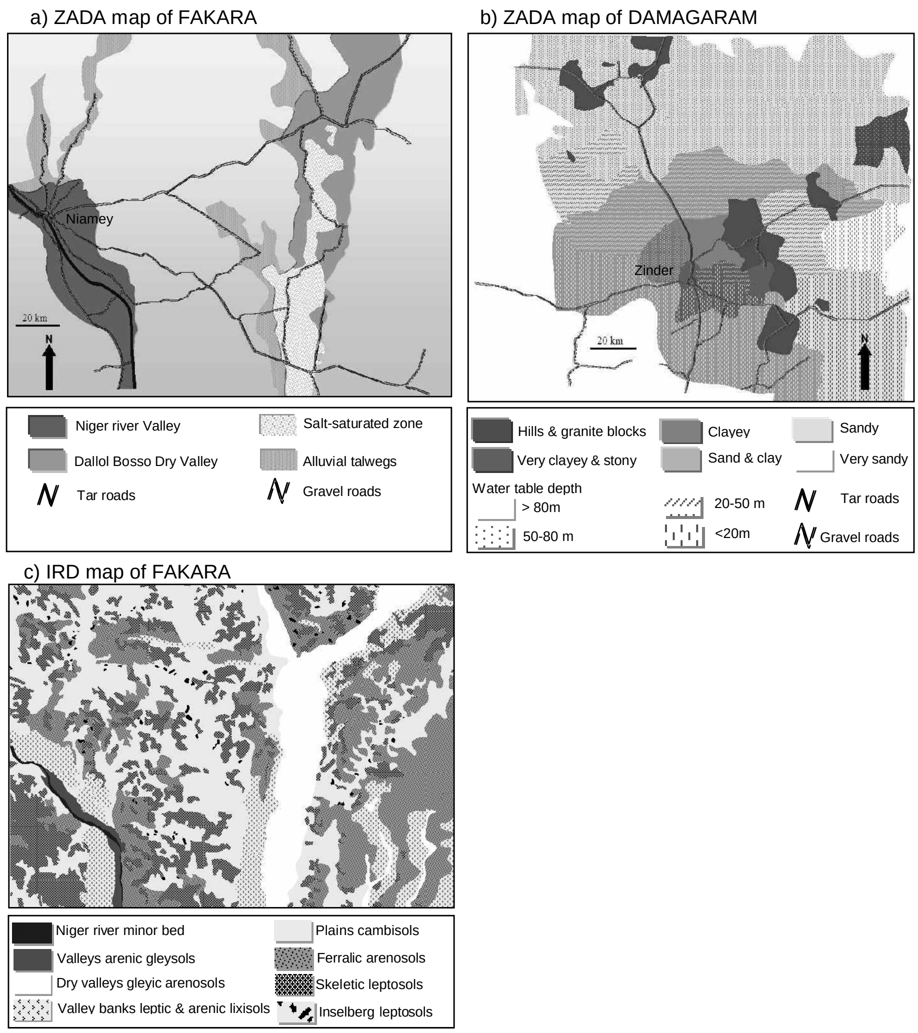


Figure 10. ZADA results of the biophysical organization of the two sites & IRD Morphopedological map of Zarmaganda (IRD ex-ORSTOM mapping service, 1974) using the FAO soil classification (Hiernaux, 1998)

The two valleys (the Niger river valley and the dry Dallol Bosso valley) and the plateaus are strictly and rapidly defined but the criterion of discrimination varies including botanic (presence of *Hyphaene thebaica* or *Balanites aegyptiaca*), hydrologic (shallow water at less than 3 meters) or physical factors (visible presence of a valley). In the same way for the site of Damagaram (Figure 10b), for the majority of interviewees (and all of the interviews that took place in very clay-rich and stony areas), the discrimination is based on combinations of such factors as the sand/clay ratio in the soil and the presence of gravel or hills.

One can compare the environmental characteristics of the different units:
For the Fakara map, the city of Niamey, Niger River and Dallol Bosso valleys are described as enjoying the highest level of natural resources, mainly because of their very easy access to shallow water through wells (less than 3 meters). The main tributary of the former river in the center of the dry Dallol Bosso valley is subject to an intense evaporation process and thus is very salty (K-Cl in the north of the area, Na-Cl in the south). Water here is therefore accessible, but is suitable for livestock only, not for humans and crops.
Thus, the ease of access to shallow water (between 3 and 10 meters) defined two SHU around the two valleys with small talwegs where gardening can be practiced and where wells are easy to dig. The 1/200,000 IGNN map in combination with post-map-making village history interviews leads us to conclude that all the villages which were founded before the 20th century are situated close to the valleys or one of the talwegs[92]. The territory between the two valleys is thus defined linguistically as "dry and hard", or Fakara in the Zarma local language.

As a confidence building step, one can compare these ZADA biophysical results from the Fakara map with the pedomorphological map from the well-documented IRD Niger Database (IRD, 1974). We have superimposed on the ZADA map the surface occupied by the hardened lateritic plateaus in order to see their spatial distribution and coverage using Spot5 images (2004) for presentation purposes. As shown in Figure 10a & c, results are comparable; the IRD map (down) shows more geographical and pedological precision but does not discriminate the plain ("plain cambisols" in the IRD map) and valleys ("alluvial talwegs" in the ZADA map of the Fakara) where irrigation is possible. The ZADA map (Figure 10a) shows new information layers (the salinity and the valleys extension defined on the basis of water accessibility) and is easier to present to development operators and villagers.

The site of Damagaram is described by farmers and nomadic herders using a soil texture gradient as a crop production indicator in combination with rainfall. Sandy zones are said to have better yields during dry years when

[92] These pre-colonization founded villages are historically either composed of Fulani, at that time mainly semi-nomadic herders, or either composed of Zarma, at that time solely farmers. Toponymy supports the conclusion: villages with Fulani names are concentrated in the centre of the Dallol Bosso valley, where livestock raising can only be practised, and villages with Zarma names are located along the border of the valley, where water allow to garden and crop;

clay-rich zones are said to be more productive than the sandy ones during rainy years. Hilly zones are described as the harshest places to live, since the land is too small for cropping between the granite hills, ground water is very deep and grazing areas are rare.

Thus, the two territories are certainly very different in their spatial and biophysical organization, but the fact that a majority of interviewees have described their areas based on this organization is strongly linked with the fact that it influences the dominant activity distribution.

3.3.2 The environmentally adapted economic activities

Both sites' biophysical characteristics relate to a diversity of uses (Figure 11).

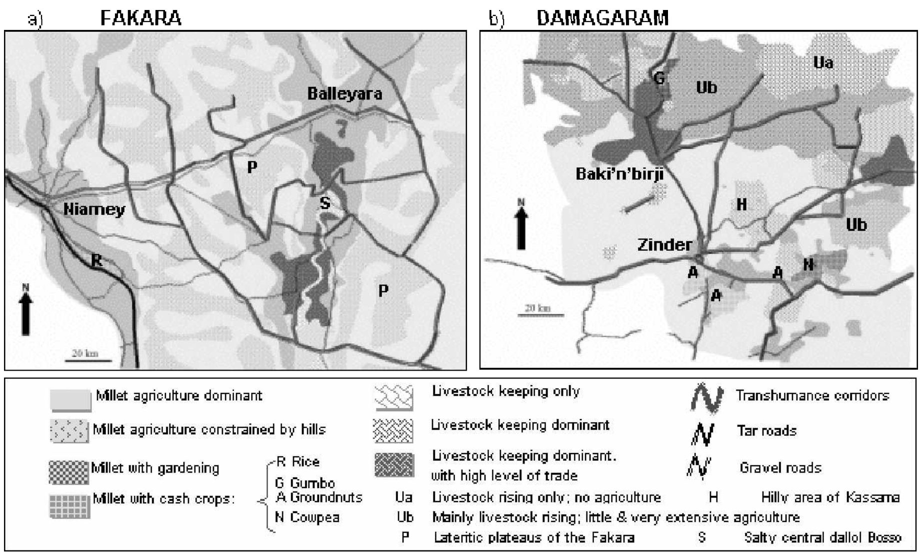


Figure 11. ZADA results for the dominant activities at the two sites

Agriculture constitutes the dominant activity in places described as favorable based on criteria such as soil quality and access to water by rain or wells. These same criteria determine, together with road access, the areas where agriculture is mixed with cash crops. Thus, rice is grown in the perimeters distributed along the Niger river (R) in the site of Zarmaganda (Figure 11a), and interviewees of the Damagaram site (Figure 11b) clearly identified areas of production of gumbo (G), peanut and cowpea, with groundnut cropped in sandy soils (A) and cowpea in clay-rich soils (N). These zones have been described as the downstream basins that receive alluvium and water from hilly areas. They are fully farmed and densely populated.

In both sites, the natural resource scarcity of certain parts of the area makes livestock keeping dominant. The hills in the north of Kassama (H) in the site of Damagaram are the exception, as these very stony hills are very poor grazing areas, even for goats, but constitute good water-collecting basins for livestock thanks to their slopes and impervious soils. They are thus considered by the majority of farmers we interviewed as the least favorable zones of the entire site. This is in agreement with the results of the PRA campaign of the NGO AQUADEV between 2000 and 2003.

The site of Damagaram, with an average rainfall for the Sahel (250 to 400 mm), is located at the northern limit of the Sahelian arable zone. The unfavorable areas are the northernmost zones where rains are too low, the soil is too sandy to hold enough water and wells must be drilled excessively deep (>50m). This area differentiates itself into an area where very extensive agriculture remains (Ub) and a second area (Ua) where no fields can be cropped.

The site of Zarmaganda, with higher rainfall (450 to 550 mm), has two types of areas allocated to grazing (Figure 11b): Plateaus are allocated for livestock grazing by semi-nomadic Fulani herders and increasingly by sedentary Zarma farmers. However, sand deposits on small areas of the plateaus allow very extensive pearl millet agriculture. As opposed to the first type, the second type of area is purposely chosen. The central dallol Bosso mainstream natroned and/or salty lands cannot be cropped but is auspicious for raising livestock due to the "salty cure" it gives to herds.

Actually, both areas are zones of herd convergence. Transhumance corridors[93] are organized in a network often parallel to tracks, tar or gravel roads. They mainly link northern pastoral areas to the main markets along roads, from which livestock is routed toward urban consumption centers (Niamey or Zinder) or dispatching centers (Balleyara in the Zarmaganda site; Baki'n'Birji in the Damagaram site). The latter are close to places that we defined as livestock keeping and trade areas.

3.3.3 The intensification of practices: an urban influence

A weekly market census by the administrative authorities made it appear as though there were fewer markets than we counted, particularly at the Damagaram site, where a lot of small markets are inter-related. As shown in Figure 12, Niamey (around 1 million inhabitants) and Zinder (around

[93] These corridors are travel routes for herds, so that herds can cross village territories and cause as little damage as possible to the surrounding fields and therefore limit agro-pastoral conflicts.

200,000 inhabitants) are the main urban centers that determined the organization of the farming system.

The site of Zarmaganda is described as a structured system: all the interviewed people referred, after a long hesitation, to the hierarchical market structure. Only one interviewee described the area in this way in the case of the Damagaram site. Two big markets organize the Zarmaganda site. Niamey is the main consumption market where products converge for urban needs. It also plays a role as an exchange node between the countryside and western coastal countries: Ghana and Côte d'Ivoire are the main seasonal migration poles for rural Zarma workers. The second market, Balleyara, is a trade market, particularly for livestock, since it is the crossing point between the northern nomadic herding territory, the dry valley livestock road, and the roads leading to the Nigerian Hausa markets in the south. The impact of Niamey city is lower than expected: the majority of interviews have shown no polarizing effect except for an urban straw collection area[94].

The site of Damagaram is, on the other hand, in the process of being structured, according to a gradient of demographic density from the south to the north. Interviewees considered that there is no free land to crop anymore in the south of the Zinder-Birni'n'Kazoé gravel road. The land north of this road, once reserved for nomadic herders, is colonized progressively by settlers coming from the south of the mapped area and even beyond, up to the border of Nigeria. Some spaces remained unsettled, as they are too far to the north, where the soil is very sandy (TO). The zone that borders the Zinder north axis road is particularly affected (B) by these new rural settlements, but this movement competes with another urban-originated expansion: urban tradesmen from the city of Zinder are settling new intensive farms (C), producing for the urban Zinder market, increasing land prices along the road and preventing rural-originated settlements.

[94] Bacaër *et al.* (2004) underlined the extension of the fuelwood collecting area of Niamey, which seems to include the whole area covered by the map.

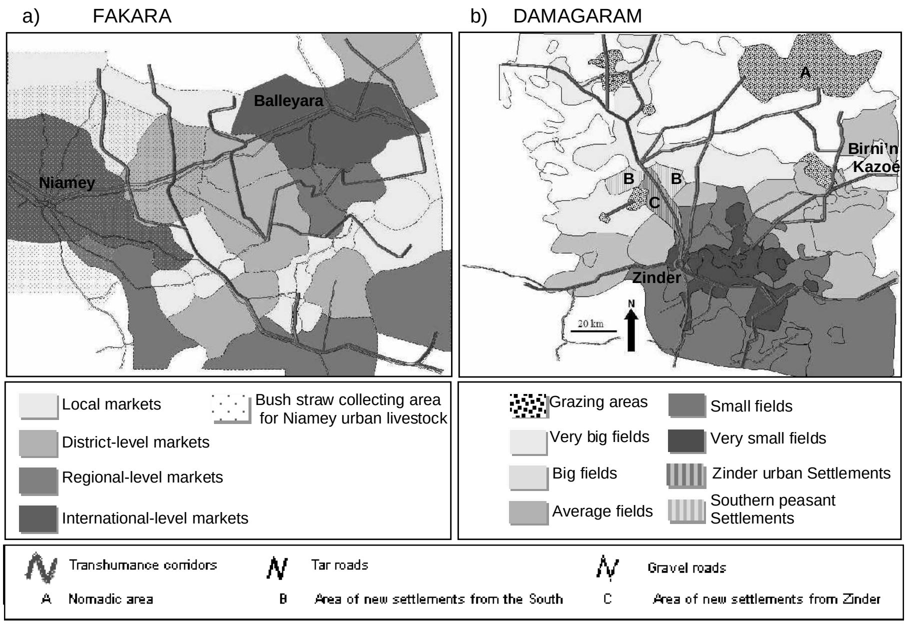


Figure 12. ZADA results on human occupancy dynamics and organization in the two sites

Thus, the interviewees' description underlined the difference between the two sites: the site of Zarmaganda is structured in commercial networks but does not seem to be as affected by settlement dynamics as the site of Damagaram.

3.3.4 Access to basic infrastructure

Depending on the importance of each type of infrastructure facility for the interviewees, they variably described the access to facilities (sanitation, schools and wells). In Damagaram, those interviewed underlined the almost universal access to wells, and thus eliminated this factor as discriminative, because NGOs and the government have launched an important well-construction program. On the other hand, in the site of Zarmaganda, wells were mentioned as still being in the stage of primordial infrastructure[95]. Access to school facilities is variously described as well, and there may have been confusion about the definition of these facilities (school vs. high

[95] This is likely related to the fact that the main symbolic act for village foundation in the Zarma area is to dig a new well. In the Hausa area, founding a village is more associated with new field clearings. Wells are then politically connoted infrastructures in Zarma land.

school; Moslem path vs. laic path), so we did not use schools and wells as comparative factors.

Dispensaries are clearly defined. For the Zarmaganda site, the number of recorded dispensaries agrees with lists from NGOs and the national administration (CARE, 2002). For the Damagaram site, our census and the one given by the administration did not correspond. Many of the governmental dispensaries are not currently active and some that we recorded are not registered. Some NGOs cleared old dispensaries without notifying national services. We illustrated the medical services coverage within a 15 km radius of the recorded dispensaries, as shown in Figure 13, since a distance of 30 km is the maximum distance a villager can walk in one day and public transportation is not really affordable for a large majority of the population. The site of Zarmaganda, where the capital city is, is thus, paradoxically, less covered (64,8% of the territory) than Damagaram (82,1%). We don't know why this difference exists. We suppose that the presence of the biggest hospitals of the country in the capital city leads operators to not develop medical infrastructures within a certain fringe around the city.

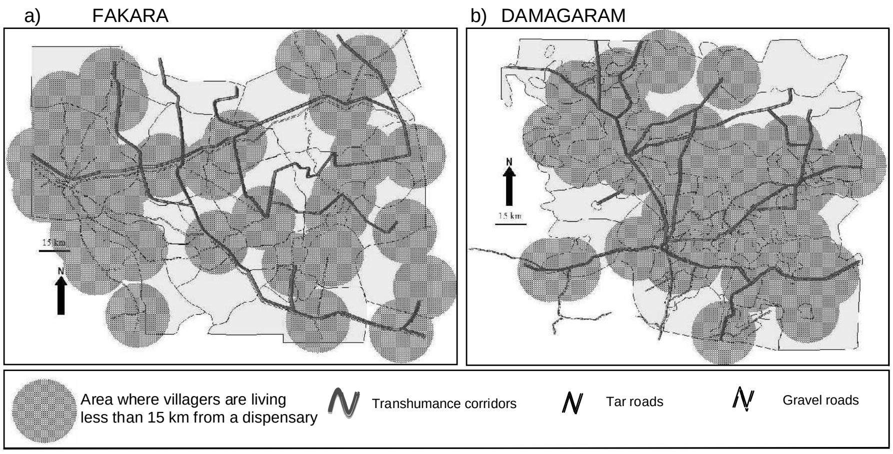


Figure 13. ZADA results on dispensary access coverage for the two sites

3.4 Discussion

As summarized in Table 4, ZADA should be considered as a complementary tool to include in a panel of methodologies according to each particular purpose.

Table 4. Comparing methodological tools for land investigation in the context of Nigerien Sahel

		Remote sensing	Field survey observations	PRAs	ZADA
Information sources	Medium	Satellite images	Field observations	Population assembly and interviews	Resource person interviews
	Tool	Image processing & GIS	GIS	None	GIS
	Topics	Land cover, and then Biophysics & land use	Biophysics & agro-ecology	All expressed dimensions	All expressed dimensions
Input	Cost	2 750 € [1]	5 150 € [2]	1 330 € [3]	1 925 € [4]
	Time	15 days	30 days	10 days	15 days
	Expertise	Remote sensing, biophysics & agro-ecology	Biophysics & agro-ecology	Mainly humanities	Mainly humanities
	Language	None	Little	Local	Local
Output	Semantics	Low	High	High	Very high
	Topology	Low	High	High	Very high
	Spatial resolution	Very high	High	Very low	Low
	Repeatability	High	High	Low	Medium
Study area size		Regional to national	Local	Local	Regional
Quality assessment		Field campaigns & data correlations	Repetitions	Cross-checking within a village	Cross-checking between maps, with external data
Purpose		Data collection & correlation.	Data collection	Variable collection	Variable collection, GIS crossing with various sources,
Objective		Scientific legitimacy, research-oriented for decision support	Scientific legitimacy, research-oriented	Local legitimacy, action-oriented	Local legitimacy, action-oriented

[1] Average 2 images to analyze, with an average cost of 1,000 € each, average minimum monthly salary 1,500 €
[2] Average minimum monthly salary of a 7 persons team: 4,150 €; mission logistics & materials: 1,000 €
[3] Average minimum monthly salary of a 5 persons team: 2,650 €; mission logistics & materials: 450 €
[4] Average minimum monthly salary of a 5 persons team: 2,650 €; mission logistics & materials: 600 €

- ZADA is low-cost, fast and explores at the regional level human dynamics. Moreover it is a tool for a better dialogue between scientific disciplines and results: each of the ZADA missions costs 1,925 €, including wages and transportation logistics costs. ZADA requires fewer funds than other data acquisition methods. Apart from a long period of anthropological participatory observation, there is no other way to identify so quickly and at such low cost several human-based development factors.

- The ZADA results are more action-oriented: because the discrimination factors are derived from interviewees and not from experts, one can suppose that planning development actions upon these factors will be more focused on indigenous issues. It is therefore also a tool of dialogue between researchers and development agents. Eventually, the method may be used as a tool for development agents, forcing them to better take into account the hierarchy of local constraints. The method is an interesting educational tool for new researchers, operators and students and information is acquired more quickly than during PRAs.
- As a tool to be used to fill the knowledge gap at the regional level, ZADA allows to underline new phenomena:
  - Permanent fluxes, such as the bush straw collecting area or the market areas, can be identified, therefore redefining villages as interdependent and open systems.
  - Temporal human dynamics, such as the settlements of traders along the Zinder-Tanout road or the settlements of southern villagers in the northern part of Damagaram, are highlighted, by reintegrating villages in their historical evolution as a medium-term prospective, which is particularly relevant for development planning in a so rapidly evolving context.

Social studies are usually considered by many scientists from the so-called hard sciences to be confusing, especially due to the fuzzy, merely qualitative and non-comparative character of results (Soini, 2001). Here, these social results are based on reliable information, are statistically analyzable, repeatable, comparable with other methods and comparable between several zones. They can be integrated into a GIS, to permit further analysis by combining them with other sources of data, such as pedological maps for instance. ZADA, as a modeling tool, can help to bridge the divide between the social and biophysical studies.

However, the tool has several drawbacks from a research point of view, which are linked to its advantages:

- As a perception-based tool, social factors can induce strong bias during sampling (see Table 4) and mapping, which can reduce the representativity of the interviewees.
- Emic [96]toponymy provides some fuzzy definition of the geographical limits, related to their richer semantic definitions. The SHU subdivision into various dimensions can refine the geographical limits but this step needs caution not to omit some elements through a too rapid

[96] Emic: indigenous conception and system of values and hierarchies, to be opposed with etic, i.e. an external point of view.

simplification. Therefore, the last step of the method, i.e. combining maps, is a very time consuming step, which lowers the time efficiency of the field steps.

SHU limits are geographically precise with respect to topology but not spatiality. For instance, gardening zones define the territories of villages where irrigated gardening is practiced and not the specific spatial territory of the irrigated plots. Although it marks out a relevant pattern for action by discriminating village units, it does not create spatially precise research-oriented outputs.

3.5 Conclusion

ZADA cannot be considered as a panacea. However, this tool provides a local, perception-based guideline for reasoned development actions and research, and therefore supports the objectives of development agencies or researchers as a mean for assessment of the relevance of their action. The strong interest in this tool by NGOs and researchers in social and development studies in Niger, and the conversely clear dismissal from hard science researchers, illustrates where the real research and development policy stakes are in the country.

4 Individual interviews

The purpose of this step is to build for each site a correspondence between the biophysical and socio-economic constraints and the activities at the village level. For logistical reasons, the Fakara site was the object of more advanced investigations. Investigations at the two other sites took place after the ones on the Fakara in order to identify factors that may differentiate them from the Fakara. The field investigations were organized in several successive steps.

4.1 The village sampling of the three sites

Every site was crossed and explored by transects[97] going through several villages (14 villages for the Fakara site, 8 for the Gabi site, 6 for the Zermou site). For Gabi and Zermou, transects were followed by a series of PRAs (6 at Zermou, 5 at Gabi). Such methods helped to better understand the village organization and to characterize, with the support of the ZADAs, the criteria on which villages are selected. Three to four villages were then selected in

[97] This method of reconnaissance of a geographic territory consists in crossing through and straight on into the concerned territory by foot or by vehicle, in order to identify organization sequences of this space in avoiding biases due to roads and other means of communication.

order to explore the highest possible diversity of villages taking in account the necessity to limit as much as possible the number of villages within each site to stay as long as possible in each village (local impregnation, villagers' familiarization to the presence of the researcher). The stratified sampling of each site follows:

- For the Fakara site, we chose four villages in the zone of the consortium and in its perimeter. Two criteria were used to select the villages:
    - Presence inside or outside of the area recurrently affected by projects.
    - Size, roads and access to shallow water for dry season gardening. The three criteria are confounded because gravel roads link only big villages where dry season gardening is possible.
- For the Gabi site, four villages were also chosen according to three criteria: The access of the village to a fraction of the goulbi and thus giving access to dry season gardening, the possession of a portion of the forest reserve that constitutes an unofficial grazing and woodcutting area. The last criterion is the south-north position along the axis of the goulbi that defines the access levels to the Nigerian border and thereby the part of the bootlegging/trade in family incomes. The four villages may be stratified along this pattern as follows[98]:
    1. North of the "canton" / access to the goulbi / access to the forest
    2. Center of the "canton" / access to the goulbi / access to the forest
    3. Center of the "canton" / access to the goulbi / no access to the forest
    4. South of the "canton" /no access to the goulbi /no access to the forest
- Finally in Zermou, three villages were investigated according to two criteria: The presence of stony hills in the village territory meaning that land is rare and water is very deep. The second criterion is the fact to be in or out of the zone of the AQUADEV NGO. The three villages may be stratified along this pattern as follows[99]:
    1. Presence of stony hills / presence in the AQUADEV area
    2. Absence of stony hills / presence in the AQUADEV area
    3. Presence of stony hills / presence outside of the AQUADEV area

4.2 The interviewed people & the interview methods

The sampling was brought about by a segmentation of individuals according to a two-criteria stratification: Gender is the most fundamental criterion of discrimination regarding the access to activities. The second criterion is the

[98] The small size of the investigated village sample is due to time and budgetary limitations.

[99] The small size of the investigated village sample is due to time and budgetary limitations.

degree of responsibility, i.e. the number of people that depend upon one individual.

- A first household census and first informal discussions were carried out with the chief, the notables and the elders of each village, allowing us to be locally introduced. It helped us to discriminate the population by local criteria: richness and/or abundance based on several assets (manpower[100], herd size[101]). The purpose is to explore the highest possible diversity of adults from a village, i.e. villagers usually over 16. A particular attention was paid to the ratio between enlarged and mononuclear families, in the village and the sample. A dozen of these households were selected in our census in order to cover the largest possible diversity of households. A second household sample was selected through random selection from every quarter of the village. This census gave us a global idea of the proportions of the concerned groups.
- Finally, five families were chosen for each site for their particular characteristics (families whose family head is a woman, families of craftsmen, of traders).
- Two people from every selected household were interviewed, in order to have a larger and more diverse point of view of the local diversity of the individuals. Each person was interviewed once or twice depending on the number of activities he/she manages. Thus, beyond the unavoidable interview of the family head or his "substitute" during the dry season, the second person is alternatively an elder, a young bachelor man or girl, or a married woman[102].

The number of individual meetings was 126 in the four villages of Fakara, not including the investigations on village history with elders and village chiefs. For Gabi, 26 individual meetings were realized, and 23 in Zermou, not including investigations on village history. These field investigations

[100] The manpower unit is defined as the Farming Labor Unit (F.L.U.). For our case and based on our observations, female and male adult manpowers are equivalent (one can even consider that the female manpower is more important locally) and equal to 1.

[101] The field surface criterion is not relevant: in this case, surfaces should be measured on the field, which means a whole cadastre that people fear. Asking the surface is not efficient enough, except through the required seed quantity. Moreover, our first investigations strongly suggest that this is not a discrimination factor between villagers of the same village in the places where the work was implemented.

[102] Practically, interviewing women, especially unmarried ones, means many difficulties from which the least is the continuous presence of a duenna, i.e. an older woman checking that things remain decent.

were carried out from mid-2004 till the end of 2005. The interview method consisted in semi-direct interviews focusing on the main activity carried out by the interviewed person at the time of the interview, following thereby the methodological principles of Olivier de Sardan (2003). We have paid attention to the adequacy between the timing of the interviews and critical dates for each activity[103].

4.3 Assessing the implementation of development actions in practice.

The institutional position given by our own involvement in a development project helped us to get access to the network of experts in Niger. Our long-term field investigation also allowed investigating the complex relationship between project and villages and assessing the practical implementation of development actions. We tried to analyze these actions from the operators' point of view and the villagers' one, using a participatory observation approach[104]. We first used the operators' official documents or documents coming from other operators as a mainframe to confront unofficial expert communications and local situations.

The analysis of the development operators' practices was done through different cross-checkable methods: (i) 4 to 12 villagers from each study site were re-interviewed on their personal relations with development projects. These persons were selected because of gender and level of responsibility and their will to interact[105]. In the same way, nine elders were interviewed on their perceptions of the history of local development actions; (ii) development actions results are recorded in village-based registers that we collected and compared with head office records but also with our own village semi-direct interview data; (iii) By staying in villages and remaining as unobtrusive as possible, our everyday presence allowed observing transactions and comments between villagers and development stakeholders with a low level of perturbation and so, to have access to the interface between the project corpus and the village one.

---

[103] For instance, the propitious period for interviewing future migrants is just on the eve of the departures for seasonal migration, around October, when they are full of the bus ticket problem, rather than during the cropping season.

[104] The best moment for observation was the time when both social groups were encountering, during meetings, visits and interview times.

[105] It often happens that this depends on their own frustrations, which means that we had to integrate their testimonies in their own political and social context.

4.4 Biases & limitations

Several biases and constraints were difficult to avoid in this context:

- Information was collected and translated from Hausa to French or Zarma to French, with the help of Arabic. This can be misleading as a result of simplifications and errors that are difficult to avoid. In particular, some vernacular terms, some usual sentences and proverbs, jokes and expressions were usually not understood, which is a loss when one wants to "feel" the perception of the people in their environment.
- Numerous terms can be misleading, causing confusion between their literal meaning (for example: "a field") and the local context meaning (owned fields; owned and borrowed fields; managed fields; cropped fields not including fallows; etc.).
- The collected data are issued from transects and interviews with the villagers. The results are sometimes contradictory: we then looked at other sources (extension services, grocers & traders, etc.) in order to elaborate our concepts. Thus, these can and have to be considered like a poll result of the perception of inhabitants on their own environment.
- Numerous interviews were taking place in the presence of neighbors, which was socially impossible to avoid: their presence brought about answers that were also destined to this public. Some answers may have lost their relevance as they were becoming too much normative. Therefore, a bias appeared: people who were open to discuss alone were often young and/or members of more marginalized families, such that their neighbors were less eager to attend, who usually described their own situation and their village in a more negative manner.
- The *de facto* status of a member of a well-known institution, namely ICRISAT, has brought about clear biases in the collected information (normative and not very spontaneous answers), particularly in the Fakara where this organization has worked for 20 years. In order to reduce this effect, two villages out of four in this site were chosen outside of the ICRISAT-led consortium zone, by mobilizing independent transportation allowing to stay longer in villages. However, one cannot hide this enormous bias that constitutes the fact of being a representative of the "nassara" or the "nassara Ni"[106]. The use of the Arabic language may have tempered only slightly this situation and favored an entrance in the milieus of "literate Muslims" and local imams, even certain welcoming chiefs. Yet, this image also constitutes a risk of labeling as full of biases than the "nassara" one.

[106] Nassara = Nazarene, i.e. Christian, which means white foreigners. Nassara Ni: = he who behaves like a Nassara. Skin color, vehicle logos, clothes, outfits & materials, languages, etc. are indices for identification and categorization.

- The listed economic activities are practiced during different seasons of the year. It is therefore necessary to be present all along the year[107] to observe the annual succession of activities and the intra-annual variability. However, certain activities are extremely variable in the long-term, agriculture in particular. It is thus impossible to fall upon an average year. Average years do not exist. Moreover, for logistical reasons, it has not always been possible to be present on the sites at certain crucial moments (men returning from migration, first rains and sowing in particular).

As a conclusion, one may summarize the axes of the field methodology:

- The purpose of the individual interviews was to acquire micro-level informations to build individual behavior rules and their conditions of application that rule production and economic activities of Sahelian villagers. Interviews with different people at different times of the year and on different activities and purposes were realized in the three selected sites of the Sahelian Niger, to build such rules.
- The purpose of the different socio-anthropological collective tools was to acquire enough information at the macro level on socio-anthropological issues concerning the accesses and limitations of access to economic activities according to groups of villagers, villages and regions[108]. On more environmental issues, variables were defined through interviews but related data are coming from literature.

The SimSahel model is built based on the results of this approach. Nevertheless, the conception of such a model should be clarified and the approach we used for the field and the characteristics of the field itself have a strong impact on the model building and the model.

[107] The main constraints as perceived by a villager may shift along the year according to the period in the year and different from one year to another one: millet availability before the cropping season, cash availability before taxes, the Tabaski, the migration departure, etc.

[108] For instance, as noticed through the ZADA, the transportation cost for migration is an important factor of discrimination between villages. Through this differentiation, one may therefore consider this factor as a very important discrimination criterion between villagers within the same village.

CHAPTER III: BUILDING THE AGENT-BASED SIMSAHEL MODEL

According to Landais & Deffontaines (1987), a model is a "theoretical and finalized representation of a reality formulated on the basis of situated observations, of a predefined framework that will then be applied to study cases and permits to give representations quickly". A model serves to establish structural relationships and functions existing between the factors that one would like to analyze. The objective is to determine the type of relationships existing between these factors and the weight of each factoring the relationships (Parker *et al.,* 2001). A model does not exist if it is only about a goal, an objective, that can be problem solving, decision-support or simply experimentating (Roy, 1992; Le Bars 2003). This definition adopts an operational standpoint, thereby insisting on the subjectivity and the need for an objective for every model. This definition paradoxically originated from geographers, who explicitly include maps in this definition, whatever the data origin they rely on. The intrinsic objective of a model is therefore to accelerate and/or facilitate the analysis of a subject (Perrot & Landais, 1993).

1 Simulating with Agent-based Models

1.1 The necessary choice of a distributive model

As described by Huigen *et al.* (2006), two constraints should be overcome:

- As seen in chapter 1, interactions between environment & society in Sahelian farming systems are fundamental in the global evolution of such systems. A change in the farming system organization is not always linear and does not always concern the whole population. Therefore, reconstituting this evolution should integrate such interactions and requires bringing together and making interact social, economic and biophysical factors into the same tool.
- This interdisciplinarity necessity is reinforced by the fact that access to production assets is intrinsically different for each villager. The understanding or even the simple observation of such sudden, non linear

evolutions is difficult as long as the population is considered in its globality without going further into the "black box", namely in our case the different rationalities and specificities of each villager. Revealing social changes and their impact on a farming system organization requires taking into account the differences between villagers in the processes of these changes.

Distributive models are modeling processes that allow such combinations, through the programming of behavior rules applied to numerous modeled entities. In refining these rules, one can mime various phenomena that are otherwise very difficult to copy and to understand. The main advantages of such model types are:

- Distributive models can be defined as creating as many entities (or entity avatars[109]) as needed or as allowed by the computer calculation power capacity. They thereby allow multiple interactions between these entities as defined by the implemented rules. Through this advantage and reintroducing the temporality of events, such distributive models favor demultiplication effects and thereby bring to light emerging phenomena[110] but also highlight the own inertia of all complex systems like ecological and social ones (Janssen & Ostrom, 2006).
- The behavior rules can be common to all the entity avatars but to have different implications for each of the entities according to their specific characteristics (Meurisse & Vanbergue, 2001; Chevrier & Huget, 2006). In our work, considering villagers as entities allows to simulate their different logics and the interactions between them as observed during field investigations. It is an easy way to implement the behavior variability among villagers and observe their consequences.
- Finally, and as described by Bousquet & Le Page (2004), distributive models are very easy to understand because they correspond to an intuitive conception of the reality, which can ease their transcription on different software platforms.

---

[109] We mean by "entity avatar" the different identical or quasi-identical copies of one entity. For instance several copies of a cattle constitute a simulated cattle herd.

[110] A phenomena is emerging if:

A system of interacting entities creates a dynamic phenomenon, while the programming of the states and dynamics is established at the entities' level (micro level) and without intentionality at the macro level (Müller, 1998).

The produced phenomenon, whatever it is (a process, a stable state or an invariant) but is global at the system level and that can not be deduced from the sole properties of the components and that cannot be reduced to the non interactive properties of these components.

As a partial conclusion, distributive models have several advantages compared to holistic ones: numerous entities, numerous interactions that can be complexified, an easy understanding and a large adaptability are altogether strong assets. However, these models, like all the ones that simulate situations with many elements and many interactions, may easily suffer from the "gas factory" syndrome (Boissier, 2001): the accumulation of parameterized relationships makes it much heavier, limiting the number of possible simulations over time[111] and making it difficult to discriminate between resulting phenomena. Distributive models can be described along an evolution towards more complexity, from cellular automata to ABMs. Rather than conceptually and abstractly describing the ABMs, one may prefer to describe this evolution from the most simple to the most complicated, thereby showing the interest but also the difficulties of introducing more and more autonomous entities (Ferber, 1999).

1.2 The "cellular" models

Cellular automata are based on matrices of adjacent cells representing the bidimensional universe. Each cell or cell automaton is spatially positioned. Such matrix-based models are similar to those from geographical information systems (GIS) that may also be considered as cellular automata. Transitions from one state to another are defined according to more or less complex rules based upon spatial neighborhood (each cell is influenced by its neighboring cells) or temporal contingencies (the situation of a cell at a time step t depends on t-1) (Parker *et al.*, 2001; Veldkamp & Lambin, 2001).

These models have permitted to develop representations that simulate well spatial phenomena in a spatially and temporally circumstanced manner. This has lead to their use for agro-ecological purposes (crop and vegetation cover, growth or changes, dissemination of diseases and species), particularly since their combination with GIS models (Lambin *et al.*, 2000). One of the main advantages of this spatial approach is to avoid the modeling of the change-acting element (peasant, etc.) by focusing on the effects of the latter on the territory, as the real object of study.

However, the interaction structure of these cell elements cannot be modified. Cells are geographically fixed. They cannot represent human or animal entities that can spatially shift, choose with whom/what to interact, etc. In the domain of ecosystem modeling, transformed by humans or not, only

[111] This model does not escape from this syndrome unfortunately, each simulation requires about an hour of calculation for 60 years of simulation but four to eight hours (and sometimes more!) for 100 years of simulation depending on the scenarios.

spatial elements can therefore suitably be modeled. Hence, cellular automata models are only of interest if the object of study is the territory and possibly the related resources to be analyzed along a spatial approach. The consequence is that it intrinsically distorts or ignores the human logics acting on this territory that do not necessarily seek to optimize it or the associated natural resources. Furthermore, human practices are not necessarily related to spatial neighboring relationships, which induces a strong misunderstanding: mankind is seen as an acting force on the territory, but one can not see the possible interactions between actions that are not related to the spatial dimension or simply too far away, i.e. they are linked to spaces not simulated by the model.

A model may actually need elements that have to be mobile, heterogeneous, organized according to networks and institutions, not defined by their spatial position. They may have to control or manage big or scattered territories. Finally, beyond spatial or territory-centered questions, cellular automata are no longer intuitive to build when it comes to elaborating complex social systems.

1.3 The object-based models

This cellular automata approach was then extended by establishing transition rules according to non-adjacent neighborhoods (for example temporal proximity along road networks) (Newell *et al.*, 2005). A further step was to create entities that are independent from a spatial position or that may be mobile, without neighborhood rules and able to act on other entities of the spatial matrix. Such entities were simply named objects. Every object has automatic functions corresponding to relations with other objects. An obvious example is a matrix simulation of grazing camps where cells are grazing parcels and objects are livestock: the latter are mobile on the matrix, graze the resources and manure the cells. A field object may receive information from a certain number of "farmer" objects, various "livestock" objects and from a "rain" object that regularly interact along different levels of intensity (Loireau-Delabre 1998; 2000).

The interests of such models remind of those of cellular automata, because of the absence of a global hypothesis of finality for the resources' attribution (Parker *et al.*, 2001; Gimblett, 2005). Objects may even be "virtual" in the spatial environment, i.e. not be present on the modeled territory. For instance, a "market" object, traders or politicians may have some influence on the village evolution without being actually present. They are thus interesting for envisioning the action of coordinated policies on a territory, as in the case of management of protected areas for instance (Lambin *et al.*, 2000).

1.4 What more do the Agents have?

As a first point, spatialized ABMs are equivalent to spatialized object-based models and therefore they are also cellular automata. The difference is the nature of the entities, namely the "Agents". These differentiate themselves from the objects by the fact that one can introduce rationality there, which is more or less complex and not immediate. There is not simply an automatic reaction to an exterior stimulus but more likely integration and treatment of this information and then possibly inclusion in a cognitive process. In particular, a choice and a decision may be implemented, based on a notion of temporality in the reactivity of the Agent. One can thus link a decision to a memory by creating functions simulating experience in the practice of an activity or an interaction with other entities (memory of social relationships, of the productivity of a field, etc.). This allows to envisage some heterogeneity of attitudes and to explain their origin. In general, the Agent is equipped with a limited perception of its environment. From its knowledge and the objectives that are given to it, it proceeds during its deliberations to choices between several predefined actions. Afterwards, by acting, it changes its environment, and therefore the perception that it has of it. A further step is to reconsider its knowledge in order to choose new actions.

This iterative process is all the more complex considering that the Agent is not alone to influence its surroundings and that at every time step, its universe is modified by the simultaneous actions of all the entities. Different procedures can be applied to organize the sequence of actions of the entities, such as a discrete time procedure and a regular or randomized tour of the entities on which they may act. There are several ways for Agents to influence one another: they may directly transform the others, communicate with them by sending messages (and therefore change their knowledge or their objectives), or modify the environment and therefore the perception that each entity has of it (Bousquet *et al.,* 1998).

One must consider that the limit between an object, a cellular automaton and an Agent is more a norm than a real stated barrier: an Agent with a very simple and automatic behavior Agent (without an advertised goal) may be considered as an object. An Agent that is spatially situated on a matrix and that does not move is also a cellular automaton.

Therefore, as Agents are more flexible than other entities and ABMs can include in addition of Agents (e.g. villagers) cellular automata (e.g. parcels) and objects (e.g. livestock), ABMs are therefore the most appropriate option for building a model on farming systems, especially if one wishes to include social dynamics and rationalities.

1.5 Relevance of ABMs in social simulations of rural development issues

Our issue is intrinsically linked to the characteristics of the Sahelian villages: these belong to complex societies and ecosystems, whose components are linked together by various interactions, each related to different scientific disciplines. One cannot select a single interaction among all possible ones as the main and determining relationship that conditions the evolution of such systems. These interactions have therefore to be considered as a whole, without which one cannot understand the functioning of this society. An ABM approach is *de facto* justified because such models are adapted to the context, the concepts and the question:

- ABMs are adapted to the context of "developing" countries: The low availability of quantitative data and the difficulty of launching statistically reliable investigations[112] limit the use of statistical or multi-criteria optimization models. ABMs allow incorporating more easily partial results coming from different sources (agronomic research stations, statistical questionnaires, open interviews, experts interviews, direct observations or theoretical behavior rules) (Berger, 2001; (Bousquet *et al.,* 2001; Le Page *et al.,* 2004).
- They are relevant for the analysis of social systems that are multi-active, multi-rational and where interactions and relationships play a major role. The agent-based approach can integrate quantitative and qualitative variables[113] and thus better formalize the combination of disciplines (Rouchier & Requier-Desjardins, 1998; Berger 2000).
- They are relevant through their approach, i.e. a differentiation of accesses to production means and to the related gains. Micro-economic models rest on the explicit choice of an entity but cannot deal with the effects of the interactions between several dozen entities because they are rapidly submerged by the utility functions with several hundred unknowns. Thanks to their emergence capacity, ABMs can be used according to a very empirical approach (Janssen & Ostrom, 2006).

[112] This limit is due to the choice of the relevant unit, but also the required time, the high costs and the methodological difficulties that such field investigations require.
[113] Crosschecked information (experts, local actors, direct observations) permit to grasp the dynamics, the relations, whereas data (map, demography) parameterize these relations

1.6 The CORMAS platform

The choice of the selected CORMAS ABM platform[114] is based on the comparison of the main available platforms working in our field as presented by Parker *et al.* (2001) and shown in Table 5[115].

Table 5. Available distributive software platforms for social Agent-based modeling (Parker *et al.*, 2001).

	SWARM	RePast	Ascape	CORMAS
Developers	Santa Fe Institute/ SWARM Development Group	University of Chicago	Brookings Institute, Washington, D.C.	CIRAD, Montpellier, France
Start development	Early 1990s	Early 1999	1997	1996
Language	Object C/Java	Java	Java	Smalltalk
Operating system	Unix/Linux, Mac OSX, Windows	Windows, Unix/Linux, Mac OSX	Windows, Unix/Linux, Mac OSX	Windows, Unix/Linux, Mac
Required experience	Strong skills	Some Java programming	No experience of running existing models, basic skill for changing models, & strong skills to make major extensions	None, if attending the training courses, basic skills in programming otherwise
GIS Connection	Kenge / GIS library http://www.gis.usu.edu/swarm/	In development	Beta version	Generic methods to import/export maps from/to MapInfo. Dynamic link with ArcView via Access
Statistics of runs	The statistical package R & Splus clone	Some statistical functions with the Colt library. Some simple network statistics	Many, like average & variance, Gini coefficient	User can define which data to store
Main focus of applications	Natural & social sciences, military & commercial applications	Social science	Social & economic systems	Economic & ecological simulation; natural resource management
Available demo models	Few models on website, many papers + few books with SWARM applications	Six demo-models	About 20–30 demo models	Numerous models on website, with papers and authors electronic addresses
Documentation & Tutorial	Yes	Yes	Yes	Yes
Training sessions	No	In the past (now stopped)	No	Several courses are given each year

[114] Acronym for "Common Resources Management Agent-based System".
[115] Le Bars (2003) selected this platform for equivalent reasons.

CORMAS is a simulation platform written in Smalltalk language, which is an evolution of Java, created by the GREEN team of CIRAD[116]. CORMAS facilitates model building by proposing predefined elements. Amongst these elements, the entity-types[117] are Smalltalk generic classes from which, by specialization and characterization, the user defines the particular entities for his/her needs. The assets of this platform are eminently convenient:

- The platform already exists: we would never have had the means or the capability to envisage constructing a platform for ABMs.
- The platform has existed for quite a long time; numerous courses are given, forums and symposiums are regularly organized. As for SWARM and NetLogo, it is an active scientific community.
- CORMAS is purposely built for responding to problematics that are very close to our topic, i.e. natural resources management stakes. It is more intuitive for thematicians thanks to a language that is simpler than pure Java.
- This platform focuses on interactions between local actors with diverging interests (Bousquet *et al.,* 1998; Bousquet & Le Page, 2004): it easily considers conflict notions or at least negotiation-building on the management and use of spatialized resources. Besides, a growing research orientation on joint negotiation uses this tool as an information supplier to translate strategies that emerge from local role-playing sessions. The whole process has already been applied on several occasions (Etienne, 2003; d'Aquino *et al.,* 2004; Le Page *et al.,* 2004; Daré, 2005; Bah *et al.,* 2006).
- As it is research & action oriented, it allows more easily to develop descriptive and empirical approaches when compared with other platforms that are more centered upon the elaboration of theoretical scenarios exploring the combinations of theorized attitudes.

As a partial conclusion, one may see that ABMs perfectly fit our objective: they are adapted to the field context (lack of continuous data), the questions and the approach. The CORMAS platform is actually the best software to use, as it is dedicated to analyze issues very similar to ours. However, using such tools requires establishing some principles and a modeling framework before simply implementing behavior models.

---

[116] www.cormas.cirad.fr

[117] One should not assimilate the term Agent to an individual: it is possible to create a collective Agent (a tribe, a football team, a family, etc.) where members are individual agents or even another group of entities. In our case, each villager is one Agent, connected to one Social status; each livestock head is one object.

2 From field-originated questions to SimSahel building principles

2.1 The population in its territory: an innovative subject for ABM modeling

Numerous ABMs on social simulation have already been conceived and implemented in order to examine a very large range of social phenomena. It is not possible to review all of them, and to describe a representative sample is difficult (Amblard & Phan, 2006).

The most common object of study of ABMs for social modeling is the organization of an economic activity linked with the management of a resource as an object of negotiation between economic actors (Ferrand, 1998; Campo 2003). It is about managing this activity in order to conserve and/or manage the resource. The subject is then specifically the activity itself and the associated field work consists in describing and discriminating all the actors who play a role in this activity in order to grasp all the stakes and then analyze the interactions between them. For instance, pastoral resources (Mechoud *et al.*, 1998; Rouchier 2000); (Matthews 2006; Bah *et al.,* 2006), hunted or fished fauna (Bousquet 1994; Bakam *et al.*, 2003; Kobchai, 2006), firewood (Bacaër *et al.,* 2004), irrigation water (Becu, 2001; Le Bars, 2003); (Barreteau *et al.,* 2003) (Gurung *et al.,* 2006), land (Castella *et al.,* 2005) and, by extension through the notion of stakes between actors, markets (Galtier, 2003; Phan & Beugnard, 2003), or migration opportunities (Henry *et al.,* 2003; Huigen *et al.*, 2006).

Another very productive approach is to consider the territory as the result of dynamics and interactions and not as a stake: one can thereby study the diffusion of innovations (Schmidt & Rounsevell, 2006) or the evolution of land use according to different scenarios and hypotheses (Balmann 1997; Poix & Michelin, 2000; Lambin *et al.*, 2000). In such approaches, ABMs may lean themselves to decision-support by elaborating prospective scenarios of policies acting on the spatial dynamics (Lardon *et al.*, 1998; Berger, 2001; Etienne, 2003; Happe *et al.,* 2006; Berger *et al.,* 2006). An even better suited process is orientated towards development-related action by the use of a coupling between ABMs and role-playing (Bousquet *et al.,* 2002).

The present study is based on a population approach: our object of study is indeed the population, its future as a whole and the characteristics of the different groups that compose it. It is not about the management of a resource or a territory that the population may use, but the perspectives of the population itself, through the analysis of the assets that support the living conditions of this population. Our subject is the dynamics affecting this population. For that purpose, the model has to be able to aggregate in a simple manner numerous components, i.e. the villagers' activities, in order to consider the perspectives of these people.

2.2 A prior refusal of theorization

To conceptualize a society *a priori* means assuming the existence of an inherent framework in which the reality to "be discovered" can be described. It supposes that the farming systems and the societies are elaborate systems whose understanding is possible *ex vivo*. The driving factors and stakes of a farming system cannot be conceptualized *a priori* before any fieldwork. It is then necessary to dedicate some time to identify the true driving factors rather than to set these chosen factors and to verify their modulations thereafter on the field. The typology of Gilbert (2006 pp.149-152) separates ABMs into two groups: the first one is "abstract" where models are theoretical situations focusing on a specific issue, putting apart the general context. The second group is descriptive: such models describe a real situation with all its complexity. As we consider the real Nigerien Sahel situations, we clearly stand in the second group. However, the scenarios we implement are closer to abstract models given the calls on prospective theories, as the ones for model family organization and inheritance changes.

2.3 Multiple activities and multiple finalities

As described in chapter 1, pluriactivity is essential to sustain farming and social systems in Sahelian villages. One of the big advantages of ABMs is to be able to combine and to put in balance objectives or contradictory actors. We adopt therefore the following principle: considering all components of the system, i.e. the different activities and the different categories of villagers, and simplifying their processes and behaviors is more relevant than neglecting *ex ante* some activities and population categories by focusing on the activity and/or the category which appears to be the most important (Alacs, 2004; Amblard & Phan, 2006).

Moreover and as described in chapter 1, the individual has been preferred over other aggregated units (household, residence unit, etc.) as the basis entity unit for the analysis of activity systems. Therefore, the Agent in the model is related to one single villager and not one family/farm: Besides its better correspondence to reality, the choice of this unit frees oneself from the complexity of defining a suitable unit. It also avoids the need to synthesize the different rationalities of family members into one artificial family and thus allows putting into light the diversity of strategies. The global incoherence is strongly reduced by the fact that the objectives of the individuals may be common (reputation, social reproduction, accumulation): only the chosen strategy may possibly differ, according to the position of every individual within these groups, of his/her access to production means, to information and sources of income or social capital. We then extent this individuality to all the active entities of the model: Each cell represents a parcel, every object represents a single head of livestock and every Agent represents a single villager.

2.4 Hierarchizing the complexity of rationalities & processes

2.4.1 Keep it "sophisticatedly" simple

We made the choice of an ABM with circular interactions (Verhagen & Smit, 2003): individual rules are formalized and implemented as inputs at the *micro* level, for the spatial pixelized entities as well as for the human agents or the animal objects of the model. The emerging features of such individual rules appear at the macro level, i.e. the level of families, of the village and the territory, which are the results to observe, analyze and discuss.

Among the diversity of modeling possibilities within the CORMAS platform model types, we chose to develop an empirical model based on quasi-reactive Agents (Janssen & Ostrom, 2006), i.e. based on the straight translation of the observed individual behaviors without optimization procedures (substantialist, optimizing or maximizing / minimizing determinisms) to avoid overconditioning model results and to limit as much as possible cognition rules that may imply several postulates on rationalities. The behavior of villagers is therefore not cognitive and the different steps of the various activities are implemented as simply as possible, adopting the principle of "sophisticated" simplicity as presented by Nikolopoulos (2003) to maintain the global consistency of the system. Villagers simply do what they have to do and react over time as a sequential function of the events (Fafchamps, 1993) without cognitive functions that would require absolute rather than relative parameterizing of values on social issues. Therefore, the level of understanding and interactions of agents is restricted: the objective of this modeling is to see what impact these individual behavior rules can have on the collectivity of agents. Increasing the complexity of these rules restricts very strongly our capacity to discriminate the impact of each of these rules. It is therefore necessary to simplify them as much as possible.

Thus, in the ABMs' typology of Gilbert (2006 pp.149-152), we clearly stand in the category of simple agents' empirical models. However, one scenario brings in some slightly more complex cognitive processes.

2.4.2 A stratified & empirical model: data for the framework, informations for the dynamics, theories for hypotheses

The more the human factors in our model create differences between individuals, the more they are important to integrate. However, this principle was adopted only insofar as our investigations permitted to justify the impact of this differentiation. Thus, we were able to have an idea of differences due to age, gender or lineage in a same site, but not due to ethnicity, which did not permit to distinguish between Zarmas and Fulanis for the case of the Fakara.

We separate the model into three sections according to a hierarchy of complexity and sources of information:

- The first part corresponds to the **framework** of the model, which we do not investigate on and that does not correspond to our research questions. We consequently assume its validity. For the biophysical section (climatology, pedology & phyto-ecology), rules and parameters are based upon the available published and unpublished literature (reports & documents from development or research agencies, M.Sc. & Ph.D. dissertations). Human processes that do not call upon logics of socio-anthropology of production assets' management also belong to this category and are implemented as merely reactive. These are demography, prices of external products and physiology (food, ageing, motherhood and birth, death, etc.). For those aspects, the agents are simple objects.
- The second part is made up of the rules derived from the fieldwork that we wish to apply to different situations. The behavior rules characterizing the logics of agents are based upon the translation of the investigation results following an interpretation process similar to that of Gladwin (1989), as cited by Huigen *et al.* (2006). These empirical rules concern the very subject of the work. The rule elaboration step is a sort of confidence building vis-à-vis the field step: the reconstitution of the dynamic **functioning** of the overall system testified to the good understanding of this system.
- The third part consists in considering several working **hypotheses** built upon literature but "chosen" on the basis of field observations, which serve as a base and justification for the prospective scenarios. In the model, a cognitive and more elaborate process is developed to answer

to a real proposition of strategy: the choice of involvement in one of the development proposals (inorganic fertilizers & warrantage), based on the individuals' experience characteristics.

2.5 Spatialization & temporality

We had to choose between two spatialization procedures as described by Bousquet & Gautier (1999) and applied in Castella & Verburg (2007): A first one implements at the spatial cell level the phenomena that affect it, including the human-processing ones (agriculture, etc.). The main problem of such a procedure is that it needs an intermediate step of reinterpreting the human action from a spatial point of view, increasing the risk of important conceptual mistakes. As we focus on the population, we select a second orientation where human agents are the actors of the spatial process.

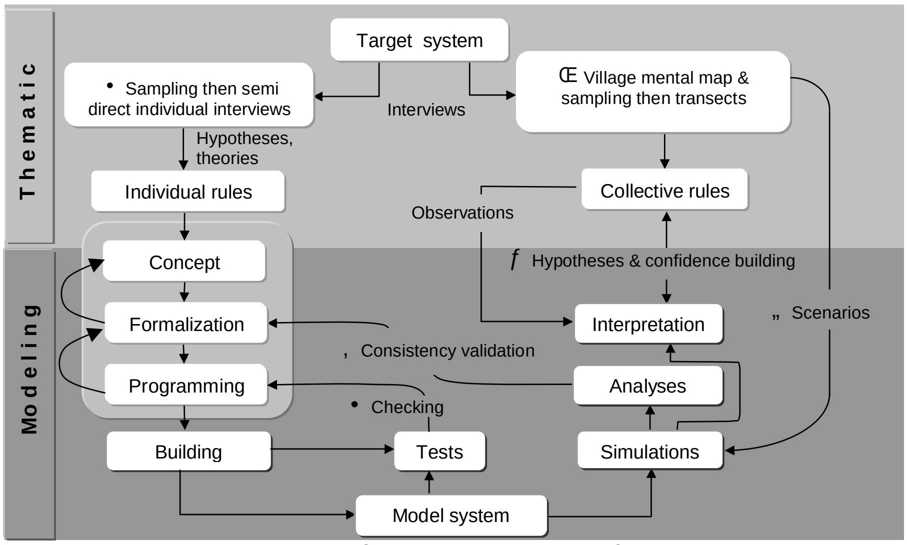
The model is therefore spatialized on the basis of a village and its territory, "the terroir". However, it is important to specify for the land tenure issue that the "terroir" is defined on the basis of usufruct and not of property. The land tenure problem in Sahelian West Africa is indeed extremely complex: there are a lot of different tenure statutes and their definitions are difficult to establish, particularly for villages in conflict (Le Bris *et al.*, 1991; Lavigne-Delville, 1998). It is simpler to focus on the resource-sharing issue within a single village. Actually, field exchanges between villagers of different villages are extremely common (Loireau-Delabre, 1998), which permits to bring back to a situation without land tenure conflict. We thus consider only the *de facto* property and not the *de jure* property.

Thus, in the ABMs' typology of Gilbert (2006 pp.149-152), we stand in the category of spatialized models. However, some processes of information exchange (marriages, food redistribution) rely on networks, whose hierarchies strongly condition the Agents' future.

3 Entities & architecture of SimSahel

3.1 The model building methodology

We have adapted the modeling methodology proposed by Drogoul *et al.*, (2000) and further used by Rouchier & Requier-Desjardins (1998). As shown in Figure 14, this work can be seen as a commuting between the perceived reality, which is intrinsically multidisciplinary, and the virtual world, where every concept borrowed from every discipline must be formalized.



Chronological & methodological steps: Œ & • on the field • ‚ ƒ „ during model development

Figure 14. Global methodology of model building, adapted from Drogoul *et al.*, (2000)

The individual relationships of the model are checked during the step • in Figure 14 to fit with the relationships between one individual and its social and agro-ecological environment as observed during field investigations. A first series of simulations are then carried out to calibrate and the model to check the consistency ‚ , i.e. the agreement between the model outputs and the collected data at the macro level. A particular attention has been given to threshold and time effects[118] and exceptions[119]. Because of data uncertainty, inconsistency or absence, we used relative values to define rule parameters rather than absolute ones to avoid artificial transition gaps. For instance, relative figures for both the health status of the livestock and the vegetation indices for the parcels are defined thanks to repeated simulations to calibrate the pasture effects as described by the literature. Therefore, such literature information cannot be used for the confidence building step ƒ : this corroboration stage is performed at the macro level through a comparison of simulated outputs related to absolute parameters about collective behavior with the ones described in the literature and/or observed through ZADA.

Finally, scenarios are implemented according to hypotheses on social transition processes that we have developed during field investigations and

[118] For example, the dependants without food effectively ask for millet to their ascendants

[119] For example, what explains that some villagers do not leave for migration?

that were already noticed by several scholars[120] „ (see chapter 3 to 6 for details on the scenarios).

3.2 Representation of the model

The use of the Unified Modeling Language (UML) as the "official" mode of representation of modeling procedures is becoming widespread. Numerous research documents use this language in their communications with other researchers. However, this use has not spread outside of the model makers' community. As several parts of this thesis have or have to be published in journals that are not only focused on modeling, we have voluntarily reduced this approach.

Besides, the SimSahel model was voluntarily conceived as a regrouping of numerous procedures, each of these procedures calling upon numerous elements that are not part of this thematic procedure. For instance, a merely agricultural and spatial procedure, as the expansion of cultivated fields of a family, is influenced by the manpower availability, the lineage and other social factors. It means that in terms of UML representation, we may have to show a lot of small sequential diagrams, each one very simple but with a legend as big as the diagram itself! Therefore, the majority of the procedures are represented in their simplest shape, i.e. mathematical functions with several parameters.

3.3 The model architecture

One single "Universe" entity is built as an "overall" entity managing all the functions that are external to the village (global climate, migration costs & gains, taxes, millet & livestock prices) as shown in Table 6.

The ZADA and the interviews have shown that socio-economic constraints are at least as important as environmental ones for all the villagers. The relative importance of various constraints depends on the villager category but also on the period in the year. We consider that the actual hierarchy of these constraints for each simulated villager is established according to this villager's possibilities of access to economic activities[121]. Therefore, the model should necessarily integrate the parameters that have appeared during

[120] For instance, the relation between inheritance system changes and land scarcity is mainly based on Raynaut *et al.* (1997), Luxereau & Roussel (1997) and Yamba (2004).

[121] For instance, the main constraint for a young bachelor should be the access to cash to get married and therefore, the access to migration as observed during field investigations

field investigations to condition the most the situation of each individual, i.e. family ranks, genders, lineages but also family organizations and inheritance systems that differentiate villagers. Meanwhile, the model should also include his/her management of the environmental constraints of the activity (distance, fertility, water, etc.).

Table 6. The Universe Class: the external world

Category	Variable	Value	Source	
Initialization	Individuals, livestock & parcels	50 villagers, 100 livestock & 3 to 7 parcels for each man	Calibration step	A
Site territory	Site soil distribution Access to shallow water distribution	See Table 7	Minet (2007) from SPOT5 images	B C
Rainfall	F_{site} $F_{drought}$	See Table 14	Adapted & calibrated from data from ICRISAT (Gérard, 2005) compared with the results from IRD-HAPEX (Le Barbé & Lebel, 1997; Lebel *et al.*, 1997)	D E
Millet price	Drought impact: I_{price} Millet price: Pmil (t)	See § 4.4.4	Calibration step Calibration step with prices from SIM Céréales (2002)	F G
Taxes		One millet bundle per capita	Own investigations, 2004-2005	H
Migration	Migration annual period Gain per week Travel costs Racket risks	See Table 21	Own investigations, 2004-2005	I J K L
	First age for migrating	16 years-old	Own investigations, 2004-2005	M

As established in § 2.3, **each elementary entity is a single individual element:** Therefore, we decided to "split" each villager Agent into a "producer" part, which manages economic activities according to its social characteristics, and a "social" part, which manages all the social–based asset accessibilities, as follows:

- The first one, called the Villager, is an Agent class that groups the functions of the simulated citizen that concerns its physiology and the production and economic actions it may realize. It is grossly the "producing" part of the simulated citizen.
- The second one is also an Agent class, the Social status, that groups all the functions of the simulated citizen that connect it with the rest of the community and thereby defines its position in the social hierarchy and its social rights to production assets. It is deliberately defined as a “weight” equivalent to the Villager and central to decision-making, as it is the interface for the access to production activities, related gains and social exchanges.

The whole model is therefore organized around this Villager/ Social status binome, with a social environment and a biophysical one, all included into the "terroir" universe. The model is established with an equivalent complexity everywhere, in order to avoid an over parameterization of one aspect compared to another.

Two other elementary entities are also built:

- Parcel is an entity type that belongs to the Cellular automaton category. Each parcel is a pixel in the model and corresponds to an elementary piece of land in the "terroir".
- Livestock is an entity type that belongs to the Object category. Each livestock head is one object, i.e. an avatar of the entity type Livestock.

For facilitation purposes, we also built several composite entity types that groups several avatars of one entity type:

- Because the family is still an important level where access to assets are defined, we created a passive Family entity type grouping the Social status and dedicated to all the social family-based relationships. The social status is subdivided into subcategories to implement the polymorphism of the villagers' behaviors, i.e. Child (of 0 to 16 years-old), adult Man and adult Woman. Social status and Families are thereby the social part of the model.
- In order to facilitate the modeling of the spatial aspect of the rainfall, we build a "group" of Parcels dedicated to the climate, thereafter called the Climate Block. The climate block and the land plot classes are thereby the classes/entities that constitute the biophysical part of the model, in connection with the "Villager".

F**or every type of entity, the Attributes permit to describe each of their characteristics.** Here appears the importance of the notion of polymorphism: a function, an action to be carried out by different villager types can mean for each of these types **different** actions to be carried out. For instance, exchanging food in a family means that children have to ask for food to the family's adults and that adults have to look after what food children have and to act accordingly. One time step corresponds to a week as field investigations suggest that it is the elementary unit for agriculture & gardening. Figure 15 presents a UML representation of the class diagram of the model. We indicate in the following parts of the text the simulated entities by capital letters.

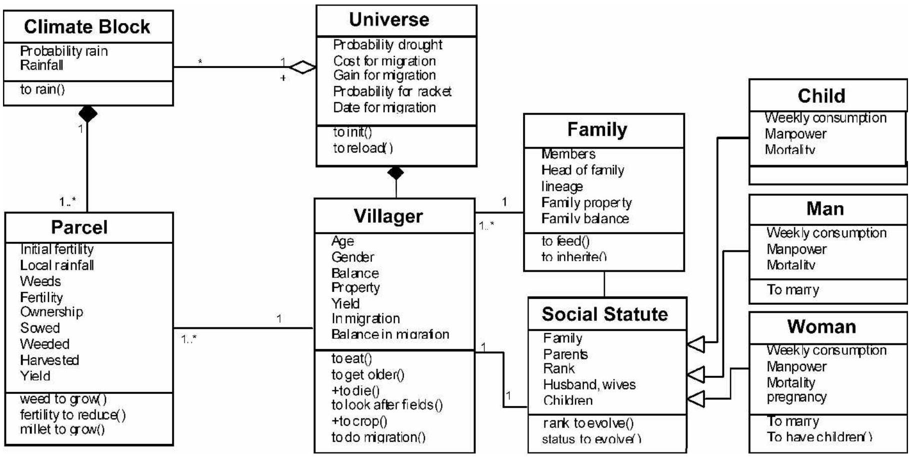


Figure 15. Unified Modeling Language architecture of the SimSahel model

The following subsections of §3 describe the different entity types:

3.4 The Spatial entities

This spatialization is made in a raster mode on a 50*50 or a 100*100 cell matrix of dynamic cellular automata representing a map of a territory corresponding to the three studied sites, and on which agents and objects can move as indicated in Figure 16.

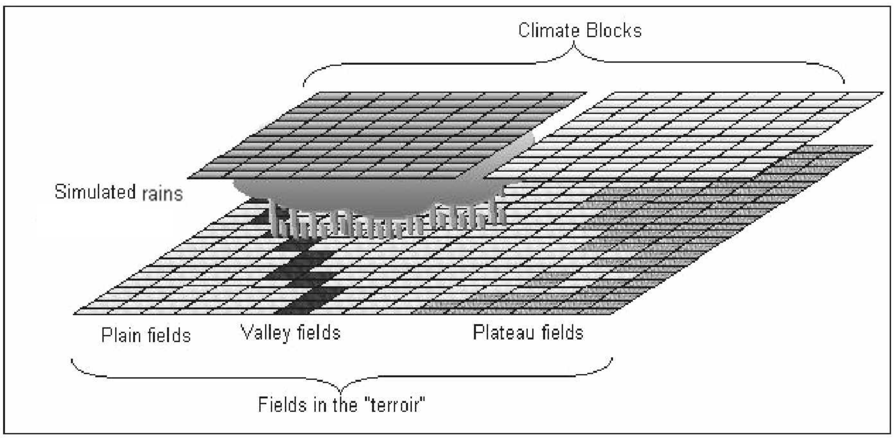


Figure 16. The spatial module of SimSahel

Each implemented map respects the proportion of the different geomorphologic units as indicated in Table 7:

Table 7. Spatial distribution and land type fertility value of geomorphologic units in the SimSahel model for the three sites

%	Gabi	Fakara	Zermou	Initial Agronomic potential *	Access to shallow water
Valley (good)	17,93	3,92	0,52	2	Yes
Plain (average)	60,01	79,31	69,77	1	No
Forested hills (poor)	21,79	0,00	0,00	0,5	No
Stony hills or plateaus (unsuitable)	0,00	16,49	29,43	0	No
Village	0,28	0,28	0,28	/	No

*A simplification from the soils qualitative description of Glättli (2005)

The related maps are shown in Figure 17. A set of small maps was initially created for use in chapters 4 & 5 on family organizations & project actions (50*50 maps to the right of Figure 17), where each pixel corresponds to 1 hectare. We have used larger maps (100*100 maps to the left of Figure 17) for chapter 6 thanks to new SPOT 5 image acquisitions that were analyzed by Minet (2007), where each pixel corresponds to 1/4 hectare. Geomorphologic unit proportions are equal on both maps. Some corrective factors have therefore been included in space-related processes of the model to avoid scale distortions: therefore, a Parcel corresponding to one pixel means one hectare for the small maps and ¼ ha for the larger ones[122].

[122] For instance, because the larger map is four times bigger, parcel yields are divided by four.

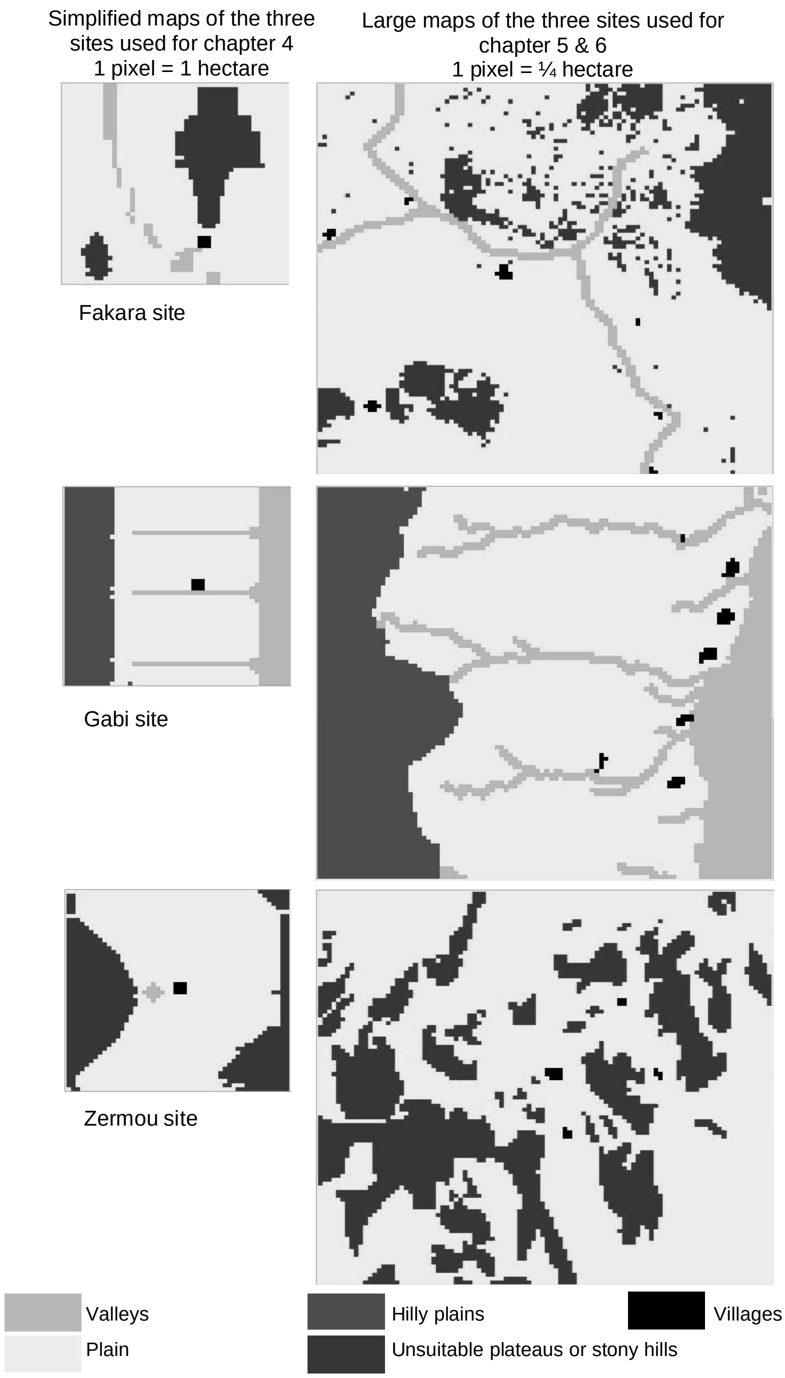


Figure 17. Schematic geomorphologic maps of the three sites

3.4.1 The Parcels

They are spatial elementary cells, i.e. pixels. They may be used as grazing lands. Once appropriated by a villager Agent, they can be used for farming/gardening purposes. They are subdivided in subclasses: village, shallow, plain, plateau and hills, each subclass corresponding to a certain range of production activities:

- Village: no production possible.
- Shallow: cropping if appropriated, gardening if borrowed and grazing if not cropped or gardened.
- Plain: cropping if appropriated and grazing if not cropped.
- Plateau and hills: grazing.
- They define the agricultural and pastoral potentialities of the territory (fertility, vegetation, access to shallow water) and their capacities to be appropriated. The biophysical processes linked to cropping and grazing impacts are thereby defined at each cell level. Each cell is considered as spatially independent from its neighbors for all fertility-related processes. Biophysical processes are described by several parameters, as shown in Table 8.

Table 8. A Spatial elementary Class: The Parcel. (Part 1)

Category	Variable	Value	Source	
Agronomic potential	Agronomic potential Fp	See Table 7 & § 4.3.2.	Simplification of the soils' qualitative description of Glättli (2005).	A
Effects on fertility	Rain effect	See Table 15	Calibration step	B
	Sowing / weeding effect			C
	Harvesting effect			D
	Grass growth effect		Adapted from Lassina (1992), Ahonon (1994) & Delabre (1998)	E
	Manure effect	See Table 15 & 4.3.2.	Adapted for discrete simulations from Pierret (1999), and Gérard (2005), Akponikpé *et al.* (2007) & Gérard *et al.* (2007)	G
	Shrub & tree growth effect		Adapted from d'Herbès *et al.* (1997), Montagne & Housseini (1998) & Wesel *et al.* (2000):	F
Fertility effect on millet yield	Corralled manure effect & resilience	See Table 16	Adapted from Gérard (2005), Akponikpé *et al.* (2007), Gérard *et al.* (2007)	H
	Transported manure effect & resilience			I
	Inorganic fertilizers (DAP+Urea mix) effect & resilience			J
	Parcel selection for transported manure	See § 4.3.3	Own investigations	K

Table 8. A Spatial elementary Class: The Parcel. (Part 2)

Category	Variable	Value	Source	
Millet cropping stages	Sowing parcel selection	Related to the fertility & distance to the village (see § 4.5.1)	Loireau-Delabre (1998).	L
	Weeding parcel selection	Related to the weeding index (see § 4.5.1.)	Own investigations, 2004-2005 + calibration step	M
	Harvesting parcel selection	Related to potential yield (see § 4.5.1.)		N
Millet production	Cycle index	See § 4.5.1. & Table 16	Millet cycle stages simplified and adapted from "le Manuel de l'Agronome" (CIRAD, 1991)	O
	Production index	See § 4.5.1. & Table 16	Harvesting values & variability from Gérard (2005)	P
Vegetation	Wood initial value	Related to agronomic potential at initialization: Hx (0) = 100 * Fp	Calibration step	Q
	Wood growth	Related to rain & fertility (see § 4.3.2.)		R
	Herbaceous growth			S
	Herbaceous initial value	Related to agronomic potential at initialization: Lx (0) = 100 * (Fp +1)		T
Weed effect on millet yield	Grass-related weed growth	See § 4.5.1	Adapted from Lassina (1992); Sangaré *et al.* (2001); Schlect *et al.* (2006).	U
	Sowing effects	See Table 17		V
	Weeding effects			W
	Harvesting effects			X
Gardening	Cycle index of vegetables	See 4.5.2	Adapted & simplified from "le Manuel de l'Agronome" (CIRAD, 1991)	Y
	Potential volume of vegetable yield			Z

Among these, two parameters should be mentioned (the other parameters are described in the paragraphs describing the related phenomena as we simulated them): the Agronomic Potential and the Fertility:

- The Agronomic Potential is a relative index (see Table 7) specific to every simulated pedomorphological unit (valley, plain & hills for Gabi; valley, plain & plateau for the Fakara; valley, plain & stony hills for Zermou; stony hills and plateaus are considered equivalent).
- The Fertility: The Fertility index is a relative value that reflects the overall fertility of a pixel, to be compared and connected to relative ratios and indices from livestock, rain and vegetation. The Fertility value of each pixel/parcel is initially equal to its Agronomic Potential. It then varies according to the vegetation growth, defined by the local pixel rainfall and the initial fertility, the cropping impact if the land is owned and cultivated (sowing and preparing the land, weeding/not weeding, harvesting) and the manure left by livestock or by villagers.

3.4.2 The Climate Blocks

They regroup 5* 5 parcels/pixels and there is no spatial dependence between them. Functions randomized for each of the climate blocks permit to simulate the spatial variability of rains as characterized by the data from local rain gauge networks established by ICRISAT and ILRI (Gérard, 2005) and compared with the results from the IRD-HAPEX Sahel experiment (Le Barbé & Lebel, 1997; Lebel *et al.,* 1997). Each block follows functions of rain occurrence and volume that are described below in the rainfall module and shown in Table 9. This option of fixed blocks means that groups of parcels under the same climate block have the same rainfall all along the simulation. In this way, the spatial relationship between parcels is grossly simulated.

Table 9. A spatial aggregated Class: The Climate block

Category	Variable	Value	Source	
Rainfall	Pr1: Weekly rain probability (in %)	See Table	Calibration step with values	A
	Pr2: Weekly mm of rain per pixel r (t)	14	from Gérard *et al.* (2007)	B

3.5 The active & communicative entities: Agents & Objects

They are presented in Figure 18:

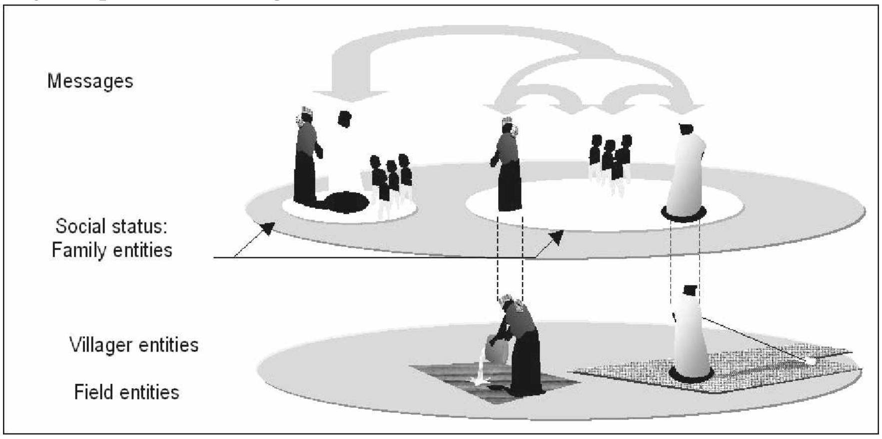


Figure 18. Relationships between Active entities in SimSahel

3.5.1 The Livestock Objects

Three subcategories are considered, corresponding to the three local species (Caprines, Bovines & Ovines). All the functions describing them (consumption, search for pasture, reproduction, death, ageing, etc.) are merely reactive as shown in Table 10.

Every head of livestock is the property of only one Villager that can sell it, give it, buy it, sacrifice it, eat it and send it for transhumance… It is "registered" in the herd of this Villager and of this Villager's Family.

Table 10. An active Object Class: The Livestock

Category	Variable	Value	Source	
Health status	Consumption	See § 4.5.4.	Calibration step; relative values to link with grass/shrub levels	A
	Transhumance period	See § 4.5.4.	(Bernus 1994; Barbier & Hazell 2000; Hammel, 2000; Lycklama 2000; Boutrais, 2007)	B
	Risk of mortality MLy (t)	See § 4.5.4.	Calibration step	C
	The average mortality rate ML	See § 4.5.4.	(Lesnoff, 2005)	D
Reproduction	Age of reproduction	1 to 10 years (See § 4.5.4.)		E
	Gestation duration, with a first weaning period	52 weeks for cattle, 30 for others (See § 4.5.4.)	(Lesnoff, 2005)	F
	Milking duration			G
Sales	Livestock prices	See Table 22	SIM Céréales, (2002); Own investigations, 2004-2005	H

3.5.2 The Villager Agents

These are the individuals of the village whatever their features, which are born, live and die; they are the drivers of all actions. The Villager Agent represents the economic and the production aspects of each inhabitant of the village. No ultimate goal is defined, as all Agents are reactive and not cognitive, with no optimization. For instance, no cognitive strategic aspects are developed with respect to marriage or inheritance procedures. Individual Agents are defined as equivalent, which means that they have the same attributes and only the values of these attributes are variable, defining individually every Agent (Verhagen & Smit 2003); Sources and descriptions of these parameters are indicated in Table 11.

- A gender, randomly defined at birth or at model initialization for the initial population.
- An age, evolving with weeks. A probability of mortality is also defined, granting an average life expectancy of 48.5 years for both genders as reported for the country by the UNDP annual report (UNDP, 2005).
- Every villager has an indicator describing his food level. If this indication becomes negative, the Agent dies of hunger and disappears. We have made the choice of a regular weekly consumption for all the Agents. As a consequence, an Agent that does not produce food (all children, the majority of adults) must die of hunger if it does not stay in a food redistribution system.
- A land property if this right is effective (see Social status).
- A livestock herd if this right is effective (see Social status).
- A garden if this right is effective (see Social status).

Table 11. An active Agent Class: The Villager

Category	Variable	Value	Source	
Health status	Consumption	1 for adults, Age/20 for children (See § 4.4.1)	Own investigations, 2004-2005[123]; Calibration step; relative values to link with millet yield levels	A
	Risk of mortality Mi (t)	See § 4.4.1	Calibration step	B
	The average mortality rate MH		FAO (2006)	C
Manpower	Manpower	1 for adults, Age/20 for children (See § 4.4.1)	Own investigations, 2004-2005[124]; Calibration step;	D
Reproduction	Age of reproduction	16 to 40 years (See 3.4.2.3)	(CARE, 2002; Guenguant *et al.*, 2002)	E
	Probability of pregnancy	1.02838% per week (See § 4.4.2)	(UNDP, 2005)	F
	Duration of pregnancy & weaning	52 weeks (See § 4.4.2)	Own investigations, 2004-2005	G
Food redistribution	Hierarchy criterion for ranking Family members	The rank (see social status)	Own investigations, 2004-2005	H

3.6 The passive entities as intermediate "work tools"

3.6.1 The Social status of individuals

To every simulated Villager corresponds one and only one Social status: this class manages exchanges (gifts, sacrifices, redistributions), social functions (marriages, creations & changes of families), and the social standing of every villager. This class permits several social attributes of a villager to evolve over time as shown in Table 12:

Table 12. A passive Elementary Agent Class: The social status

Category	Variable	Value	Source	
Social discrimination criteria	Rank	See § 4.1.4.	Own investigations, 2004-2005 & literature	A
	Reputation			B
Marriage	Marriage criteria	The reputation	Own investigations, 2004-2005; Olivier de Sardan (2003c); Calibration step	C
	The average dowry P_{dowry}	The price of two oxen (see § 4.4.2.)		D
	The effect of lineage D_{AC}	See § 4.4.2.		E
	Ceremony cost	The price of one sheep (See § 4.4.2.)		F
Births	Ceremony costs	Sheep for first male, goat for others	Own investigations, 2004-2005	G

[123] Investigations show that, even if men eat far more food during meals, women can compensate this lack a little by eating during millet cooking.

[124] One may easily observe that women have at least an equivalent FLU to men, working far longer in one day than men.

Each of the three Social Status subclasses should be considered from a social point of view. Thus, some functions explicitly use the crossed information child * gender to determine the manpower of a girl or a boy).

The Rank

Rank is updated at the beginning of each time step to take into account marriages, deaths and births but also majorities (a Villager passes his/her 16^{th} birthday as it is the age when most youngsters get the right to a portion of a parcel, or to go on migration. By default, it is equal to 1, which is the highest possible rank, defining the status of Family head. The head of family is thereby inevitably "married", even if he/she is a widow/widower and is a family founder or first heir. The following rules are applied to define the rank of adult members. The rules are based on a translation and a simplification of field observations:

- For Men, the rank increases by one point if the father is living and by as many points as he has living elder brothers.
- Women, once they get married, migrate in the Family of their husbands. Married Women have their husband's rank (dead or not), to which one adds one point.
- For unmarried Women, namely unmarried sisters in a Family, the rank is equal to the rank of the youngest adult male of the brotherhood, to which one adds one point.
- Finally for children, rank is linked to age:

$$(R_i = 25 - [Age / (52 * 100)]) \quad \text{(Age in weeks)} \qquad (1)$$

The rank defines several rights:

- The status of family head gives the right under certain conditions to mobilize the family manpower and to manage the redistribution of income of the family members (pearl millet, gardening food & income, migration income). This status gives right to land property and management thanks to the authority on the family manpower.
- Status of ancestry and progeny, the progeny defines the status of Dependent for each adult, i.e. all individuals of the same Family, linked by a tie (marriage, offspring) and of lower rank. The ancestry defines thereby the family members to whom a Dependant may ask for food.
- A right to livestock property, effective or not. Livestock does not belong only to family heads as for land. Children can receive one head from their ascendants, which they cannot manage (sacrifice, sale) until after their majority. Women can own, inherit, sell and sacrifice small ruminants.
- A right to borrow a parcel to make a garden, within the family property or that of another. Only Men can garden in the Hausa sites (Gabi and Zermou) and only Women can garden in the Zarma Fakara site. Apart from this site-specific gender aspect, only the person that has the

highest rank in the family can borrow and manage a garden by mobilizing the feminine manpower that is Dependent on her/him: girls constitute the main manpower for watering the vegetables.

The reputation

We built the reputation function base on our investigations as an addition of the different elements that contribute to the stature of a villager within the village arena. The reputation evolves along the intra-family rank, the family lineage (which remains fixed except through marriage for women) as well as the personal and family wealth. In particular, it varies according to the capacity of an individual to fulfill his/her domestic and social duties. It affects the selection of bridegrooms and the choice to get involved in a development project for one of the scenarios. For a Social status i (i.e. the status of an equivalent villager) at time step t, the reputation follows the function R_i (t) as follows: $R_i (t) = S_i (t) + [EM_i (t) + D_i (t) + DP_i (t)] / 500$ (2)

With:

S_i (t): the reputation from the social and economic means of i:

$S_i (t) = [B_i (t) + B_{fi} (t) + (A_i (t) * 5) + C_i (t)] * [1 + Wives_i (t) * 2] * L_{fi}$ (3)

With: fi: all the members of the family of i;

$B_i (t) = (\Sigma Bov (i, t) + \Sigma Oth (i, t) / 2) / 4$, the livestock owned by i (4)

$B_{fi} (t) = (\Sigma Bov (fi, t) + \Sigma Oth (fi, t) / 2) / 8$, the livestock owned by the family of i (5)

With: ΣBov (x, t): the number of cattle owned by x;

ΣOth (x, t): the number of caprines & ovines owned by x

A_i (t): the age of i; $Wives_i$ (t): the number of spouses of i;

L_{fi}: the family lineage of i; C_i (t): the number of children of i;

EM_i (t): the gain of reputation for economic characteristics:

$EM_i (t) = [PMh_i (t) + G_i (t) + Vg_i (t)] / 500$ (6)

With: PMh_i (t): the volume of pearl millet harvested at t (in FCFA);

G_i (t): the gain from seasonal migration at t (in FCFA);

Vg_i (t): the gain from vegetable gardening at t (in FCFA);

D_i (t): the gain of reputation by fulfilling social duties:

$D_i (t) = AS_i (t)*2 - AV_i (t)*5 + GF_i (t)*2 + GR_i (t) - DF_i (t)*2 - DR_i (t)$ (7)

With: AS_i (t): the value of sacrificed animals during ceremonies in FCFA);

AV_i (t): the value of the animals sold for subsistence (in FCFA);

GF_i (t): the gifts given to beggars (in FCFA);

GR_i (t): the gifts received as a beggar (in FCFA);

DF_i (t): the gifts not granted to beggars (in FCFA);

DR_i (t): the gifts not granted as a beggar (in FCFA);

DP_i (t): the gain of reputation for the implication in development projects:

$P_i (t) = Frt_i (t) + War_i (t)$ (8)

With: Frt_i (t): the number of 80kg bags of inorganic fertilizers bought;

War_i t): the number of 80kg millet bags under "warrantage".

The other attributes

- Its weekly consumption: equivalent to an indicator i, equal to 1 for an adult (Man or Woman) and variable for a Child: i= 0 for Age $\in$ [0-1[; i= Age / 20 for Age $\in$ [1-16[;
- The manpower equivalent, symbolized by an indicator MO, equal to 1 for an adult (Man and Woman) and variable for a Child: MO = 0 for Age $\in$ [0-6[; MO= Age / 20 for Age $\in$ [6-16[;
- The matrimonial status: two types of information are registered, to be married and the number of spouses for men. This permits to differentiate the masculine polygamy, but also to keep the married status in case of widowhood.
- The fact of being pregnant for a woman: only below a certain age (40 years old) and only if she is married[125]. This status persists one year and not 9 months because we wanted to take into account the severance. To be pregnant does not raise the person's consumption, as we have not observed an increase in the food given to pregnant women.

3.6.2 The Families

We "naturally" generated the network of relations by constructing functions of birth, marriage and death that generate the complexity of family ties, rather than creating an average village populated by entities that are all similar. Therefore, every Villager is linked to a family via his/her social equivalent, i.e. the Social status. Villagers enter a family when they create one (at initialization, after a first marriage for one of the scenarios), when they are born or when they get married (women moving from a family to another by marriage). This regrouping serves to manage common individual rules in a more convenient manner. Families have the following attributes as listed in Table 13:

Table 13. A passive Aggregated Class: The Family

Category	Variable	Value	Source	
Characteristics	Lineage	From 1 to 4	Calibration based on investigation results (2004-2005) & Olivier de Sardan (2003c)	A
	Family organization	See Table 18	Own investigations, 2004-2005 &	B
	Family inheritance right	See § 4.4.2.	literature	C
	AntiClan Tension	See § 4.7.1	Own investigations, 2004-2005 for the	D
	Land tension	See § 4.7.2	concept & calibration step for the parameterization	E
Property	Property access	See Table 17	Calibration step	F

[125] We have adopted a simplification by not considering the possibility of having children outside of marriage.

- The lineage is linked to families and is assigned at initialization to the first Men founding a family. It can be transmitted to their progeny and their wives at marriage. Lineage is numbered from 1 to 4, with the highest having a value of 1, corresponding to the first family founder in the village, emphasizing thereby the pre-eminence of this role of foundation. Lineages intervene in the choice of heirs, in the right to clear new lands and in a villager's reputation;
- The type of family organization: it defines one of the main questions of this research work. Two modes are considered: unitary and non-cooperative. Evolutions from one type of family organization to another has been considered on the basis of a domestic tension indicator (AntiClan tension factor) that is related to the concentration of gains between the hands of Heads of family;
- The type of inheritance right: it defines a second important question of this research work. Two modes of inheritance are also considered: Muslim and customary. The evolution between these two factors has been considered on the basis of a domestic tension indicator (Tenure tension factor) that is related to the concentration of goods in the hands of a single heir.
- Family Property and Family Livestock are the sum of livestock and lands owned by all the members of a family. The Family Property is consequently confounded with the property of the family head (Apart from very particular exceptions: remarriage with a widow owning lands and with no relatives!)

3.6.3 The messages exchanged between Villagers

These messages intervene in the social exchanges that require the transmission of information between Agents and that take place along a sequence. Message exchanges occur only for marriage purposes: the search for a future husband or wife takes place before the actual marriage itself.

4 Building the relationships between SimSahel entities

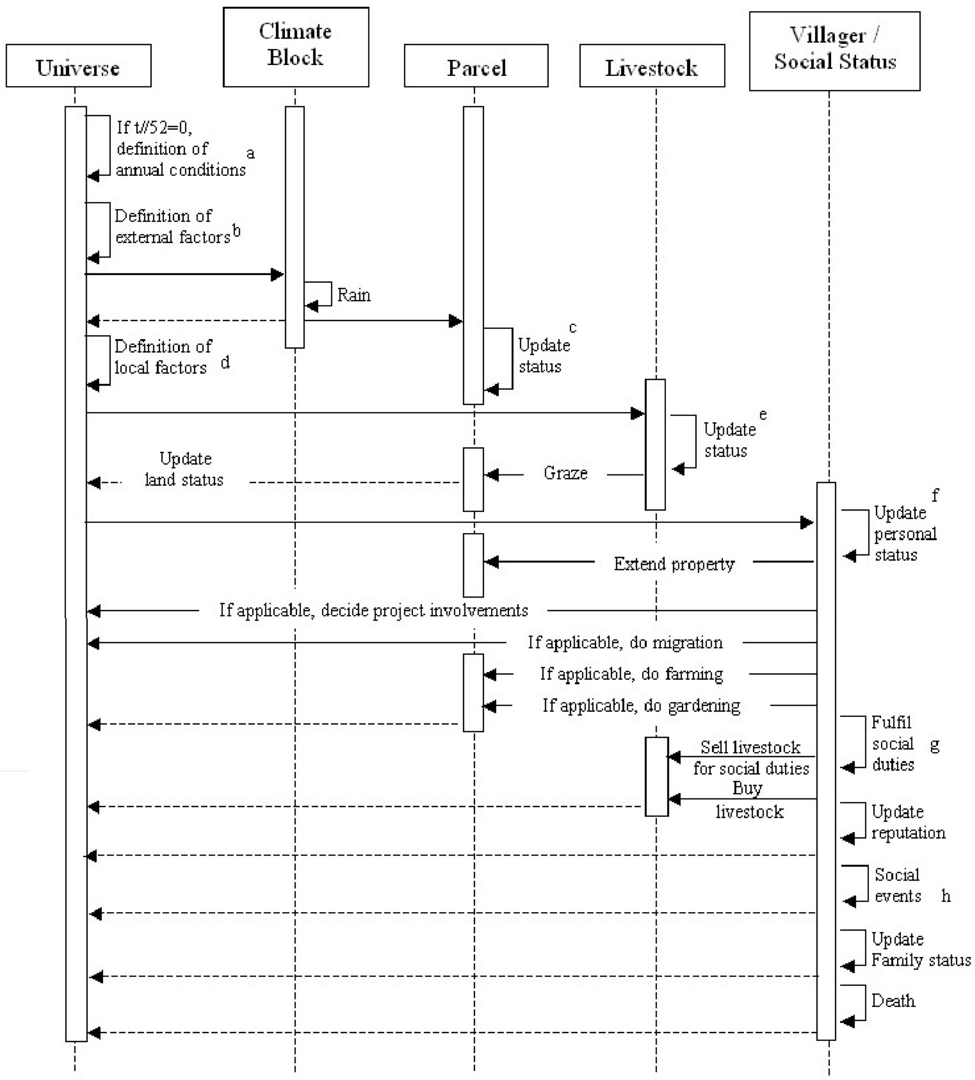
4.1 Initialization: founding a village in SimSahel

At the model initialization, 50 villagers and 100 livestock heads (one third of every species) are created in the virtual spatialized environment. The Villager Agents are age-defined (between 1 & 55 years old) and gender-defined (50% males, 50% females on average). Every adult Man receives a randomly defined lineage between 1 (the best) and 4 (the lowest), as a measure of the power of each big kinship group in the village. The very first male villager is the exception: considered as the village founder, the Agent is always attributed a lineage value of 1. It may happen that there are more (or less) male than female Agents at the beginning of a simulation, or lineages may begin with different sizes. Every adult Man takes a piece of arable land as his new property made of several parcels of fixed size (1 parcel = 1map cell of the bidimensional grid). The number of these initial parcels varies according to the lineage value between 3 and 7 parcels. Every adult Male Agent can then get married and become head of a new family.

4.2 The sequential schedule of the model

Figure 19 presents the diagram of the global sequence of the model. Two guidelines rule the schedule of actions in the model:

- In the model programming, the order on which the functions are listed corresponds to the order they are executed in the model. Therefore, the more a function needs parameters, the more this function should be placed at the end of the sequence. The sequence starts by the functions that are independent from the others, as age for example.
- Several actions and calculations need the related parameters to be previously updated because of particular events that have affected the Agent. For instance, the family updating should be placed after the function of birth of new babies, even if this last function is more complicated.



a Date of Tabaski; drought factor (t//52=0: beginning of the year)
b Millet & Ovine prices;
c Rainfall; rain cycle; crop cycle; crop production level; fertilizers, manure & transported manure levels; fertility level; property; shrub & grass levels; weeds level;
d Villagers, livestock, families, grazing areas, arable & free areas
e Ownership; age; reproduction; death; transhumance;
f Wealth; age; family members & rank; Other villagers;
g Tabaski; Taxes; births; food redistribution;
h Marriages; births;

Figure 19. The sequence diagram of one time step of the SimSahel model

4.3 The spatial module of SimSahel

We describe here the non-human processes that affect the parcel cells. The set of factors are interconnected, apart from rain. The Fertility index of a parcel is linked to rain, manure and the vegetation that grows there. Vegetation indices are themselves affected by the rain, the Fertility index, livestock feces and cropping stage impacts.

4.3.1 Rainfall

Probabilities and weekly rainfall values are determined from the climatic averages of the rain gauge network established in the Fakara site by the research & development consortium at the three sites (Gérard *et al.*, 2007). We separated the average rainfall cycle into different stages according to their levels of rain. We then calibrated the model for the Fakara site in order to make fit the means and the standard errors of each implemented stage with the observed data, but also the modeled yearly rainfall average and standard error with the observed data. The rain modules of the two other sites were also calibrated in a similar way. As the rainfall cycle for the three sites is monomodal, the year is first subdivided into one absolutely dry season from the 45th week of every year (end of October) to the 21st week of the next year (end of May) alternating with one rainy season from May to October (Le Barbé & Lebel, 1997). During this rainy season, the probability of rainfall occurrence and the rain volume rise right up to August then decrease up to October.

Two steps are considered: following Lebel *et al.* (1997) who observed that most of the inter-annual rainfall variability is due to the variation in the number of rainfall events, rather than to variations in rainfall intensities or in the mean rainfall per event, we first establish a rain event probability that is affected by an annual drought factor $F_{drought}$. A factor F_{site} discriminates the three sites. Both factors and rain values are shown in Table 14:

Table 14. Implementing the rainfall module of the SimSahel model (Le Barbé & Lebel, 1997; Lebel *et al.*, 1997)

	Week	0__21	22_29	30_33	34_37	38_41	42_44	45__52
Weekly probability of rain (in %)		0	25	75			25	0
Weekly mm equivalent of rain per pixel r (t)		0	20	40	65	40	20	0

Sites	Range of annual site-specific rain event probability factor $F_{drought}$	Annual site-specific rainfall level corrective factor F_{site}
Gabi	[0.7; 1.5]	1.4
Fakara	[0.5; 1.4]	1
Zermou	[0.2; 1.5]	0.7

At every time step, a random value between 0 and 100 is attributed to each Climate-Block to be compared with the product of the weekly probability of rain apparition (in %) depending on the stage and a site-specific corrective factor $F_{drought}$, which is built to simulate the probability of an annual drought. If the random value is inferior to the product, it rains on the Climate-Block. The value of $F_{drought}$ is randomly selected at the beginning of each year within a site-specific range of values (Table 14). It is applicable to the entire site territory and modulates the probability of occurrence of a rainfall event for the year to come. The higher the value of $F_{drought}$ and/or the higher the weekly probability of rains, the higher are the chances to have rain on this Climate-Block.

The model therefore reproduces the seasonal rainfall trend and the intra-annual rain variability that is specific to each site and thereby also the variability in the date of onset of the rainy season. The model also reproduces the gradient of variability between sites: the rain occurrence in the Zermou site is more hazardous than in the Fakara site, which itself is more hazardous than in Gabi. By defining the rainfall occurrence at the Climate-block level, we also replicate the spatial variability trend between site: the variability between Climate-Blocks is higher in Zermou than in the Fakara, which is also higher than in Gabi.

Once there is a rain event in a weekly time step, the rainfall level is established as follows: a weekly amount of rain (Table 14) is multiplied by a corrective factor F_{site}. Therefore, the higher this value, the higher the annual rainfall for all the Climate-Block where rainfall occurs all along the year.

4.3.2 Vegetation & fertility

Every cell is initially not appropriated and therefore is not cleared. All the cells are initially covered with vegetation, i.e. <u>woods</u> (shrubs & trees) and <u>grass.</u> The vegetation biomass is more or less important according to the agronomic potential Fp of the cell. As long as a parcel x is not cleared, its vegetation evolves thereafter according to a function Lx (t) for the woody vegetation and Hx (t) for the herbaceous vegetation:

At t=0, for cell x: $Lx(0) = 100 * (Fp + 1)$; $Hx(0) = 100 * Fp$;

Thus, a parcel of the plain has initially a value of 200 indices of woody vegetation & 100 indices of herbaceous vegetation. These indices are defined as relative values to be compared with relative values of livestock consumption.

The growth of both vegetations during a time step depends on the rain occurrence. For one time step with rain:

$$Lx(t) = Lx(t-1) + (0.0001 * Rx(t) * Fx(t-1)) \quad (9)$$

$$Hx(t) = Hx(t-1) + (0.01 * Rx(t) * Fx(t-1)) \quad (10)$$

For one time step without rain:

$$Lx\ (t) = Lx\ (t-1) - [0.001 / (1 + Fx\ (t-1))] \qquad (11)$$

$$Hx\ (t) = Hx\ (t-1) - [0.01 / (1 + Fx\ (t-1))] \qquad (12)$$

With: Rx (t): the volume of rain on a cell x during time step t; Fx (t-1): fertility at t-1.

The parcels' fertility is defined at the beginning of a simulation as equivalent to their agronomic potential: Fx (0) = Fp (Table 7), considered for each pedomorphological unit as equivalent for the three sites. This fertility is affected by the cropping cycle, the type of production to harvest [126], but also by the effect of weeds. Three procedures of fertility restoration are considered. Related figures and sources are indicated in Table 15:

Table 15. Implementing the fertility Fx module of the SimSahel model

Fertility		
Initial fertility factor Fp	Valley Fp = 2; plain Fp =1	
Rain	Rainy season (after the first rain occurring in the year) Fx (t+1) = Fx (t) * (1+ r (t)/(mean rainfall*10) (Mean rainfall depending on the site, see Table 14)	
Sowing or weeding	Equ. 18	
Harvesting	Equ. 19	
Weeds and grass growth (adapted from Lassina (1992), Ahonon (1994) & Delabre (1998)	Weeds value (t+1)/ weeds value (t)>1 If True: Fx (t+1) = Fx (t)-(weed value (t+1)/ weed value (t)-1) If False: Fx (t+1) = Fx (t)	
Shrubs growth (adapted from d'Herbès *et al.* (1997), Montagne & Housseini (1998) & Wesel *et al.* (2000):	Shrubs value (t+1)/ shrubs value (t)>1 If True: Fx (t+1) = Fx (t)-(shrub value (t+1)/ shrub value (t)-1) If False: Fx (t+1) = Fx (t)	
Manure (adapted for discrete simulations from Pierret (1999)	Equ. 17	
Manuring		
Animals manuring and grazing impact	Surface allowed for grazing and browsing S	
Calves and milking cows	Both seasons: S= unused plain & valley	
Other "dry" cattle	Dry season: transhumance	Rain season: S = unused plain & valley
Goats	Both seasons: S= Plateau, plain distant from at least two pixels from cultivated fields or garden	
Sheep	Both seasons: S= Plateau, plain distant from at least two pixels from cultivated fields or garden Both seasons: S= Valley & village only	

The natural regeneration by the growth of shrubs and grass is considered as a reinforcement of organic matter and nutrients in the soil, which allows to take into account a limited restoration of the fertility during the fallow even

[126] Millet in the case of the masculine "cereal culture", vegetables in the case of the dry season "gardening" activity.

if these may be short, i.e. a one year left alone parcel because of repeated sowing failures during one cropping season[127].

The soil structure is also bettered thanks to growing grass and shrub roots (Delabre, 1993). However, because these fallows are short, their impacts are not important (Banoin & Achard, 1999). We did not consider the possible spatial transfer of nutrients by wind or water erosion, meaning that each parcel is spatially independent on the fertility level. Therefore, we implemented this natural regeneration by simulating for every cell x a global indicator of fertility F. This indicator, initially equal to the initial agronomic potential Fp at t=0, grows only during the time steps when rain has fallen on this cell. This function is based on a simplification of growth indicators from d'Herbès *et al.* (1997) & Wesel *et al.* (2000):

$$Fx(t+1) = Fx(t) * \left[\frac{(1 + Rx(t+1))}{(Rm * 10)}\right] - \left[\frac{Hx(t)}{Hx(t+1)} - 1\right] - \left[\frac{Lx(t)}{Lx(t+1)} - 1\right] \quad (13)$$

This fertility regeneration influences the growth of the ligneous and the herbaceous vegetation on the parcel:

$$Hx(t+1) = Hx(t) + [(Rx(t+1) * Fx(t) / 10] \quad (14)$$

$$Lx(t+1) = Lx(t) + [(Rx(t+1) * Fx(t) / 1000] \quad (15)$$

With: Fx (t): fertility of x at t; Rx (t): the rainfall volume on the cell x at t; Hx (t): the grass indicator; Lx (t): the shrubs indicator; Rm: the average annual rainfall on the site (mm);

4.3.3 Pasture, manure & fertility

The fields are grazed by the different species along a calendar as described in Table 15. The manure from the herd that does not go on transhumance is then defined for each animal species for each pixel. Livestock grazing practices are presented in § 4.5.4.
Manure, fertility and vegetation growth are influencing one another. We first analyze the impact of their feces on parcels. This impact is split in two parts that are made independent for simplification:

The direct impact of the manure on pearl millet production

This part is used for the millet production. The related absolute parameters are known (Gérard, 2005). Except if their food intake (represented by an indicator called "paunch") reaches less than half of its maximum value,

[127] Actually, the fallows effects are complex and concern several factors of fertility: Potassium is brought by wind, organic matter may come from growing grasses and livestock while nitrogen may come from livestock urea as well but also from the atmosphere via the legumes (Delabre, 1998; de Rouw, 1998).

which may happen during dry seasons, animals defecate every week. Only the quantity of feces is considered, without distinction of quality between species. The amount of feces per time step is worth 1 for cattle against 0.2 for the small ruminants (goats & sheep).

To estimate if a parcel x is well manured (Sangaré *et al.*, 2001), one considers an indicator IFx equal to the quantity of manure defecated, divided by a maximum value, the Complete Manure, that corresponds to the manure defecated during 4 weeks by 10 cattle. Thus, a single sheep having grazed and defecated for one week would have an effect of IFx = feces value per animal according to the specie * number of animals * number of weeks / (cattle feces value * 10 cattle * 4 weeks) = $1/200^{th}$ of a complete manure! A “manure counter" is therefore created for every parcel counting the impact of any new manure and its resilience, i.e. the time the manure influences the parcel fertility.

We consider that all non-transhumant animals spend each night in corrals at compound of their owners which means that half of the feces is in the corrals (Ayantunde *et al.*, 2000; 2002). Therefore, we share the feces of each animal in two categories, which their effects are both indicated in Table 16[128].

- The first half of the feces, which remains on the cell where the animal was at daytime, is considered as simple manure. To estimate the effect of a partial manuring, we consider that the effect of manure lasts 3 years * IFx. Its effect on yields is also multiplied by IFx.
- The other half is assimilated to the manure produced by the animal in the corral at night and is thereby considered as transported manure. It is transported from the corral and spread by the owner on one of his parcels that the owner chooses, which means that this action leads to a potential differentiation between fields according to the field owner’s herd. To estimate the effect of a partial manuring, we consider that the effect of transported manure lasts 1 year * IFx and its effect on yields, reducing slowly along the years, is also multiplied by IFx. Thanks to this transported manure, we simulate the effect of fertility concentration on parcels belonging to livestock owners.
  The choice of the parcel by the Villager follows:
  C_x Manure = p - Fx (t) - (Dx +1) (16)
  With: Fx (t): Fertility of x at t; Dx the distance from the village to the parcel x, p: a random factor $\in$ [0-1[, that avoids the overtaking of parcels in case of equality in this hierarchization;

[128] These values correspond to Complete Manure.

Therefore, the less a parcel is fertile and the closer it is to the village, the more the Villager privileges it.

In effect, there are some differences in the management of manure between the three sites. However, we do not have real villager criteria that may explain such differences. Therefore, we do not implement any differences between sites for the manuring procedure as we assume that these differences make little difference in the fertility restoration processes.

Table 16 presents the coefficients of a linear regression that corresponds to several fertility-related factors affecting a millet yield constant. To establish the effect of fertility on yields, we therefore straightly add every week the value indicated in the second column of this table, meaning the number of pearl millet bags per parcel divided by the number of weeks of which the manure has an effect on the crop process. The third column of this table indicates thus the F value in millet bags to add per week to the basic potential millet yield thanks to manure and transported manure.

Table 16. Human–managed fertilization processes on millet yield, adapted from Gérard (2005), Akponikpé *et al.* (2007), Gérard *et al.* (2007)

	Grain yield ($Kg\ ha^{-1}$)	Grain yield (80kg bag/ha)	Grain yield effect used in the model (80kg bag /ha /week)
d. f. residuals	1029	12.86	
Constant	104.1 (<.001)	1.30	
Corralled previous dry season	239.3 (<.001)	2.99	0.18
Second cropping season after manuring	168.2 (<.001)	2.10	0.12
Third cropping season after manuring	186.5 (<.001)	2.33	0.14
Transported manure	78.5 (<.001)	0.98	0.06
Fertilizer (DAP + Urea mix)	83.4 (<.001)	1.04	0.15
Days between sowing and first weeding	-2.7 (<.001)	- 0.03	
Days between first & second weeding	0.5 (0.030)	0.01	

Manure impact on the fertility value Fx and vegetation values Lx and Hx

These relative fertility indicators are calibrated according to vegetation for the consistency of the whole cycle. The same value IFx is used to translate the positive impact of this manure on the global fertility of the parcel:

$$Fx(t) = Fx(t-1) + [\ 1/(1000 * (1-IFx))] \quad (17)$$

With: Fx (t): fertility of x at t; IFx the indicator of the impact of the manure.

Impact of stages of the crop process on the parcels' fertility

For each weekly time step during which the parcel is cropped (from a successful sowing to harvest) the fertility decreases linearly:

$$Fx(t) = Fx(t-1) - (1/1000) \quad (18)$$

At harvest, it decreases proportionally with the size of the yield, because this decrease is related with the exported yield result:

$$Fx(t) = Fx(t-1) - [(VYx * Rbb)/(1000 * F_0)] \quad (19)$$

With: Fx (t-1): fertility of x at (t-1); VYx the harvested grain mass in millet bags; Rbb: the average number of millet bundles per millet bag: Rbb = 8; F_0 = the initial agronomic potential of the parcel.

4.4 The social module of SimSahel

After the model initialization step, gender and family rank are the most important factors for a villager Agent within the village context. They determine the access to all the social and/or economic activities, i.e. marriage, property, food and money redistribution, pearl millet farming and migration for men, gardening for women. Parameters describing the socio-economic part of the model are summarized in Table 17:

Table 17. Parameters used for the socio-economic part of the model

Marriage	Assortative sequential criteria for discriminating female bachelors
Wife limitations	Limited to four wives
Livestock effect	A (i, t) = Bfi (t)/8+Ofi (t)/16+ Bi (t)/4+Oi (t)/8 with: Bfi (t): bovine livestock owned by the family Ofi (t): ovine & caprine livestock owned by the family Bi (t): bovine livestock owned by I Oi (t): ovine & caprine livestock owned by i
Family situation effect	F (t) = (Family size – Rank (i)) – Children size (i)
Family lineage effect	L = (lineage amount (4) +1) – Li with: Li: family lineage of I
Total	Vi = (A (i, t)+ F (t)) * Li
Ceremony costs	The price of one sheep
Dowry costs	200 kFCFA (300 €, same amount for all, independently from lineage: it is an assumption as differences according to family situation may exist
Property access (after initialization)	
Maximum “allowed” property	Family lineage effect (i) * Family total manpower (i, t) * R with R a random value: R = 1 for 50% of chances. R=1.5 for 25%. R= 2 for 25%:
“Semi-randomized” search effect:	Search of new parcels starts from the village pixels. The number of trials for a villager I: N = Family total manpower (I, t)
Parcels comparison criteria:	C (j, t) = Fertility (j, t) – Distance to Village (j)
Food & money redistribution	Individual rank based assortative classification of the dependents
Millet farming & migration for men	Only the man with the highest rank (or by default his widow) can own and therefore manage the land by ruling the dependent male manpower
Gardening	Only the allowed manager with the highest rank can borrow and therefore garden by ruling the dependent female manpower

We insist on the fact that any simulated social organization as well as the considered scenarios are in any case theoretical. They did not exist, they do not exist and will not exist. Here, we mimic what has been observed by repositioning at the heart of the farming systems some essential elements concerning production means' access and family organizations. Our simulations cover long periods (60 & 100 years). Let us simply remember that according to Olivier de Sardan (2003), 100 years ago in 1907, slavery was just officially abolished and nearly ¾ of the population were slaves! The 40 following years have seen the conjunction of escapes from extortions of the colonial power (forced labor, heavy taxes) and the end of the insecurity (Luxereau & Roussel, 1997), leading to an explosion of the number of newly created villages. These are contexts that are difficult to be historically reconstituted and even more difficult to simulate. Thus, even if our simulations are long-term based, they provide insights on the functioning of the present-time systems and not really as neither a reconstitution of the past nor a real prospective for the future. This prospective is possible only if the main determinants of social changes remain the same in the future.

4.4.1 The Villager: Ageing & dying

The chosen rules are extremely simple and are similar to those considered for livestock. Every Villager Agent disposes of a health indicator P that reflects its nutritional status. Every time step, the Agent ages by one week and has to feed himself to sustain according to an age-specific consumption value (1 for adults whatever their gender, age/20 for children). If such a villager's food requirement is not fulfilled by the food redistribution system or if he does not feed him/herself, the nutritional status value decrease. If it becomes negative at the end of a time step, the villager entity is suppressed and considered dead.

Meanwhile, there exists an "accidental" mortality rate (diseases, etc.), which depends on age and the nutritional status, eventually allowing Agents an average life expectancy of 48,5 years for both genders as described in the UNDP report (UNDP 2005). At every time step, the Agent i sees this risk of mortality vary. One considers Mi (t) a value to be compared to a randomly generated value between 0 and 1. The higher Mi (t), the more the villager has a chance to survive:

$$Mi\,(t) = (Pi / Pmax) * (1 - MH) \quad (20)$$

With: Pi & Pmax: P the nutritional status; Pmax, the maximum value of P, that is equivalent to the annual consumption ([129]. For humans, the most difficult period is obviously the "soudure", when millet is lacking in storehouses. The Pi/Pmax ratio therefore falls dramatically during that period, in particular for the most vulnerable persons and the most socially “remote” from the individuals who are in charge of the food redistribution.

[129] This value is merely arbitrary and may be brought to the equivalent of 1 to 2 months, maximum time of survival of a human being deprived of food

MH: the average mortality rate at each time step, which varies according to age but not to gender. The first year of life based on the infant mortality rate

from FAO (2006):	$154\ /_{00}$	MH= 0.33%
From 1 to 5 years:	$108\ /_{00}$ the mortality rate	MH= 0.06%
From 3 to 40 years		MH= 0.02%
From 40 to 50 years		MH= 0.03%
Above 50 years:		MH= 0.06%

4.4.2 The family structure: modes of inheritance & family organizations

The family: the inheritance system

Inheritance makes sense only in the case of the death of a landowner or a livestock owner. The possibly positive balance of cash of the deceased is considered as being redistributed during the funeral ceremony. Two modes of inheritance are considered. In the two systems, children have no right on land, even for the future, as underage heirs are almost always denied from their heritage once they get adult. Women can inherit parcels under rare circumstances when they become family heads (widowhood without relatives).

The customary mode of inheritance

We first implemented a lighter version of the customary inheritance norm such as typically described during our first collective interviews and meetings: In this version, lands were shared between the male heirs in an unequal manner. However, the first calibration tests of this procedure induced a rapid fragmentation of land properties that do not correspond to observations. We have made the hypothesis that some hidden and complex mechanisms of coercive compensation were put into place in order to avoid this fragmentation and thereby to give the entire heritage to one heir. Actually, either this one-heir version is recognized as the formal inheritance rule, either it constitute a tacit and interwoven system: Thus, the designated heir does not necessarily correspond to the official one, as Muslim laws being respected too much for being violated in such a blatant manner. Therefore, an official manager is designated as a regent for the account of a "minor" (woman, sick man or child). The values of “shame” and non-ostentation being very strong, none of his younger brothers, and even less the sisters, will dare to protest thereafter for a better sharing. The usual tactic is therefore to leave the situation "rot", up to the point when the presumptive heir abandons his/her prerogatives on the land property.

Therefore, the inheritance procedures are implemented as follow: they differ for livestock, as movable goods, and land, as immobile goods.

- **Livestock** follows a sexually discriminated rule: The livestock owned by women is transmitted by default to the direct adult female descendant of the highest rank, otherwise one searches the female heir within the family with the highest rank. In case there is no female Agent in the family, the livestock is returned to the original family of the woman if she was married. If she was not, it is shared between the members of the present family. In the same way, the livestock owned by men is transmitted to the descendant of the highest rank.
- **For the land**, we chose a "brutal" version of the common customary mode of perpetuating family exploitations, assuming the following rules: total transfer of goods of the deceased man to the elder son or, by default, the adult of the highest rank and preferably a man, leaving the others to exploit new lands somewhere else. Actually, as long as adult family members remain, the one whose rank is the highest becomes the new head of the family and receives the land. Thus, in the case of widowhood, the widow can on certain occasions inherit the lands[130], in particular a young widow without adult male children. If there are no more adults in a family, the property goes back to a family head chosen randomly amongst the family heads of that same lineage[131]. The children that possibly remain in this family without adults are adopted by the concerned heir: they move to the new family where they are fully included apart from the fact that they are registered with the lowest position in the list of the person in charge of the food redistribution and in the inheritance hierarchy, because they are not offspring.

The Muslim mode of inheritance

In this inheritance mode, land and livestock are shared in a sexually discriminated manner. The livestock owned by a woman is shared equally between the direct heiresses; the land and the livestock of a man are also shared equally between the direct male descendants. The collateral parents cannot therefore expect a share except in the case of the absence of direct descendants of the “right” gender.

---

[130] In the former context of movements and of land settlements, male non-heirs receive according to their merits and called for settling outwhere (Luxereau & Roussel, 1997)

[131] Obviously, there is no random choice for real inheritance. The problem is that observing in the field such practices is obviously difficult, as deaths of landowners do not occur everyday and such negotiations are quite secret. We may have complexified these modeled rules (the heritage goes to the closer relative, the relative who gave food, etc.) but these modifications mean little in practice because the most important is the existence of a transmission within the same lineage.

The family: Family organizations

A described in chapter 1, different family organizations seem to have existed in the Sahelian Niger, with a possible evolution from the unitary and patriarchal mode to the non-cooperative and mononuclear one. The implementation of the differences between these two family organizations is implemented as shown in Table 18. All behaviors we described are therefore affected by these organizations as they condition the access to assets to carry out economic activities. For instance, migration departure is conditioned by the cash availability and both agriculture and gardening require family manpower that depends on the family organization.

Table 18. The simulated characteristics of the two analyzed family structures

	Unitary Family Structure	Non Cooperative Family Structure
Family structure	Married sons remain at home;	Married sons leave home and build new families
Condition for marriage	The family head, most often the father, pay the dowry.	The groom pays the dowry.
Sharing food	All income is given to the head of the family, who shares them among members[132]. Therefore, the family balance is equal to zero when he dies.	A "family granary "as an account to share to fulfill the demands of family members [133]. Family members' balances are maintained whatever happens to the head of the family.
Availability for seasonal migration	The head of the family defines his manpower needs for each millet cycle stage. Only he can allow a young male family member to leave earlier for migration	A young male family member can leave for migration during the millet-cropping season if there is still an elder with a higher rank staying at home.
Fields extension	Families do not explode and cropland expands based on family needs	The direct heir has all the inheritance; others have to settle somewhere else.

4.4.3 The family functioning: marriage, births & food redistribution

The family: marriages

As we focus on family organization impacts and not on marriage rationality, we did not implement a negotiation procedure between candidates on the basis of rules of marriage as theorized by Simon (1955) and implemented for Agent-based simulation by Small (1999) or White (1999). We implemented the marriage system along a simple assortative mating principle (Becker,

[132] Therefore, all gardening incomes remain part of women incomes in the non-cooperative scenario whereas, in the unitary scenario, even this money goes to the balance of the head of the family.

[133] Redistribution is limited to dependants of each active person in the family. It also means that a person who cannot afford expenses for all his/her dependants can "ask" the head of the family or any person with a higher rank within the family for support, only for that particular time step.

1974): marriages are matched through a comparison between mating members within the same reference value system, the individual reputation (see §3.5.2), which is a combination of their family characteristics (lineage, size, family livestock and land) and their personal ones (rank in her family, her livestock). As a sequential principle, this method has the lowest emergence effect, is simple and fits better with the observed situation. After majority (16 years old for boys and 12 years old for girls), marriage can occur if the young male adult Agent can support all marriage costs, through the money he brought back from migration for instance. Muslim people marry up to four times if they can afford the costs. Males sort the female adult bachelors according to personal reputation (see §3.5.2). As a strict condition to own land and thereby to become a "citizen" in the village, each male adult Agent has to marry at least once. Earning enough money to afford the dowry is therefore vital for each bachelor in his village.

We excluded the possibility of marriages within the same family (no incest) but we linked the choice between exogamy and endogamy with the mode of family inheritance: if the inheritance mode is the "local Muslim" type, the choice of families is first based on parties of the same lineage. If the inheritance mode is the "customary" type, the choice of families is first based on parties of different lineages. The choice is made through message sequences: they require the presence in the village of the two bridegrooms. Therefore, the period of marriages is, as observed on the field, around the cropping season and mostly just after the return from migration and after the harvest, when families have cash for paying ceremony costs and dowries:

1. At this date, all men send to single women a message of "information" worth $(1-R_i(t))$, with $R_i(t)$ their individual reputation value (cf. § 4.1.1). Men can get married up to four times.
2. Women who received messages at this date sort them out according to the value of the message and send back to the first of them their own message of "information". Men sort out their messages then in the same way. If he is a "good deal", he can receive several messages in this way. He sends to the first of them a message of acceptance following an equivalent hierarchy to the one of women.
3. The two individuals are defined therefore as bridegrooms. The woman loses her lineage and takes the one of her husband. She also changes families to become a member of that of her husband. However, she keeps her livestock if she had any.

Costs of ceremony are high for any family, and reach on average 750 kFCFA (1150 €), including a sacrificed sheep but not including the dowry to pay to the bride's family. However, it is necessary to note that innumerable small gifts are given to compensate this dry loss for the family.

Consequently, we simplified this expense by bringing back the ceremony costs to the dowry and the price of one sheep that is paid by the head of the household, i.e. the groom or the "father" of the household, depending on the family organization. This amount has to be paid immediately without possible recourse. Yet, it is clear that this expense has a social role, maybe as a dilapidation purpose as described by Mauss (1924). But we do not know if the objective of this dilapidation is the increase of the prestige of the family, the lineage or other levels. Historically, the dowry was the equivalent of a compensation grant to the bride's family. Symbolically, the dowry price remains fixed on the standard of about two oxen. Olivier de Sardan (2003c) talks of three oxen in the 70's for the better-endowed people living along the river Niger. In the first version of the model having permitted the writing on families' organizations (chapter 4), this amount was stationary whatever the lineage. In the following versions, this sum varies depending on lineages, according to the following rule: As lineages are classified from 1 to 4 by decreasing order (1 is the best, 4 the last), we create a dowry value D_{AC} such as:

$$D_{AC} = \frac{P_{dowry} * 2 * [(\Sigma \text{ lineage values}) / \text{population size})]}{(\text{lineage value of the groom} * \text{lineage value of the bride})} \quad (21)$$

With: P_{dowry}: the price of two average oxen, i.e. 160 kFCFA (293 €). The average dowry cost is around the price of two oxen while the dowry is thus as high as the bridegrooms belong to high lineages.

The family: births

In the simulation, children cannot take place but in the framework of a marriage and if the husband is living in the village at the time of the conception. We put an age limit of 40 years old for conceiving babies according to the Niger sanitary conditions (Médecins Sans Frontières 2005). According to our observations women can get married very early, sometimes even before 12 years old. However, and except certain deviances[134], the "consumption" of marriage occurs later. Consequently we set the minimum age for having children at the majority of 16 years old[135]; the probability for a woman to get pregnant at every time step is therefore fixed, as defined from women fecundity data (UNDP, 2005): 7.1 living children per woman, the highest rate in the world, and a fertility period of 24 years (from 16 to 40 years old). As carrying a child takes a year (pregnancy & returning of

[134] In particular when they make intervene in strong gaps of wealth ("the purchase" of a young girl by a big aged tradesman) or some exotic crypto-Muslim ideologies.

[135] Many may easily retort that exceptions are numerous. However the HHLS data of CARE (2002) and the report from Guenguant *et al.* (2002) give the ages of respectively 14.8 years & 16.6 years for a first child. Yet certain authors think that first births occurs more and more at a younger age.

menstruation cycles), we obtain an annual probability of 7.1/24 that is to say, including the infant mortality rate MH (see §4.4.1) and reasoning by series 1.02838% per week. Once a woman gets pregnant, a whole year (52 weeks) is necessary for the appearance of a child as a new Villager[136]. The pregnant woman consumption does not rise while she is pregnant.

At this date, a new villager is thus created with his/her features: a Child statute (with all the associated individual characteristics), the lineage of his/her parents, the inclusion in a family and the capacity to know all its members, including the ranking hierarchy and the differentiation between direct lineage defining Dependents from others. He/she also receives the possibility to inherit, according to the evolution of his/her rank within the family. He/she is also integrated in the list of members of the lineage and the village. Every birth is the opportunity for the sacrifice of an animal if the family has some, always a sheep if it is a first son in the family, which may imply to sell some millet to buy the sheep, and if a girl or a cadet boy a sheep or by default a goat of the herd if there are some.

The family: food redistribution

Food redistribution is the most important hierarchy-related process within a family. At each weekly time step, each adult Agent classifies its dependent relatives taking into account the “social distance” between them, i.e. the difference of social ranks within gender and age groups[137]. Only dependents with a negative balance are considered. The food manager first feeds male adult Agents, then his wife/wives, then other married female adult Agents, then unmarried ones (his adult daughters or great-daughters) and finally children[138]. When men are not present in the family (i.e. during migration periods), the food distribution manager is the woman with the highest rank, usually the wife of the head of the family. Conserving a personal reserve equivalent to one year of food[139], the food distribution manager distributes to every one the equivalent of his food deficit if sufficient food is available. Otherwise, the person in charge redistributes what he/she can.

---

[136] 9 months of pregnancy and 3 months of weaning for then to consider the child as a living baby, an individual villager that consumes even a very small amount of food.

[137] It groups all family members who have a lower rank and are directly related, i.e. the children but also younger brothers and sisters, and wives for the husbands.

[138] This is consistent with the observed commensality procedure in villages and particularly in the largest families. The most productive members seem to be favored in a family: men eat alone before women who feed babies, and finally children eat the remaining food.

[139] This artificial convention allows avoiding the sudden and incoherent death of adults.

We have implemented the redistribution principles between parents and offspring that differ between the two family organization modes, as described in § 4.4.2.2:

- In the patriarchal & unitary family type, the head of Family is the unique depositary and the sole in charge of food redistribution in the family. When he is absent because of migration, a temporary Family head is designated according to the principle of the highest rank. This person can thus be the first wife of the Family head.
- In the non-cooperative family type, every Adult classifies his family's dependent members, namely his/her offspring and is in charge to feed them. When this adult is absent because of migration, a substitute is designated, according to the principle of the highest rank. If the adult or his/her substitute does not have enough food to feed all his/her offspring, he/she can ask his/her head of family for support. Therefore, there are more persons in charge and the social "distance" between a giver and an asker is shorter than in the patriarchal mode.

If millet lacks, the person in charge (the family head or the temporary one) can buy millet on the market at the present actualized price. If he/she does not have enough cash, he/she can proceed with the sale of livestock along the following classification: he-goat > ram > she-goat > ewe > ox > cow, cows being thus the last to be sold.

4.4.4 The outside environment: price fluctuations & taxes

Pearl millet price

The pearl millet price variability is based upon the fact that in spite of the spatial and temporal variability of the rains, the big crises and famines affect simultaneously large parts of the Nigerien Sahel (Alpha Gado, 1993). As a result, the drought parameter $F_{drought}$ (see § 4.3.1) that affected the previous cropping season is memorized. In order to simulate the effect of drought on millet prices, we use the cube of $F_{drought}$ is value as a rough estimation of the inelastic characteristic of the millet demand: $I_{price} = F_{drought}^3$ (22)

During average rainfall years, one considers that the price of one millet bundle Pmil evolves from 750 FCFA at harvest and evolves thereafter throughout the year according to the following function:

$Pmil\ (t) = Pmil\ (t-1) + (10^6 / I_{price}) / T_{noHarvest};$ (23)

With: $T_{noHarvest}$: the period during which one can consider that there is no new millet reaching the markets that may lower the millet price, namely the whole dry season plus the period of sowings and weedings: $T_{noHarvest}$ = 48 weeks.

Taxes

The date of payment of the tax intervenes at one fixed date, the 42nd week, which is a little after harvests. It is based on the number of family members, whatever their age. The amount is the equivalent of a millet bundle per capita. It means that a family head may have to sell an animal for paying this tax. The collected sum disappears and is not reinvested in the village.

4.5 The Production module of SimSahel

It regroups the economic activities of villagers: agriculture, livestock keeping, seasonal migration and gardening.

4.5.1 Agriculture

The expansion of lands after initialization

At the beginning of the 20th century, the Nigerien Sahel population begins to conquer its own potentially arable territory. Farming systems have evolved during this century towards a more extensive mode with generalized land clearings and multi-activity. Considering the demographic growth during the last 30 years (7,1 children on average per woman, UNDP 2005), the cultivated field expansion has accelerated during this period. It seems to have reached its limit in several locations of Niger, with a progressive land saturation that is reflected in a dramatic fall of the pluriannual fallows (Banoin & François 1998; Mortimore *et al.*, id.), and even their nearly total disappearance in the south of the country (Mahamane, 2001).

We consider the expansion of the family property to be a consequence of the will of each family, defined by its own growing needs. As only married male heads of households can appropriate land, the field expansion is family-based.

After the initialization, a family can expand its property. Parcels have to be arable, i.e. not on a plateau or on a stony hill, and not yet owned by another villager. Parcel selection is done through a hierarchization of the available parcels. Unlike more Sudanese zones, Sahelian farmers do not preferentially use depressions and valleys because they are not well suited for millet. Besides, the tool people use for weeding, the hilaire, is better adapted to sandy soils (Raynaut *et al.,* 1997 pp. 209). However, the soils of depressional areas are interesting because they better preserve the moisture and shallow water is easily accessible through wells, meaning that one can garden there by watering (Raynaut, 1989). We consequently consider that the interest for valley soils exists but is not primordial, considering the efforts required to reach them (distance to the village) and to cut the abundant woody vegetation before cropping it (Loireau-Delabre, 1998 p.170-186). We consider the following criterion of parcel hierarchization CSx:

CSx = [p + Fx(t)] / [Dx * Lx (t)] (24)

With: Fx (t): Fertility of x at t; Dx the distance from the village to the parcel x (Loireau-Delabre 1998); p: a random factor $\in$ [0-1[, that avoids the overtaking of parcels in case of equality in this hierarchization; Lx (t): the woody vegetation indicator;

We simulate this capacity of expansion as follows. A family wishes to expand into new lands not yet appropriated if the average of its previous harvest falls below a threshold value equal to of six months of food for the family[140]. However, this family can consider this expansion only if it has enough manpower (Gavian & Fafchamps 1996) and if the lineage of the family authorizes it.

If Pf (t) $\leq$ [MoF (t) * (5-Lf) * 10] (25)

With: Pf (t): the size of the family property at t; MoF (t) the family manpower at t; Lf: the family lineage.

If this condition is met, the family can add new fields, as described in Figure 20. The first attempt, indicated by * on the figure, begins from the village cells [141]. The number of authorized random search attempts per week reflects the capacity of a family to look for new fields and is equal to MoF (t), the family manpower at t.

[140] It happens quite often, particularly in the case of Zermou (AQUADEV, 2006)

[141] This centralized procedure rebuilds the radial aspect of field expansion in Nigerien Sahel.

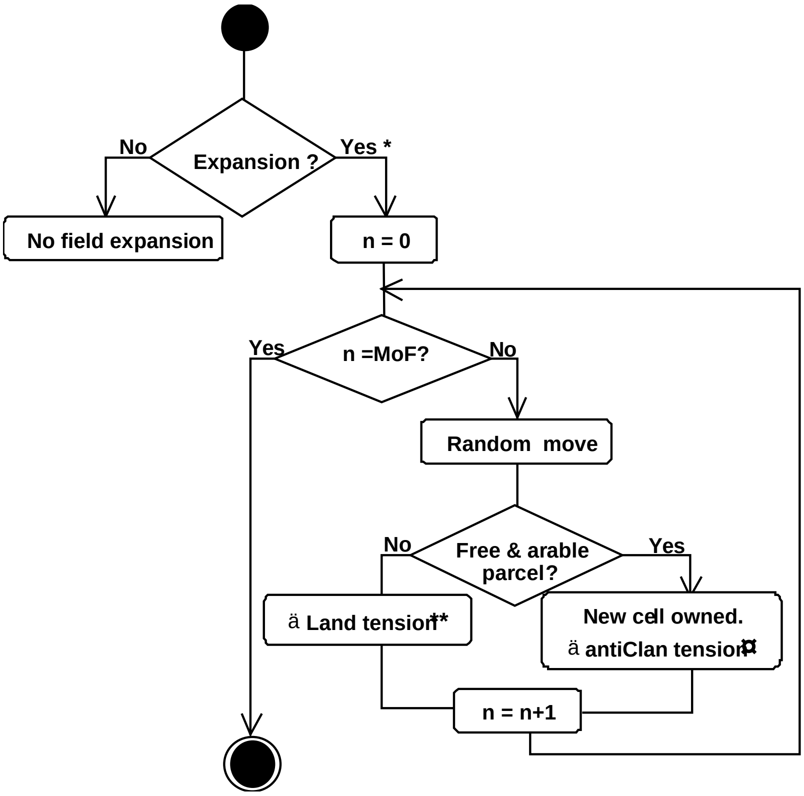


Figure 20. UML representation of the field expansion rule

Two articles corresponding to chapters 4 & 5 concern thus territories, which their populations are not already under a full land, pressure because they correspond to 60 years simulations. The third article, corresponding to chapter 6, is based on 100 years simulations.

Inorganic fertilizers & crops

As there is still considerable confusions among villagers regarding the different categories of inorganic fertilizers[142] (e.g. NPK, Urea, Diammonium Phosphate = DAP, etc.) and because fertility is already simplified in the model into one single index, we group all inorganic fertilizers into a single category that is hereafter called Fertilizers. Fertilizers have a positive effect on crops from sowings to weeding times. As indicated in Table 16, the residual effect of inorganic fertilizers lasts one year unlike organic manure,

[142] These confusions may even concern extension services & development operators: fertilizer bag categories were once mixed and a trader who has put cement in bags instead of fertilizer has once swindled one UN development operator!

which lasts 1 or 3 years. The parcel is considered as fertilized during this 1-year period. The effect of fertilizers on crop yield is modeled by adding each week linearly the value of 1.04 bags of millet per parcel divided by the number of weeks during which it is supposed to have effect, i.e. 7 weeks from sowing to weeding. Thus, we do not consider a rate effect, assuming that people use a uniform quantity on their fields.

Inorganic fertilizers may have also a negative effect as recalled by Minet (2007): several scholars (Affholder, 1997, de Rouw, 2004; Koning & Smaling, 2005) have noted that adding inorganic fertilizers can reduce yields in case of poor rainfall season through the "burning" effect of the nitrogen, which increases the plant evapotranspiration. Trials implemented in fields often show this interaction between soil and rainfall, leading to different yields under equivalent conditions of soil and management depending on the annual rainfall distribution. Moreover, villagers repeatedly mentioned this risk during interviews. We have therefore implemented this risk for the millet maturation period: At every time step, there is a 1 for 1000 risk of burning the production by the use of inorganic fertilizers or organic manure. If this burning occurs, the yield is divided by two.

Interactions between vegetation and agricultural production

Each time an action takes place on a parcel (sowings, weedings and harvesting), the grass and shrubs on it are cut for a part. The herbaceous and woody indicator values Lx (t) and Hx (t) are therefore reduced as shown in Table 19. Otherwise, when the farmer does not act on the parcel, grasses and shrubs grow the same way according to local rain and fertility as described above.

The grass is considered during the crop growth period as <u>weeds</u> for crops. Weeds evolve according to parcel fertility, rainfall and the farmer Agent weeding actions (Lassina 1992; Montagne & Housseini 1998; Sangaré *et al.*, 2001; Schlect *et al.*, 2006). They affect millet production only if the millet growth level is lower than the weed growth level. The weed growth indicator Ax (t) is given by: $Ax(t) = Ax(t-1) + [Rx(t) * Fx(t-1) / (10 * N_{CA})]$. (26)

With: Rx (t): the volume of rain on cell x at t; Fx (t-1): fertility of x at t-1; N_{CA}: the number of weeks needed for a maximum growth of weeds, i.e. 16 weeks.

Once the crop cycle has been completed and the millet harvested, the model translates the weed growth indicator into a grass indicator, which is added to the herbaceous indicator Hx (t). If Ax (t) has a higher value than the millet cropping cycle indicator, simulating in this way the competition between the two plants, it reduces the latter indicator is reduced at each time step. The related function is described below in the weeding part of the cropping cycle.

Table 19. Impact functions of the pearl millet crop process on herbaceous and shrubs/trees growth on a parcel

	Herbaceous	Ligneous shrubs & trees
Sowing: done & succeeded	Hx (t) = Hx (t-1) / 5	Lx (t) = Lx (t-1) / 2
Sowing: done & failed	Hx (t) = Hx (t-1) / 2	Lx (t) = Lx (t-1) / 2
Weeding: done & succeeded	Hx (t) = Hx (0) * 0.05	Normal growth
Weeding: done & failed	Hx (t) = Hx (t-1) / 2	Normal growth
Weeding: not done	Normal growth	Normal growth
Harvesting	Hx (t) = Yield /10 + Ax (t) * 10[143] *	Normal growth

* Yields: the volume of pearl millet in kg; Ax (t) the weed factor (27)

The pearl millet cropping cycle

Only male adult Agents can crop millet fields. They have the power to manage that land, but it does not mean that they have total rights on the yield. One parcel produces millet only if it has either been appropriated or borrowed by a villager Agent. Crop growth is governed by the available manpower a villager Agent can mobilize to carry out the right cropping practice at the right time, by rainfall and by the fertility status at each time step.

The stages of the pearl millet cropping cycle

The cropping cycle is based on temporal sequences of actions because of the uncertainty one farmer encounters along the process, following Fafchamps (1993) and Gavian & Fafchamps (1996). The cropping cycle starts from the first rain occurring on a cell, meaning that every parcel has its own growing season, i.e. its rainy season that the farmer knows.

Each of the three stages of the crop process which requires labor (sowing, weeding, harvest) requires one week of work or less by a single person on a 1 ha parcel (the maximum requirement is for weeding, which needs 5 to 7 mandays.ha^{-1}). A fourth stage is coded, called "maturing", which takes into account the burning effect of inorganic fertilizers on millet. In the model, we therefore consider a specific number of parcels that one person can sow, weed or harvest per time step. This number depends on the stage, as indicated below in the stage process description. Each of the stages corresponds to a precise interval of time in the cropping season during which the Villager must lead the action to its term, otherwise a failure may occur on this parcel (Table 20). A stage is either a total success or a failure.

[143] After the harvest, millet straw is integrated in the herbaceous part that can be grazed by livestock. These straws do not grow but one considers that this will be compensated for the stimulation of growth of the weeds after harvest if rain continues.

Table 20. Periods of the millet cropping stages

Sowing:	From the 1st week after the first rain until the 8th week excluded
Weeding:	From the 8th week included until the 12th week excluded
Maturing:	From the 12th week included until the 17th week excluded [144]
Harvest:	From the 17th week included until the 21st excluded

To achieve these successive stages the villager must mobilize his available family manpower, which depends on the family organization type. For each of these stages the Villager observes the state of his parcels. If the available manpower is sufficient, he achieves all the required operations. Otherwise, he calculates the number of parcels that can be dealt with in one week and hierarchies his parcels in order to minimize losses. The remaining parcels will have to be dealt with the following week but with no particular priority upon the other parcels. If they are not treated within the attributed time, the parcel's crop is lost. The following UML figure illustrates this sequence (Figure 21):

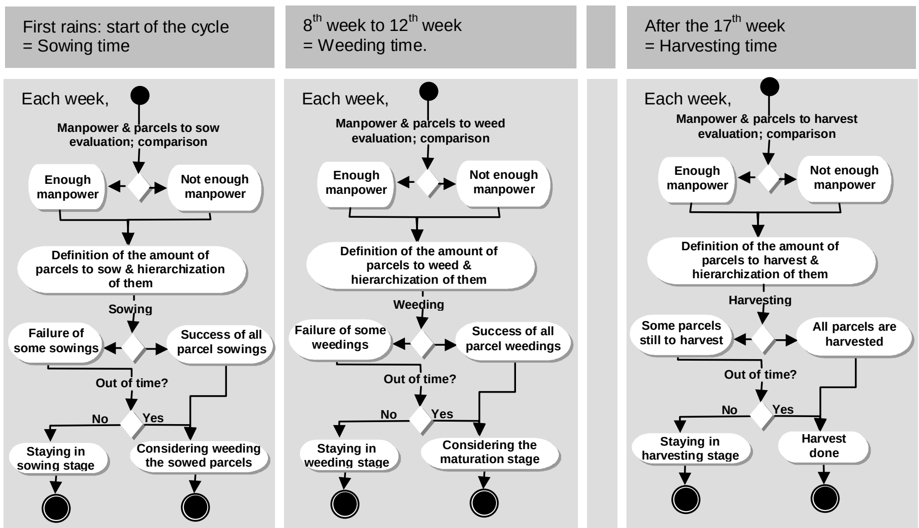


Figure 21. UML figures for the three successive millet crop cycle steps which requires labor, each one representing a sequence of evaluation & action

The indicators of growth & of production of pearl millet

Pearl millet growth is the result of two indicators: The first one is the indicator of the degree of achievement level of the millet growth cycle ICx (t), simplified and adapted from "le Manuel de l'Agronome" (CIRAD, 1991 pp. 674-679)

[144] During this period, it is mainly about expecting good rains & children scaring birds.

$ICx (t) = ICx (t-1) + [(1 + I_s) * Fx (t) * (Rx (t) / R_{max} (S)]$ (28)

With: I_s= I (Si)- I (Si-1); i from 1 to 4; I (Si) & I (Si-1) the indicators of each of the four stages; Fx (t): fertility of the cell x at t; Rx (t): the volume of rain on the cell x at t; R_{max} (S) the maximum volume of rain per week that can fall during the specific Si period as indicated in Table 2.

The second indicator is the yield potential IPx (t), which evolves with the cropping cycle. Any difference with the optimum of cultivation makes it decrease. For example, this happens if no rain falls during sowing or maturing times, or if the weeds indicator overtakes the ICx indicator, meaning that weeds penalize the millet growth. If the cycle does not fail, this indicator becomes at harvest the quantity of millet to be harvested. The function IPx (t) is different according to the stages of the cropping cycle, as described hereunder.

Sowing pearl millet:

We consider that a FLU[145] can sow 10 parcels (namely 10 ha) in one time step. There are no real manpower constraints for this step. Thus, in case of sowing failure (for example no rain after sowing), the Villager can retry a sowing the next week. As the sowing period lasts 7 weeks, the Agent can make 7 attempts at sowing as described by Loireau-Delabre (1998).

The criterion of hierarchy of parcels for the sowing follows C_x sowing:

C_x sowing = Fx(t) – (Dx +1) - p (29)

With: Fx (t): fertility of x at t; Dx the distance to village from the parcel x, p: a random factor ∈ [0-1[, that avoids the overtaking of parcels in case of equality in this hierarchization;

Once the farmer tries a sowing on a parcel, the cycle indicator ICx (t) evolves for this stage according to:

I_s = I (Sowing) – I (0) = (2/100). If ICx (t) ≥ I_s, the sowing is successfully passed and the indicator IPx (t) becomes:

$IPx (t) = I_0 + E + F$ (30)

With: I_0 the initial pearl millet constant = 1.30 bags of millet (Table 16); E: the impact of inorganic fertilizers per week; F: the impact of manure per week.

[145] The manpower unit is defined as the Farming Labor Unit (F.L.U.). For our case and based on our observations, female and male adult manpowers are equivalent (one can even consider that the female manpower is more important locally) and equal to 1. We condition the child manpower capacity on age, i.e. for a child i in the village: Manpower (i) = Age (i) / 20.

Weeding pearl millet:

As the period of weeding lasts 4 weeks, several weedings are to be realized. As seen above, weeds can decrease the production level IPx (t) if the weeds indicator Ax (t) > ICx (t). In this case the weed impact factor follows:

I_{weeds} (x, t) = ICx (t-1) * [1 – Ax (t)] / 100 (31)

Otherwise, weeds have no impact: I_{weeds} (x, t) = ICx (t-1) (32)

With: ICx (t) the cycle indicator; Ax (t): the weeds indicator;

We consider that a FLU can weed a maximum of 0.1 to 0.2 ha per day and we simplify the calculation by considering that a parcel of 1 ha can be weeded in one time step by one FLU. Weeding is the main bottleneck in terms of manpower. In case of weeding failure, no attempt at weeding or the weeds have grown well after a first weeding, the Villager can retry a weeding the next week. Weedings may be attempted up to four times. The criterion of parcel hierarchization for the weeding follows C_x weeding:

C_x weeding = [I_{weeds} (x, t) / ICx (t-1)] + p (33)

With: I_{weeds} (x, t): the weed impact factor of x at t as described above ICx (t) the cycle indicator; p: a random factor ∈ [0-1[, that avoids the overtaking of parcels in case of equality in this hierarchization;

Once an attempt is made to weed a parcel, the cycle indicator ICx (t) evolves at each time step of that stage as follows:

I_s = I (weeding) – I (sowing) = (5/100) - (2/100) = (3/100). Once this 3/100 value is reached, the weeding is considered as successful. During the whole weeding period, the indicator IPx (t) evolves at each time step as follows:

IPx (t) = IPx (t-1) + E + F + I_{weeds}(x, t) (34)

With: E: the weekly inorganic fertilizers impact; F: the weekly manure impact; ICx (t) the cycle indicator; Ax (t): the weeds indicator;

Maturing of pearl millet:

This period takes into account the risk due to inorganic fertilizers as described above. No manpower is needed during this stage. The cycle indicator ICx (t) evolves at each time step of that stage according to I_s as follows:

I_s = I (Maturing & harvest) – I (weeding) = (10/100) - (5/100) = (5/100). Once this 5/100 value is reached, the maturing stage is considered as successful. During the entire maturing period and unless a failure occurred (for example because of no rain), the indicator IPx (t) evolves at each time step as follows:

IPx (t) = IPx (t-1) + F + ICx (t) /100) (35)

With: F: the impact of manure per week; ICx (t) the cycle indicator;

Harvesting pearl millet:

Once the maturing period is achieved with no cycle failure, the parcel must be harvested. The number of bags of millet harvested is equal to the final indicator Px (t). We consider that a FLU can harvest a maximum value of 0.2 ha per day and we simplify the calculation by considering that a 1 ha parcel can be harvested in one week by one FLU. The harvest is therefore also a bottleneck in terms of manpower. The available time lapse for a harvest is 4 weeks and in case of non-harvest during this period, the harvest product is considered lost.

The parcels' hierarchization criterion $C_x$harvest for a harvest is based on the quantity of millet to harvest: $C_x$harvest = VYx + p (36)

With: VYx (t): the number of bags of millet to harvest on x; p: a random factor $\in$ [0-1[, that avoids the overtaking of parcels in case of equality in this hierarchization;

4.5.2 Gardening

We assimilate gardening to only one crop and we do not distinguish among different vegetables. One gardener can only cultivate one parcel: indeed, because the simulated pixels are supposed to be grossly one hectare in size, we allow each parcel of the territory to bring 10 gardening plots altogether. Actually, we consider that only 10 normal size gardens can be managed in one ha parcel and not that one garden reaches $1/10^{th}$ ha, because it is already extremely big for a private garden.

The conditions for gardening

Four conditions are necessary for an Agent to garden:

- Only one adult Agent per family has access to gardening. He/she can mobilize the available female manpower from then on in a similar fashion than the head of the family for millet cropping.
- Condition of gender, of age and of rank: In a generic manner, we will name henceforth the gardener as the “gardening- Agent” whatever its gender. This activity is restricted to one gender, men or women, depending on the simulated site:
  - On the site of Fakara, only adult women with the highest rank in their family and having stepdaughters or unmarried daughters at least 12 years old can garden. Thus, the more families there are in a "terroir", the larger the number of women who can garden.
  - On the site of Gabi, only adult men that have the highest rank in every family, i.e. heads of family, can garden. We consider that, since the site of Gabi is very close to the border with Nigeria and men commonly perform round-trips, men can at the same time garden and work abroad in seasonal migration (they put to work the child female manpower during their absence for the regular and heavy work of vegetable watering).
  - On the site of Zermou as for Gabi, only the heads of families can garden. We consider however, that, given the distance with the

Nigerian border, round-trips are impossible: migration and gardening cannot be led together.

- Condition of family property: the family must possess some parcels, even if these are not suitable for gardening.
- Condition of millet cropping cycle completion: Gardening is not possible for a family that has not harvested all its parcels yet. It is therefore a dry season activity, particularly during the first part of this period, which is called the "cold" dry season (from November to February). Once the new rainy season starts (first rain), pearl millet sowing may start and gardening products of are considered as lost because they have not reached maturity[146].
- Condition of manpower: the "gardening Agent" must have access to feminine manpower in the family that is adult or at least more than 12 years old and will be responsible for watering the vegetables. This obligation must be filled all along the vegetables' cycle.

Borrowing lands

Once these conditions are met, just after millet harvest, the gardening Agent borrows a parcel for gardening. As indicated in Table 2, only parcels of valleys and depressions have access to water, through shallow wells. These parcels are thus the only ones to be truly irrigable. If the family of the gardening Agent does not own such parcels, she/he borrows it from other families, preferably of the same lineage and preferably parcels close to the village. A parcel can contain at most 10 simultaneous gardening plots. This operation has to be repeated every year, meaning that one gardener has no guarantee to get access to irrigable plots. At the end of the simulation, when a population and the number of families are important, it may therefore happen that a family cannot find free irrigable plots to borrow.

The gardening cycle

Dry season vegetable gardening follows an equivalent sequence of actions to that of millet farming.
Once the parcel is borrowed, the vegetables' cycle takes place, considering that the dedicated feminine manpower is sufficient as long as it does not "disappear", for instance because of marriage or death. Two indicators equivalent to those of pearl millet cultivation are considered, one for the stage of advancement of the vegetables' cropping cycle ICMx (t), the second indicating the potential vegetable yield IPMx (t), adapted & simplified from "le Manuel de l'Agronome" (CIRAD, 1991 pp. 838-841):

[146] Gardening cycles rarely reach an entire year in practice, which means that the problem rarely occurs.

ICMx (t) = ICMx (t-1) + (1 / WGC); (37)

With: WGC: the number of weeks needed for achieving a cycle: WGC = 16 weeks. Once the cycle is finished (ICMx (t) > 1), the vegetables are harvested and it is possible to consider another gardening cycle on the same plot.

IPMx (t) = IPMx (t-1) + (52.5 / WGC) * (MOF (t) / 2) * man(t) * fer(t) (38)

With: 35 kFCFA (52.5 €) the average value as observed for a gardening plot; $MoFe_i$ (t): the available feminine manpower (all girls more than 12 years-old depending on the gardener Agent). There has to be at least the equivalent of two FLU to guarantee a complete harvest; man (t): we consider that manuring a gardened plot increase yield by 30%. This manure is considered as transported manure and therefore its effect lasts 1 year: man (t) = 1.3 / WGC; fer (t): we consider that fertilizing a gardened plot with inorganic fertilizers increases yield by 20%: fer (t) = 1.2 / WGC. Its effects lasts for 1 year;

At every time step, there is a risk of production burn of 1 for 1000 as a result of the use of inorganic fertilizers or of organic manure which makes dividing the harvest by two.

The redistribution of the gardening gains

The way in which the products of the harvest are redistributed depends upon the family organization. In the case of a unitary family, all the gains, including those of male/female gardening, go back into the hands of the Head of Family. In the case of a non-cooperative family, a fraction of the gains is handed out to the common family pot. This part (PEX) begins at 90% of the total gains but depends on the degree of altruism according to the AntiClan tension indicator defined in the family attributes[147]:

PEX = 90 – (AntiClan tension / 10) (39)

The remaining part stays in the personal balance of the gardening Agent. It constitutes the main source of income for the purchase of small livestock by women in the Fakara. On the two other sites, it permits men who may not have left for migration to accumulate money, in particular in Gabi. Zermou carries very few lands permitting gardening.

4.5.3 Seasonal migration or "exodus"

Every year, just before and after millet harvest, the majority of men leave for seasonal migration to make money by various jobs and trades. At the same

[147] This rises at every "bill" that one may have to give in the hands of the head of the family, meaning that the higher this index, the lower the share given to the household head. This indicator therefore reflects the progressive frustration and the growing temptation of dissimulating gains from the family to keep them for his/her own, as observed in the field.

time, this decreases the pressure on the family millet stocks. We consider indeed that during this period, men provide for their entire needs and the gains they accumulated correspond roughly to the value brought back to the village. Costs of transport, risks of racketing and weekly gains are indicated in Table 21:

Table 21. Migration periods, costs & risks for the three sites

Migration annual period for all sites				15/12 to 15/02.			15/02 to 15/06.		15/06 to 15/12
	Gabi			Fakara			Zermou		
g (t)	15	2	6	15	2	6	15	2	6
Travel costs	5 kFCFA (7,5 €)[148]			30 kFCFA (45 €)[149]			45 kFCFA (67,5 €)[150]		
Racket risk	0,5%			1%			2%		

g (t): the weekly gains for seasonal migration (see § 4.5.3.2

The conditions for the departure for seasonal migration

Only men have access to this activity and only if they are older than 16. The decision to depart depends first on the type of family organization:

- In the case of a unitary family, departure is allowed only after millet harvest, because the head of family does not permit an earlier departure.
- In the case of a non-cooperative family, the head of family and the oldest son do not leave until the harvest is over, whereas the others can leave.

There remains the constraint of the price of the ticket for the minibus. It is the main permanent constraint for migration. The cost of the ticket varies depending on the site reflecting the distance to the border and the final destination. It is therefore more difficult to migrate from Zermou than from Gabi. The source of the money needed to pay for the ticket depends on the family rank and the family organization plays a role as well:

- In the case of a unitary family, the Head of family is in charge of giving the money. He therefore selects the most experienced person, by starting with himself, possibly leaving the youngest to wait for their turn. This enhances even more the power of the Head of Family, who may or may not have the required amount for the departure of all the wanting men.

[148] This low value is due to the fact that Gabi migrants go to Katsina and other close Nigerian Hausa cities and even only to the border, mainly for trading/bootlegging.
[149] This price is the average cost, including "gifts" for custom officers, for going to Kumasi (Ghana) or Bouaké (Côte d'Ivoire) as the main destination for the majority of migrants of the Fakara.
[150] Despite the common Hausa language, Zermou migrants have no real access to jobs/trade in Hausa-speaking cities of Nigeria. They have to reach Yoruba cities in the south of this country, which explain the transportation costs, including "gifts" for custom officers.

- In the case of a non-cooperative organization, married men having left the parental home must find by themselves the required amount and therefore takes money from the common family pot[151]. Young unmarried men are not hierarchically dependant from a Head of Family but are still economically dependant, especially if they have never left for migration before and therefore, have no savings, or if they still have not saved enough. The Head of Family may in this case provide money for the ticket payment. As a consequence, poor youngsters may leave only after harvest depending on the wish of their Head of Family and only if the latter has enough money. The date of departure of these people is therefore conditioned by the amount of money saved from the previous migrations. Otherwise, if the migration candidate has sufficient savings from previous migration campaigns to pay for the ticket, and if the condition regarding the obligation of primogeniture is fulfilled[152], the departure can be made in advance.

The gains from seasonal migration

All information on migration gains come from our own investigations of 2004 & 2005, confirmed by other scholars (Ada & Rockström 1993; Reardon, 1994; Rain, 1999; Timera, 2001; Mounkaïla, 2003; Hamidou, 2005; Van Dyck, 2007). Gains are considered equivalent between sites, as they are achieved abroad. They depend on the number of years of migration experience. We define a weekly function of gain accumulation as follows:

$$G_i\,(t+1) = G_i\,(t) + g_i\,(t) * [1+ (N_i / 10)] \qquad (40)$$

With: G_i (t+1) & G_i (t) the gains of the individual i respectively over time t+1 and t; N_i the number of years of experience of the individual i; g_i (t), the weekly gain in €, that varies according to Table 21.

For instance on the Fakara site, the first period as indicated Table 21 corresponds to the cocoa harvest in Ghana and in Côte d'Ivoire, during which Nigeriens make clothes' hawking between cocoa producers and cities.

A random variable is introduced during the return trip of the migration campaign: every man has a "chance" of being racketed by the different custom services he meets, depending on the site he belongs (see Table 21). He thereby loses his entire gains.

[151] That can include the gains of the sale of a sheep owned by his wife!

[152] If the migrant candidate is the elder son in a family whatever the family organization, he must stay at home to perform the harvest with his father. Otherwise, he can escape this duty.

Coming back from seasonal migration & redistributing

To come back from migration, the migrant should overcome two constraints:

- First, all migrants are allowed to come back to the village at the start of the cultivation season. More precisely, the first rains appearing on a parcel owned by a migrant family are the signals for this migrant to come back. Either men come back during the rainy season (they can come back during all the duration of the rainy season) or they do not come back at all for this year and villagers have to wait for them until the year after.
- The second condition is linked to the pride of the migrant: coming back as a "winner", i.e. with a certain sum of money and gifts, is eminently important for prestige reasons. Bringing back an amount of money equivalent to his own needs for the following year and the price of a return ticket seems to be the minimum for returning home[153]. This value is therefore the minimum amount to be saved before returning home. If this has not been achieved, the migrant should retry the following year. Finally, the number of years of experience is recounted upon return to the village. Staying therefore two years in migration is thus counted as a sole year!

The redistribution of the migration gains depends upon the family organization. In the case of a unitary family, all the gains, including those of migration, come back in the hands of the Head of Family. In the case of a non-cooperative organization, a fraction of the gains are put back in the domestic common pot. This part (PEX) starts at 90% and is adjusted on the basis of the AntiClan tension indicator[154]:

$$PEX = 90 - (\text{AntiClan tension} / 10) \quad (41)$$

The amount of savings permitting the departure is therefore strongly linked to the AntiClan tension: the higher the tension, the earlier departures can be realized, the longer the exodant stays in migration, the higher his migration gains, the higher the AntiClan tension, etc.

4.5.4 Livestock rearing

Three livestock species are considered at all three territories: sheep, goats and cattle. No animal can be present in the territory without being appropriated by a villager[155]. These animals are born, live, graze or browse, reproduce and die. They can be bought, sold, given and slaughtered.

---

[153] For as long as the money does not stay in his pocket since it is redistributed and has therefore mainly a symbolic value.
[154] This rise has the same effects than for the gardening activity as described above.
[155] We have therefore not considered the transhumance passing on the "terroir".

Implementing the life cycles of livestock

Pastures

As described by Turner *et al.* (2005) and as noticed during investigations, there is a growing tendency in all sites of not herding sedentary herds, which means that in the present time situation, livestock graze along a free pasture process. Only fields and gardens are protected from their intrusions. Parcels are grazed by the three species of livestock. Only the parcels that are non-owned or owned but not used (cultivation or garden) can be grazed or browsed as indicated in Table 15. The three species[156] graze or browse differently:

- Caprines privilege the woody vegetation: at every time step, an adult caprine consumes a value of 1 on bushes of the cell. If it does have to move on another cell during this time step for searching pasturage, it only assimilates a value of 1 otherwise, it assimilates a value of 2.
- Sheep privilege the herbaceous vegetation: At every time step, an adult sheep consumes a value of 1 on the cell's herbaceous. If it does have to move on another cell during this time step for searching pasturage, it only assimilates a value of 1 otherwise, it assimilates a value of 2.
- Cattle privilege also the herbaceous vegetation: At every time step, an adult cattle consumes a value of 5 on the cell's herbaceous vegetation. If it does have to move on another cell during this time step for searching pasturage, it only assimilates a value of 5 otherwise, it assimilates a value of 10. Some cattle (dry animals i.e. non-pregnant & non-milking females, all males & heifers aged of at least 3 years-old except for maximum two oxen per family) can be sent for transhumance outside the territory (Bernus, 1994), meaning that they do not graze nor they manure any parcel. The transhumance period corresponds to the dry season, after consuming all the residues of the harvest, i.e. from the end of harvests on all the "terroir" to the next first rains (Turner *et al.*, 2005). During this transhumance time, the transhumant animals assimilate 10 per week meaning that they get fatter. Actually, it seems that the real advantages of transhumance is that herds do not pasture the resources of the "terroir" they belong, but also and mainly, they charge themselves with mineral nutrients (salt in particular) that have a very strong impact on their health, which we assume as having a feeding effect on their "paunch" (Barbier & Hazell, 2000; Hammel, 2000; Lycklama, 2000; Boutrais 2007).

Several animals can coexist on the same parcel and they can move on the whole allowed territory looking for interesting parcels according to their

[156] We consider that the youngsters (age < 52 weeks for cattle and 30 weeks for goats & sheep) do not graze or browse or have a negligible impact on vegetation and thereby, their presence does not increase the impact of their mothers.

"taste", by selecting the parcels in a perceived territory of 5-cells of range around them upon the indicator of woody or herbaceous vegetations according to their species.

Life and death of livestock

Every time a week, the "paunch" of an animal decreases with a value equal to its consumption (5 for bovines, 1 for the others). If the "paunch" sees its value under zero, the Livestock object dies.

The mortality rate is variable according to the age, the species and the "paunch" status of the animal. Values are defined according to Lesnoff (2005). Every time step, the animal sees this risk of death following a function MLy (t) to compare to a randomly generated value that is defined in a [0; 1] range. More MLy (t) is high; more the animal has odds to survive.

$$MLy (t) = (PLy/ PLmax) * (1 – ML) \quad (42)$$

With: PLy & PLmax: Each animal health status directly linked to its food status, i.e. the ratio between its "paunch" level P and the maximum value Pmax of it, that is of 30 times the weekly consumption: For cattle, it is thus of 150 and for the other species, it is of 30. In the end of the dry season, the PLy/PLmax ratio decreases dramatically, in particular for sheep (less grass in particular if all the lands are cultivated, small paunch). ML: the average mortality rate according to the age and the species as shown in Table 22:

Table 22. Average livestock mortality rate (Lesnoff, 2005).

The first year:	
For cattle, we consider 15% of mortality:	ML = 0.31%.
For caprines and ovines: 20 to 25% of mortality:	ML = 0.42%.
For an age within 1 and 10 years old:	
For cattle, we consider 10% of mortality:	ML = 0.19%.
For caprines and ovines: less than 5% of mortality:	ML = 0.06%.
For an age superior to 10 years old and for all species:	ML = 1.33%.

Reproduction & births

Females of all species can reproduce between the ages of 1 and 10 years. Animals reproduce according to their health status: Only females having a PL/PLmax ratio higher than 0.66 can have calves. We consider that every female in good health can calf every year: this average smoothes over the numerous twins and the sterile females by considering that one compensates the other (Lesnoff 2005). Therefore: Pl = 3/52. We have not considered as necessary the presence of a male reproductive animal, as villagers do not practice any selection and leave this role to the young males of different species. The duration of gestation is of 52 weeks for the cattle and 30 weeks for the others, including a first weaning period, where the calf does not graze or browse. The duration of milking is equal to the duration of gestation, during of which the mother and the baby do not leave for transhumance. After this period, the baby is considered as a fully weaned animal.

Implementing the uses of livestock

As seen in § 4.1.1, livestock and its uses are included into the calculation of inter-family reputation. Meanwhile, it serves as savings for the various gains.

Buying and selling livestock

For any adult Villager, buying animals is conditioned by the existence of a millet stock big enough to feed its Dependants during at least a half-year. Women can buy small ruminants, preferentially an ewe and if not a she-goat. Men buy preferentially cattle, and if not possible a sheep and if not, a goat, and preferentially female ones. Meanwhile, the heads of family try as soon as possible to always have in their herd a male sheep in forecasting of feasts and other social obligations. They first privilege this purchase. Outside of this social function, villagers privilege the purchase of females. Villagers can sell animals in three opportunities, bound to a social necessity:

- When demands of the Dependents of a Villager exceed its stocks in millet or in cash terms, this Villager sells an animal for a sum that permits to respond to these demands. It privileges in the sale, firstly caprines, then, if that is not enough, sheep then cattle.
- When a social event requires the sacrifice of an animal (preferentially a sheep), a Villager can sell a goat to complete the necessary sum to the purchase of this animal.
- When family capitation taxes have to be paid.

Males are sold preferentially. Animal prices are related to the class of age and the species, according to Table 23.

Table 23. Livestock prices (in €)

Age of the animal	Bovine	Ovine [1]	Caprine
0-1 year-old	30.5	Ovine Price / 4	6.7
1 –8 year-old (male)	146.4	Ovine Price * 1.2	22.9
1 – 8 year-old (female)	122	Ovine Price	27.5
8 – 10 year-old		Ovine Price * 0.8	18.3
8 – 12 year-old	97.6		
> 10 year-old		Ovine Price * 0.5	11.5
> 12 year-old	61		

[1] The price of sheep also varies along the year, according to the time of the Tabaski[157]: Until 13 weeks before the feast date, prices stays at an average value of 15 kFCFA (22.9 €) to be corrected by a factor indicated in this Table. During the last 13 weeks, prices rise from 20 kFCFA (30.48 €) until 35 kFCFA (53.38 €), meaning that the increase is (30.48 /13) € per week.

[157] Aïd-el-kebir or Aïd-el-Kebch: the main religious ceremonies of the Muslim calendar. Its date is based on lunar months and thereby comes every year 10 days on average in advance comparing with the previous year. The next decade will be characterized on a "Sahelian" point of view by the fact that the feast will come in the period between harvesting time and migration time.

Livestock rising is thus annually accounted as the difference between the total value of the herd of the year and the one of the previous year.

The implemented social role of the livestock

They are accounted in the calculation of the individual reputation, as representative of the family and individual wealth of the Villager. They can also be given, solely for the majority of a child by his/her family head, provided that families already have some (there is no animal purchase for such occasions). If it is a boy, he receive an ewe or if not, a ram otherwise, a she-goat otherwise, a he-goat otherwise, nothing. For girls, the hierarchy goes as follows: she-goat > he-goat and otherwise, nothing. They are slaughtered at three occasions: births, marriages and the Tabaski. Villagers sacrifices males preferentially: a ram and by default a he-goat. Their sacrifice gives reputation points to the owner who by then has fulfilled his social duties (the father for births, the bridegroom for marriages, the Head of Family for the Tabaski).

5 Assessing scenarios with SimSahel

Here we present the different scenarios that are implemented on the model base and that are used for comparison purposes in the next chapters. These are also the bases for the confidence building steps in § 6.3.

5.1 Assessing scenarios on family organizations

The purpose of chapter 4 is to compare the outputs of two scenarios, each one ruled by one family organization type as presented in § 4.4.2.2, in the site of Fakara only. The family organizations are implemented in the three different sites in chapter 5 according to present-time observations and as described in Table 7. The chapter 6 presents a mode of transition between these two family organizations in the three sites, considering that the simulated history of all sites begins with the unitary family organization.

5.2 Assessing scenarios on development actions

These scenarios are implemented only for chapter 5. They combine two parameter variations, i.e. presence of development actions and the nature of the social "currency" in the village.

The two development actions, i.e. warrantage and inorganic fertilizers, are here implemented. The success of a development action is not defined by its very characteristics but results from the villagers' perception of this action, whatever its intrinsic quality. The factors and constraints selected for implementation in the model are thus defined on the basis of the villagers' perception as the ones that determine the interest in the development actions and as observed during field investigations. The model is not based on the binary relationship between a villager and the project but includes the project actions as a component of the pattern of activities of a villager Agent. Warrantage and inorganic fertilizers are proposed to villagers at t=0. For each adult married villager, choosing to be involved in one of the actions is the only cognitive function of the model: it is based on a gain comparison with or without using the action.

The gain comparison depends on the chosen "currency" that is used for this cognitive function: The gain is based on food & income stock in the "economy" scenario and reputation in the "reputation" scenario, with the reputation defined as in § 2.4.1 and as implemented in § 3.6.1.2. In case of no experience, each adult villager Agent who manages millet fields or gardens tries the action type for the coming year.

5.2.1 Warrantage

Inventory credit choices are made after the harvest. As a saving choice, the first step is to determine if the Agent (i.e. the head of the family or, if absent, the highest ranked adult) has the capacity for saving. It means that we consider that every villager relies on the necessity to keep at least enough millet for half a year for all the family members who rely on him/her:

$$SM_{fi}(t) > CA_{di}(t) / 2 \qquad (43)$$

With: di: the number of family members of i relying on i at t; SM_{fi} (t): i family millet stock at t; CA_{di} (t): annual food consumption of the dependents di;

The second step is then a cognitive decision based on personal experience, through a comparison of the mean gain between past years with saving through warrantage and past years with no savings or with saving through livestock:

$$W_i(t-1) + X_{fi}(t) > NW_i(t-1) + Y_{fi}(t) \qquad (44)$$

With: W_i (t-1): the total value of the previous years with warrantage; NWi (t-1): the total value of the previous years without warrantage;

- If warrantage was used the last year [t-52; t]: X_{fi} (t): the total "gain" of the family of the last year [t-52; t], including the difference in cash of the value of the livestock between t-52 and t. The "gain" is either "reputation" in the reputation scenario or "income" in the economy scenario; Y_{fi} (t) = 0.
- If warrantage was not used the last year [t-52; t]: X_{fi} (t) = 0; Y_{fi} (t): the total "gain" of the family of the last year [t-52; t], including the difference in cash of the value of the livestock between t-52 and t.

Warrantage is in our case a financial transaction: selling millet through this action type allows buying its own inorganic fertilizers at the same price (majoring a 0.15 € per bag for shelf stocking) than it was sold.

5.2.2 Inorganic fertilizers

Inorganic fertilizers applications are possible throughout the millet-cropping season. Only millet field or garden managers can buy inorganic fertilizers. The price of the bag of inorganic fertilizers is 50 kFCFA, i.e. 75 €. According to the microdose recommendations (Abdoulaye & Sanders, 2005), 0.2 bags of inorganic fertilizer are poured on one parcel of 1 ha, meaning that fertilizing one cell in the model cost 10 kFCFA, i.e. 15 €. Gardens need 10 times this value, meaning that, because we consider that one garden is one tenth of a cell (see § 4.5.2), fertilizing a garden also cost 15 €. As a production choice, the first step is to determine if the Agent has the financial ability to afford some inorganic fertilizers. Setting aside at least enough millet and/or cash for half a year requirements for him/herself and its dependants, the ability depends on whether or not the value of the family's millet and cash stock exceeds the inorganic fertilizers needs[158]. The capacity is defined as follows:

$$SM_{fi}\,(t) + SC_{fi}\,(t) > NF_i\,(t) \qquad (45)$$

With: SM_{fi} (t): millet stock of the family i; SC_{fi} (t): cash stock of the family i; NF_i (t): inorganic fertilizers needs based on the property which had a better mean production with inorganic fertilizers than without.

The second step is also a cognitive decision based on personal experience, through a comparison of the mean gain from past years with and without inorganic fertilizers, similar to that used for warrantage.

Inorganic fertilizers impact start from their application. They have several effects on millet depending on the crop development (sowing, sowing, maturation and harvest stages). During the maturation stage, there is a risk of 1% per week to lose the harvest in fertilized fields because of the chemical burnt it can occurs (de Rouw, 2004; Koning & Smaling, 2005).

[158] We have eliminated the use of livestock as a potential cash source to buy fertilizers, as we never observed anybody selling animals to buy fertilizers in any case. This is consistent with the general assumption that animals should be considered as savings or speculation products but not as a source for productivity increase investment

5.3 Family evolutions with social pressures

The complex structure of Nigerien farming systems cannot be considered as "traditional" but as the result of political and historical stakes. Therefore, modeling a village society and its related farming system must be temporally based and determined not by the present-time situation but by the initial conditions, i.e. the foundation of the village.

The two related transition processes are implemented only for chapter 6. As presented in chapter 1, the rural Nigerien areas during the 19th century were under the threat of pillage and slave raids, forcing villages to regroup themselves under protective chieftains. As a consequence, we consider that a century ago, the populations of the three sites were in majority organized according to the unitary family mode, as described in § 4.4.2.2, and that the inheritance system was based on the "customary" model, as described in § 4.4.2.1. The two types of family organizations are differentiated according to Table 18.

5.3.1 Family disintegration with declining economic hierarchy.

Our first implemented transition process considers that the family organization has exploded along this 20th century. This was introduced in the model by building a family attribute called "antiClan tension" or Tac, initially equal to zero at the family creation step. It then evolves according to two effects. For all the adult family members who are not family heads or first heirs, having to give back part of the gain generated in the activity of which he/she was the manager (migrant coming back from migration, gardener bringing back the gains from his/her garden), in the hands of the family head increases the Tac. Tac also rises at every new land extension (as shown by ¤ on Figure 20), underlining the impact of this extension in the explosion of families[159]. In the two cases, the evolution is simulated as follows: for each event having an impact as described above:

$$Tac\ (t+1) = Tac\ (t) + 5 \qquad (46)$$

The family can shift from the unitary mode towards the non-cooperative one if: $Tac\ (t) > 100 * MoF\ (t)$ (47)

[159] Nearly all the villages where local history was investigated have witnessed a conflict between brothers or cousins within the "reigning" family during the 20's to 40's era. A possibility to settle alone on empty lands can be considered as a permanent attraction for villagers; we included this attraction at family level because more lands because of field expansion means more economic power of the family head and more work for the members of the family while they may get this new land for themselves.

If this condition is met, the marriage of a young groom means leaving his family and create his own on newly occupied lands. This new family has its own initial value Tac equal to 0 as an initially unitary family. A part of the gains stays in the hand of production activity managers and food distribution processes within the family are shortened but weakened as described in Table 18.

5.3.2 Inheritance evolution with growing tenure constraints

The second transition process considers that the land availability constraint, growing with the difficulty of finding new lands, brings a growing "frustration" of the non-heirs. This frustration is simulated through a family attribute called "land tenure tension" Tf, initially equal to zero at the family creation, that evolves at every failure in the search of new empty lands (**on Figure 20), as follows: $Tf\ (t+1) = Tf\ (t) + 5$. (48)
This value can grow rapidly according to the number of attempts: more the family is big and grows rapidly, more this Tf value increase quickly. The family can adopt a "Muslim" inheritance mode if:
$Tf\ (t) > 200 * MoF\ (t)$ (49)
This procedure takes effect only after the death of the head of the family. It then imposes the sharing of lands and of livestock according to this local version of the "Muslim" rules, i.e. all fields are equally shared between the male heirs of the head of the family (brothers and sons) while livestock is shared between male heirs for two thirds and female heirs for one third.

6 Validation and confidence building

6.1 The problem of empirical model validation

As described by Bonaudo (2005) and Amblard *et al.* (2006), there is no absolute validation of a model. As Popper (1985) said, a theory and therefore a model are valid as long as one has not proved the opposite. Therefore, a model may be temporarily accepted if it simulates well certain dynamics in a certain domain of validity. This model validation, i.e. tests of comparison with some exterior data and tests of robustness by changing parameters of the model, corresponds here to a "confidence building" approach. We have therefore compared several model collective results with data from other studies and methods, as described in Chapter 3§6.

Finally, the major problem of this empirical approach is that it is virtually impossible to validate with a complete sensitivity analysis. The model is limited by the time that every simulation takes, one & a half to three hours for a 60-year simulation, eight to twenty-four hours for a 100-year simulation. It is from then on impossible to elaborate a real sensitivity analysis to define and discriminate the impact of every factor, because it would mean for about 50 parameters and a minimum of two degrees of liberty 250 simulations! As noticed by Amblard *et al.* (2006), it is from then on desirable to proceed to regroupings of variables to decrease the number of simulations to make. However, this number will remain very high. A comprehensive sensitivity analysis requires a prior setting up of an experimental plan.

6.2 Testing the sensitivity of selected parameters

We have tested variations of six parameters chosen to belong to three different categories (biophysical, economic & social). These tests are done on the average site of the Fakara during two human generations, i.e. 60 years = 3120 time steps using as reference the parameterization used for the simulations presented in chapter 6. Two biophysical parameters from the literature are tested (the drought factor and the livestock), the four others were derived from our own investigations.

The first two of these latter factors concern external production activity-related parameters that influence the behavior of the villagers (the migration cost and the inorganic fertilizer price) and the last two relate to internal parameters of the villages' society (the marriage cost and the inheritance transition speed). These four factors may also be differentiated between two factors describing the structure of these societies (the migration and the marriage costs) and the other two that drive our scenario hypotheses (the inorganic fertilizer price and the land tenure tension).

Twenty simulations of each situation are carried out and the mean results at the end of the simulations are shown in Figure 22. The six output variables are chosen because of their impact on the model system. The significance of the results is tested with a variance analysis (ANOVA) at 95% of significance, using MATLAB© (the standard errors are not shown on the figures for clarity purposes). The factors' variations occur at the beginning of each simulation.

The results show that the two biophysical factors originated from the literature have important effects:

- Livestock reproduction variations around the parameterized value of 3/52 per week (see § 4.4.4.1.3, Figure 22a) have obviously a large effect on the number of animals. However, increasing the number of livestock has virtually no impact on any of the other factors except a limited but significant decrease of the vegetation. This lack of effect is because most of this additional livestock is based on cattle leaving the "terroir" for transhumance during 9 months each year. Reducing the size of the livestock herd results in improved vegetation and, to a lesser extent, soil fertility. Moreover, a livestock decrease reduces the number of families, which can be explained by a slowing down of the rate of marriages because of a reduced access to the savings for dowries.

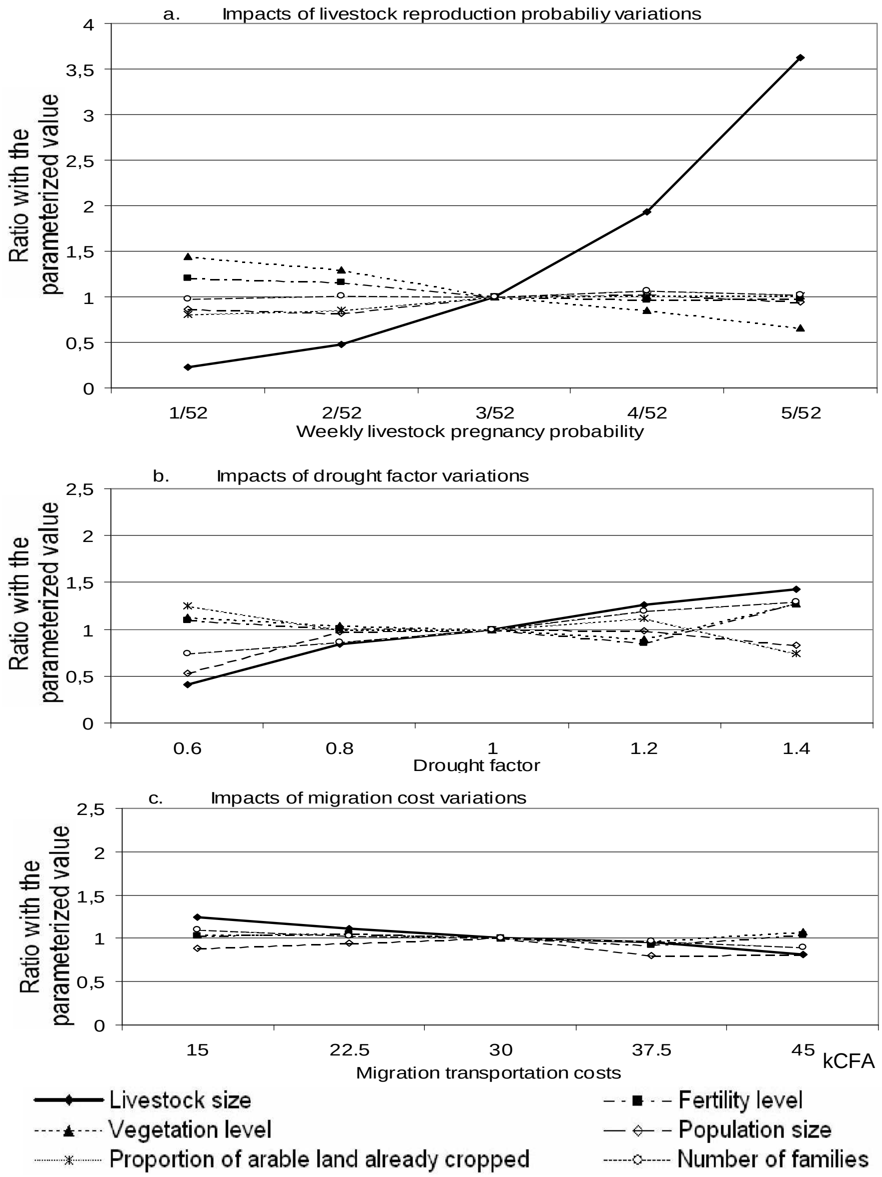


Figure 22 (Part 1). Results of the sensitivity tests on several selected parameters

- Testing different values of the drought factor around its value of 1, corresponding to the range of values used for parameterizing the three different sites, has significant effects on all the tested variables (see § 4.2.1, Figure 22b): livestock and the number of families continuously increase, whereas the population growth and thereby the cropped arable land growth first increase then decrease as the rainy season becomes wetter: this latter phenomenon is due to family-related transitional factors as described in chapter 6. A densely populated environment induces a lot of families to orient themselves towards external activities (migration), whatever the quality of the local environment. Environmental factors seem paradoxically not to be significantly affected: actually, a drought of 0.6 (equivalent to the Zermou site) reduces agricultural activities to the benefit of migration and livestock keeping activities, thereby reducing the impact of human activities on the resources of the "terroir". On the other hand, a high drought factor, meaning a wetter environment, highly increases the two environmental indicators (vegetation & fertility).
- In Figure 22c, migration costs were varied around the value of 30 KFCFA (~45€): such variations have no significant impact on global vegetation and fertility levels because of the importance of the transhumant herd as in the drought factor test. The livestock herd size and the number of families decrease significantly with migration cost: the easier to migrate, the more migrants can save money through livestock and the more easily they can get married. The population level reaches a peak around the mean value of 30 KFCFA. We can suppose that it is due to two effects: the easier it is to migrate, the more migrants stay abroad, thereby reducing their time in the village having babies (their presence is necessary in the model for women to get pregnant). On the other hand, the more it is difficult to migrate, the more it is difficult to get married and have children as well. Therefore, the cultivated land proportion is not significantly affected: the more it is difficult to migrate, the more the population crop thereby compensating for the reduction of the population and of the number of families.

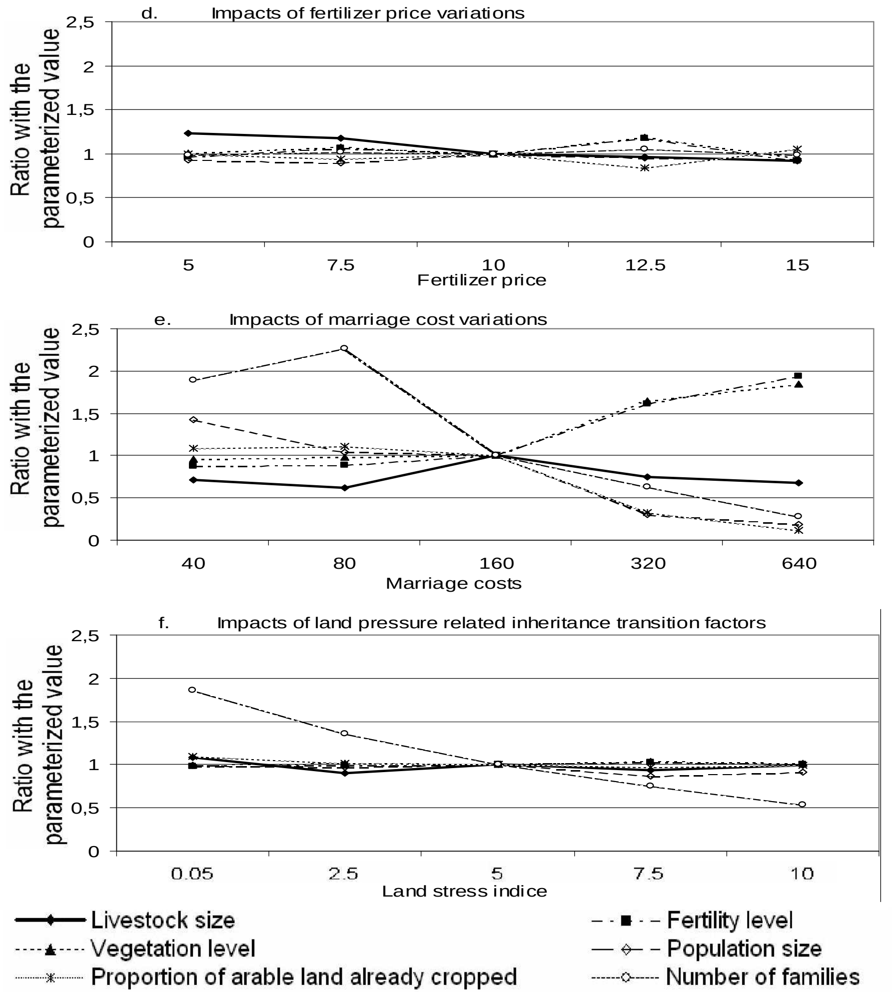


Figure 22 (Part 2). Results of the sensitivity tests on several selected parameters

- Figure 22d shows the impact of inorganic fertilizer price variations around the parameterized value of 10 kFCFA (~15€). The variability of the annual yield at the village and the family head level seems to be so high that changes in fertilizer price have no significant impact on five of the tested parameters. Only the livestock numbers increase significantly when fertilizer price is very low. In this case, the villagers appear to save as much grain yield as possible by buying as much livestock as possible (the major part of the additional livestock is due to an increase of the livestock purchases).
- Figure 22e shows the impact of marriage cost variations around the parameterized value of 160 kFCFA (~240€). Whereas a reduction of

this value has no impact on fertility and vegetation as well as on the arable land proportion, the population is significantly increased in the 40 kFCFA case. At the same time, the family number is doubled and the herd size is lowered. Actually, the reduction of the marriage costs allows a lot of youngsters to get married. Consequently, the proportion of small families increases, thereby reducing the saving capacity to invest in cattle.

- Finally, the last figure (Figure 22f) shows the impact on the same indicators of land pressure-related inheritance transition factor variations around the parameterized value of 5. Only one indicator is significantly affected by the evolution of this factor in this context: for very low values of the factor (1% of the parameterized value), the number of families obviously grows reaching the double of its value at the current parameterized level.

As a partial conclusion, one may note that the more the parameters we selected come from the literature and belong to biophysical disciplines, the more they affect the system. Actually, they condition so strongly the system structure that they create in fact new environments and contexts. Other parameters do have an effect on only some parts of the system.

Considering these sensitivity test results, this model can be considered as quite well constrained by the different parameters of its structure. The model is not very sensitive to changes on the considered parameters, meaning that differences in simulation outputs between scenarios are meaningful.

6.3 Confidence building

6.3.1 Comparing simulation outputs based on the two family organization types with external data

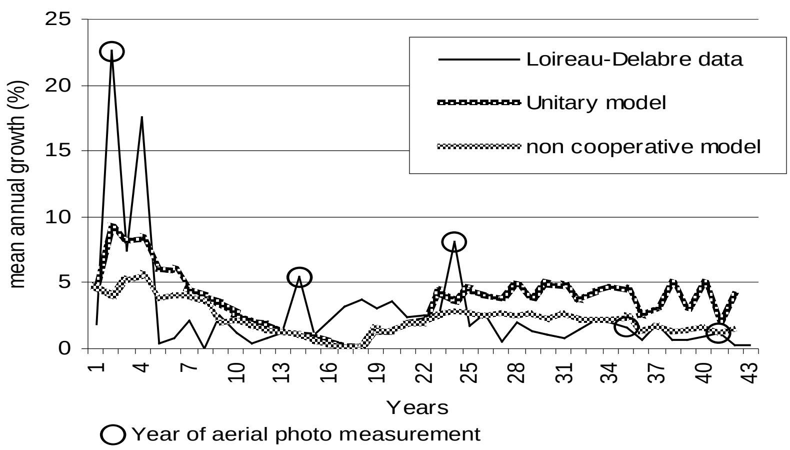
This confidence building is carried out by comparing simulation outputs of two scenarios for the site of Fakara as described in chapter 4. For each scenario, fifteen simulations were run for a period of sixty years (i.e., two generations) each of 3120 time steps. The two scenarios, each one with one family organization as described in 5.1, are compared to each other and with literature data:

- The collective non-cooperative family hereafter referred to as the scenario with a Non Cooperative Family Structure (NCFS).
- The Unitary concept of the enlarged family hereafter referred to as the scenario with a Unitary Family Structure (UFS).

The two scenarios lead to different population growth rates, from 50 inhabitants at the beginning to 472 inhabitants (± 240) for the UFS (average growth rate of 3,91% per year), and to 176 inhabitants (± 81) for the NCFS (2,19% per year). The General Census of Niger reports growth rates of

3,44% per year over the 1977-1988 period and 2,75% per year over the 1988-2001 period for the Tillabery region but, within this region, 2,3% per year for the Kollo department, which includes the Fakara. Assuming that one has evolved in reality from a dominant UFS type to a dominant NCFS, then we may consider that the model has correctly simulated the demographic growth and the impact of the family organization on this growth.

Loireau-Delabre (1998) being currently the best reference on the Fakara recent history, we compare the evolution of the acreage of cultivated fields that she simulated and the model simulation results (Figure 23).



Year 1 of simulation = 1950 for Loireau-Delabre data (Round symbols correspond to the years for which aerial photographs were available).

Mean annual cropland growth rate	Loireau-Delabre data	Non cooperative Family Structure	Unitary Family Structure
All years	2,22% per year	2,32% per year	3,68 % per year
First period (1950-1972)	3,91% per year	2,45 % per year	3,35 % per year
Second period (1973-1993)	1,65% per year	2,18% per year	4,03 % per year

Figure 23. Comparison of the annual growth rate of cultivated land for the two scenarios simulation outputs and interpolated data from (Loireau-Delabre 1998).

Her acreage is derived from five aerial photo interpolations (1950, 1965, 1975, 1985, 1992), combined with demographic data from the national Census and village demographic trends from Guenguant (these latter results were afterwards published in Guenguant *et al.* (2002). The Loireau-Delabre results for the first 20-year period show a similar cultivated surface growth rate than the one from the UFS simulation results, with a value higher than 3% per year. For the next 20-year period, the Loireau-Delabre results show a decrease of this rate that corresponds better with the simulation results of the NCFS, with values around 2% per year, whereas the UFS scenario results in an acceleration of this cropland expansion.

Loireau-Delabre explains the observed decrease with the lack of potential arable land. However, in the simulations, this explanation does not hold as people still have a lot of land available by the end of the simulation period. In the NCFS, social constraints explain the decrease in population growth because of the lack of support for the creation of new families. This constraint was implemented based on the results of our investigations: one can nowadays observe a clear lack of solidarity for some particularly poor families, with little land and/or manpower and/or having suffered low crop yields recently. We therefore can suppose that such families are only precursors of the future, when land constraints will be stronger and generalized, as Yamba (2004) described it for the Maradi region.

6.3.2 Comparing simulation outputs based on the two project actions with external data

This second confidence-building test is carried out by comparing simulation outputs of two scenarios with available data for the same site of Fakara. The two scenarios are based on development actions as described in §5.2 and implemented in chapter 5. These scenarios are combined with the two "currency" possibilities, i.e. money or reputation as described in §3.6.1:

- A scenario where warrantage and fertilizer availability are proposed to villagers with either money as the currency hereafter named FEFW (Fakara Economy Fertilizer + Warrantage) or with reputation as the currency, named FRFW (Fakara Reputation Fertilizer + Warrantage).
- A scenario where none of such development proposals are implemented for the villager Agents with either money as the currency, hereafter named FEC (Fakara Economy Control) or with reputation as the currency, hereafter named FRC (Fakara Reputation Control).

For each scenario and site, thirty simulations were run for a period of sixty years (i.e. two generations). To acquire some confidence in the model, we compared the simulated production assets from the four scenarios with available data for the Fakara site (Table 24).

Data reported by different authors are actually highly variable among each other[160], particularly regarding herds. Our field results are consistent with data from the three authors, i.e. the results fall within their range. The difference between our field and simulation outputs is that, thanks to our hypotheses, we have corrected the probable interview biases of overestimating the proportion of enlarged families and underestimating the child manpower. Concerning our simulation outputs, livestock distribution and size fit better with observations of Loireau-Delabre (1998) and

---

[160] They are even more variable than our simulation outputs from different scenarios.

Abdoulaye (2002) whereas the other simulated factors (family size, family manpower and proportion of the "terroir" corralled with livestock) fit better with La Rovere (2001).
We suppose that the bigger livestock herd in our simulation outputs reveals the importance of the "transhumant offshore cattle savings" that may be omitted by interviewees. The lower family size in our simulation outputs reveals the proportion of small families that are usually less often interviewed. Finally, the higher manpower level in proportion of the family size in our simulation outputs is due to the inclusion of the child manpower but also to the fact that we considered that women and men have the same FLU.

Table 24. Comparison between the four Fakara scenario simulation outputs and external available data

FAKARA without projects	Family size	Family manpower (in FLU)	Average livestock owned per family			% Area corralled with livestock	Household Sample size
			Cattle	Goats	Sheep		
Loireau-Delabre, 1998; Zarma villagers only	9,1	6,8	1,3	2,1		36,9	221
La Rovere, 2001 p.47/ Zarma villagers only	8,6	4,8	0,7	0,1	0,1	10,2	366
Abdoulaye, 2002	NA	7	3	4		NA	100
Own field results	8,2	5,2	2,0	1,41	0,2	NA	67
FRC (simulated)	7,2 ± 0,2	5,7 ± 0,5	3,4	1,17	0,2	8,9	NR
FEC (simulated)	7,1 ± 0,2	5,4 ± 0,5	3,2	0,93	0,3	15,4	NR
FRFW (simulated)	6,9 ± 0,2	5,6 ±0,5	2,8	1,37	0,5	10,4	NR
FEFW (simulated)	7,0 ± 0,2	5,6 ± 0,4	2,4	0,80	0,5	8,1	NR

FLU: Farming Labor Unit; NA: no data available. NR: not relevant

As a conclusion of this last section, the model appears fairly robust regarding several parameterized crucial indicators and sensitive enough regarding several literature-originated indicators. The confidence building steps show that the model reasonably reproduces the dynamics of local situations. However, the latter steps have also shown the difficulty to obtain "real" figures: the three authors we cited above obtained very different figures for crucial parameters. Such differences may be due to the inherent effect of the interview processes, the issues and the methodology. Thanks to its empirical approach and its balanced conception between sociology and agro-ecology, as long as the model is used to simulate rural societies of the Nigerien Sahel and to test scenarios based on reliable theories and conceptions about the same geographical and sociological context, it is believed that this tool can be used to estimate the relative "weight" and power of the various considered factors. Therefore, the model should be considered as an efficient "trend provider" but not as an "absolute figure provider".

CHAPTER IV: IMPACTS OF FAMILY ORGANIZATION IN SAHELIAN RURAL MULTI-ACTIVITY SYSTEMS: THE CASE OF FAKARA, NIGER

Note: This chapter is adapted from a text accepted with major revisions for publication in 2007 in Agricultural systems and still under reviewing (Saqalli M., Gérard B., Bielders C., Defourny P. Assessing the impacts of family organization in Sahelian rural multi-activity systems using an empirical Agent-based model: A case study from Fakara, Niger"). A first version of the text was presented at the 6th Conférence Francophone "Modélisation, Optimisation & Simulation des Systèmes: Défis & Opportunités" (April 2006).

1 Abstract

The complexity of family organization and the diversity of income sources are often neglected while analyzing development issues in Africa. The purpose of this research is to analyze the impacts of this complexity on income and sustainability in the case of farming systems in villages of Sahelian south western Niger, where rains are low and irregular, soils are poor and social relationships are vital. An individual-centered agent-based model (ABM) combining different scientific disciplines is used to evaluate the consequences of two types of family structures as identified during field investigations: a unitary family structure (UFS), where families remain enlarged, under the rule of a patriarch, and a non cooperative family structure (NCFS), where families are mononuclear and not decision-centered. Multiple sources of income (millet farming, migration and gardening) are explicitly taken into account. Long-term simulation results show that family organization has strong effects on income levels and distribution amongst villagers, but also on demographic growth: no support from parents in the NCFS forces young unmarried males to postpone their weddings. Even if millet farming still remains the main source of income, gardening and migration are necessary to bridge the gap until the next harvest. In the NCFS, resilience is greater partly because of a greater

proportion of income is derived from activities other than farming. Results suggest that the UFS, which is the most dominant in southern Soudanian environments, is a more productive "version" of the system but also a more fragile one in Sahelian conditions. The NCFS fits better with recent demographic growth and cropland growth data whereas the UFS fits better to 1950 to 1980 data. One can then suggest a historic shift for that particular society from a dominant unitary mode to a non-cooperative one, as it occurred for more densely populated sites in southern Niger.

Key words: Sahel, family organizations, Agent-based simulation, social criteria

2 Introduction

Since the 1960s and independence, rural societies in Sahelian West Africa have reacted in a very limited way to agriculture programs supported by development agencies. The poor relevance of development aid strategies with regard to the socio-economic environment is often pointed out as a major cause of this low impact. Many development programs have underestimated several socio-economic factors (Biershenk *et al.*, 2000):

- Villages were considered as almost closed systems in which pearl millet cropping constitutes the quasi-unique economic activity, other local activities are viewed as minor complements and off-farm activities are merely indicators of an overall degradation in living conditions. Improvement of grain yields per unit of surface is therefore often considered as the only way for productivity increase of these farming systems while manpower productivity is neglected (Koning & Smaling, 2005). However, the period from the 20's until the 90's was for Niger a period of fields extension in a quite empty territory, meaning that the most limiting resource was labor rather than land (Yamba 2004). Moreover, multi-activity is a structural characteristic of these societies (Paul *et al.*, 2003). Milleville (1989a) noticed: "In many cases, agricultural production systems constitute only components of a broader rural or peasant strategies; the latter extend beyond not only agricultural activities but also the geographic local area". Therefore, farming systems cannot be understood without making reference to a "system of activities" Lavigne-Delville, 1999) where agricultural productions are part of a palette of activities, spread out along the year and gender specific (Mazzucato & Niemeijer, 2001).
- The "household" is viewed as the main economic, production and consumption unit (Gastellu & Dubois, 1997). However, the point is not obvious: Gastellu (1980) raised the issue of the valid analysis unit as far back as 1980. Several units were proposed for Sahelian Africa, each one having its own limitations when it comes to defining a holistic unit,

> based either on domestic criteria (temporary or permanent residence, or consumption, also called the "pot unit"), or economic criteria. The latter is confronted with the complexity of overlapping modes of conditional ownership, uses (production, consumption, accumulation) and transmissibility of production means (Lambert & Sindzingre, 1995; Lazarev & Arab, 2000). The definition of these units is also constrained by the plurality of the objectives and strategies of the different family members. Whichever way the family unit is defined, there will be inconsistencies and exceptions (Vaugelade, 1997).

Development operators may continue to encounter difficulties in their approaches of local realities: While many development agents and researchers postulates the large household as the main local human unit, inducing to work only with the head of the household, one may observe locally the importance of the youngsters within families and the large proportion of mono nuclear families. In a development-oriented purpose, we propose to discuss and redefine the nature and the organization of the family as the main unit to use in economic calculations for local development project planning.

The objective of the present research is therefore to investigate the impacts of family organization on family economic activities and the resilience of such families along generations, explicitly considering multiple sources of income. More specifically, the research question is to assess through a modeling approach the consequences of the interactions between individual strategies within a family as affected by family structure. These interactions are not necessarily coherent among themselves but not necessarily antagonistic either. Two family structures are then compared:

- A collective non-cooperative family, which is nowadays the most common in the study region (Abdoulaye, 2002 p. 23), and referred to as the Non Cooperative Family Structure (NCFS). They constitute 76% of the families of our sample.
- A unitary concept of the enlarged family, still the main concept of African families as used by development agencies, hereafter referred to as the Unitary Family Structure (UFS).

We position this work in the economics debate between unitary structures and collective non cooperative ones (Radja, 2003; Donni, 2004): the latter correspond to a multi-decision family organization where there is a collective organization but not based on a cooperation efficiency as defined by Pareto (Sen, 1983 in Meignel, 1997); for instance elders and males are typically favored.

Different modeling approaches have been used to analyze social and economic questions of the rural world as reviewed by Lambin *et al.* (2000). Agent Based Models (ABMs) were found particularly useful for simulating the multi-disciplinary approach of a multi-sectorial reality (Berger, 2001). For instance, a recent article presents an ABM for a Sahelian environment focus on a Senegalese site forage production and by then its carrying capacity, with population activities (farming and livestock keeping) and rainfalls as the main variables (Bah *et al.*, 2006). In the present study, the object of our modeling is the population itself and factors affecting it.

The whole methodology of the model development is described in chapter 3. More precisely, the assessment of the scenarios that are here compared is fully described in § 5.1 of this chapter 3.

3 Results & discussion

For each scenario, fifteen simulations were run for a period of sixty years (i.e., two generations) each of 3120 time steps. Simulation outputs were obtained for the entire village, at family level and at gender and age group levels. The various orientations towards the different economic activities are firstly discussed, in order to analyze thereafter their impacts on the social resilience of the related village societies, i.e. their wealth situations and inequalities, but also their environmental resilience, i.e. the situation of the local affected natural resources.

Comparing village level simulation results and available data, i.e. our macro level field investigation results, literature review and the Niger national census, confirmed the consistency of the model and served as a confidence building exercise. Analyzing the effects of a multi-decision family organization was then carried out through a comparison between the simulation outputs of the two family structure scenarios we proposed. We indicate in the following parts of the text the simulated entities by capital letters to avoid confusion between simulated outputs and observed behaviors.

3.1 Millet farming as a basis, others as necessary activities

Simulation output shows that gardening practice is strongly affected in both scenarios by the generation effect (Figure 24):
Available female manpower is a constraint that can be fulfilled only after a dozen years of simulation. Beyond this generation aspect, one can note that this activity spreads less rapidly or even decreases in the UFS: stepdaughters always stay in the family of their mothers-in-law in this scenario and

because they must work for them, they cannot start their own garden even if their own manpower conditions are fulfilled. In the NCFS, the splitting of the population into many small families makes it possible for many female adult Agents to garden, but only when they are old enough. As a result, the generation factor is a strong constraint for female adult Agents in the UFS whereas the number of female gardeners increases rapidly in the NCFS.

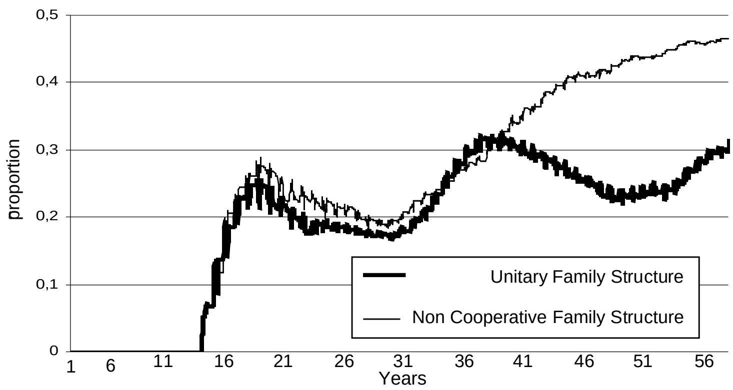


Figure 24. Simulation outputs for the proportion of female Gardeners

For both family structures, simulations show that the proportion of male adult Agents leaving for migration remains quite constant, around 50% (Figure 25).

Between the 20th and the 45th year of simulation, a lot of young second generation families are created but their children are not yet adult. In the NCFS, male adult Agents in these families must stay longer in the village, at least until the pearl millet harvest, as they are alone to do the work in their fields and with nobody else to ask for help. This explains the dip that one can observe in the proportion of migrants during that period, represented by the two annual maximum value curves corresponding to the two scenarios. On the other hand, in both scenarios, annual minimum value curves showed that a certain proportion of male adult Agents remains abroad for an entire year at least once (see the * on Figure 25): these are the ones who are too inexperienced to bring back enough money at the end of the dry season, particularly in the NCFS where no family help can compensate this loss.

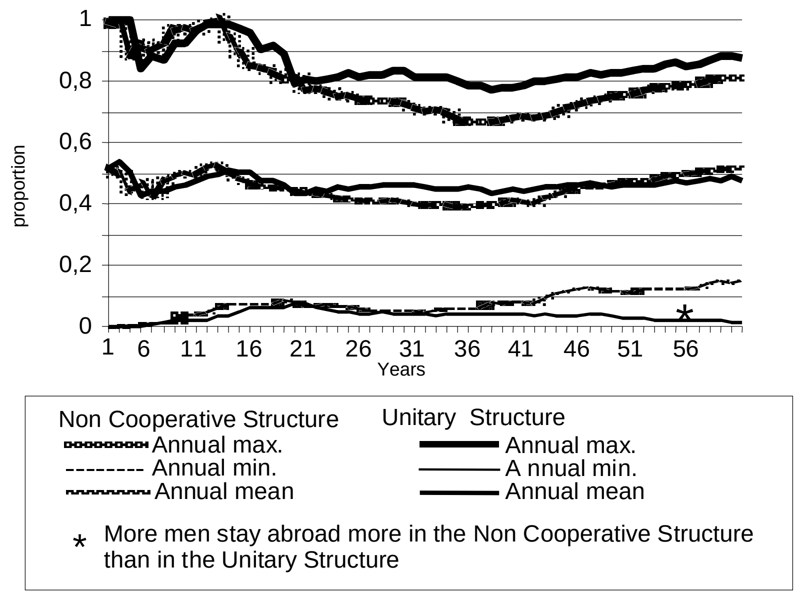


Figure 25. Simulation outputs for the proportion of male Migrants

The need to stay for more than one dry season abroad is reinforced by the fact that the essential condition of access to land is marriage. From then on, the number of migrants who stay abroad more than one dry season increases with the number of young Adults. The male average age for marriage is 17,4 years (± 0,3) for the UFS and 20,6 years (±1,1) for the NCFS. Thus, the rule we proposed about an anticipated departure during the cropping season for youngsters has little effect in the NCFS. Because male adult Agents quickly take their independence in this scenario, this rule plays only during the short time the young male adult Agent is still unmarried because he has not accumulated enough money yet. One can consider that this is the last resort of a father to force a son to work in his fields when he cannot afford or does not want to pay his son's wedding costs. Married male adult Agents leave for migration but they stay abroad for a shorter time (25.4 weeks vs. 38.7 weeks for the bachelors in the UFS; 31.7 weeks vs. 40.2 weeks in the NCFS). Finally, because of the migration delay effect on marriage in the NCFS, the total population increases more rapidly in the UFS, reaching an average value of 497± 275 while NCFS has an average value of 178± 47.

As indicated in Table 25, simulated activities represent very different proportions in the villager Agents' income: in the UFS the proportion of total income derived from pearl millet agriculture is more important, because of migration and marriage rules. On an annual basis, the sequential organization of activities (gardening then agriculture, followed by migration with some overlapping) is an incontestable advantage for the populations' survival in both scenarios.

Table 25. Simulated outputs for the two family structure scenarios showing part of each activity in villagers incomes

	Pearl millet cropping	Seasonal migration	Gardening
Unitary family structure	86,2%	11,7%	2,1%
Non cooperative family structure	80,3%	16,9%	2,8%

Figure 26 presents an example of a yearly distribution (year of simulation = 50) of these sources of income in the UFS. Thus, in term of economic activity setting up, leaving the management of all the assets in the hands of the head of the family provides to this one a slightly stronger power.

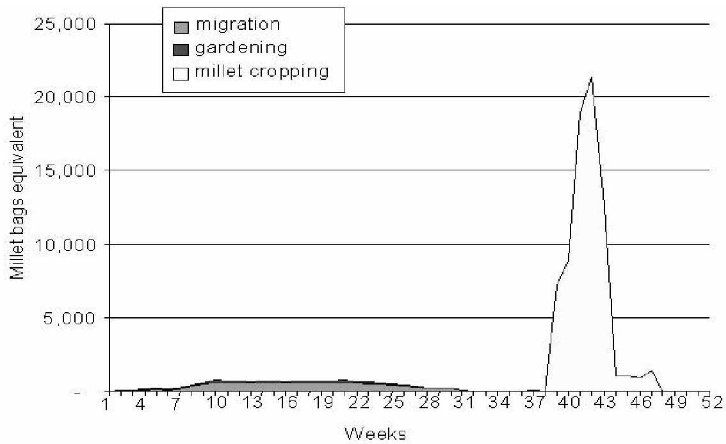


Figure 26. Simulation outputs for the unitary annual village production cycle scenario for the three simulated activities (year 50)

3.2 More food for all, same quantity for each

3.2.1 Income & inequalities

The two scenarios present a level of income that evolves differently, with an average advantage of 48% at the end of the simulation for the NCFS, thanks to a better adequacy between cropped surface and population and to a longer migration time after the 18th year of simulation. However, simulated income distributions were different between the two hypotheses for the four strategic groups defined on the basis of gender and level of responsibility criteria. Figure 27 shows simulated balance levels combining "real" personal income and family redistribution.

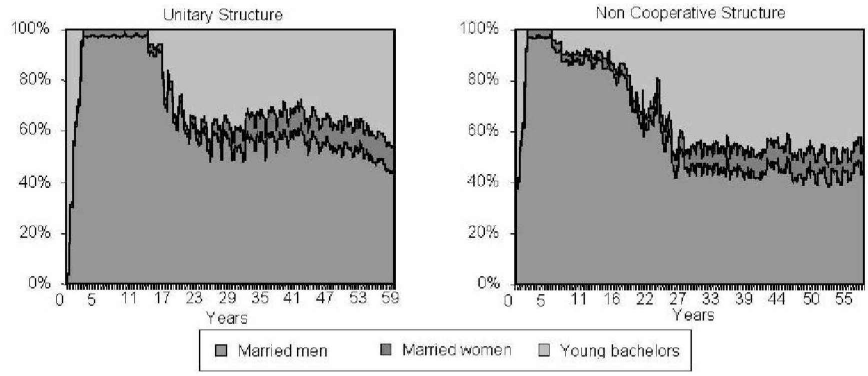


Figure 27. Total village income shares for the four gender / marital groups

Married male adult Agents provide the main source of income through millet cropping and migration activities. For this group, millet cropping is actually the largest source of income but this production cannot be considered as usable cash, i.e. there are few opportunities to use it as a source of investment because it is meant almost entirely for consumption:

- The contribution of married female adult Agents in the overall income is actually not negligible, contributing about 10% in both scenarios through the gardening activity only. Without this activity, they would be in the same unsteady situation as unmarried female adult Agents. Moreover, garden products are "providentially" available at the beginning of the harsh season, between April and June, just before returns from migration.
- The contribution of unmarried male adult Agents is artificially inflated: they accumulate an important income during migration. They put back a large part (80% in our model) in the common balance, i.e. the domestic granary for the NCFS and the family head balance for the UFS (in that case, the head of the family can thereafter transform these gains into livestock). One should also notice that migrants are fed abroad during migration times: their balances are not affected by consumption.
- Finally, unmarried woman or children Agents do not have any income because they are not formally "producers" in the model (one should add strong quotation marks to this word: the part of work women have to do in the reality is enormous but we mean here they have no personal gain from it).

Regarding economic activities, the unitary family structure seems more "productive" due to earlier marriages. This social organization, by lifting some social obstacles, allows a faster growth of the population and a bigger field extension. However, it does not raise the average living standard compared to the NCFS.

3.2.2 Fertility & livestock

Simulated Livestock populations are not equivalent, in both sizes and specie distributions: the NCFS scenario produces 162.43 livestock units on average (105.60 Large Stock Tropical Units (LSTU) while the UFS allows 463.12 units on average (341.75 LSTU). The transhumance, by sending away during the dry season all the “dry” bovines (i.e. all bovines but calves and feeding mothers), has the same effect than migration for humans for the local environment: simulations tested without transhumance produces a collapse of the grazing capacity and the soil fertility and by then the whole farming system. Largely due to a higher capacity of investment of the heads of the families, proportion of cattle is higher in the UFS than in the NCFS (67.24% vs. 56.27%) while the proportion of sheep is paradoxically lower (3.45% vs. 3.90%). This difference is almost significant and may be due to a higher concentration of the money in the hands of the migrating head of the family, while women are left without investment capacity during the dry season.
Meanwhile, one can observe that the livestock per capita ratio is higher for the NCFS than the UFS (0.54 vs. 0.43), which should be related to the better income per capita standards of the NCFS scenario.

Result outputs suggest that the UFS scenario induces more stresses on the biophysical factors supporting the farming system: Land occupation is twice the figure for NCFS (50.35% vs. 26.89%), due to the higher population growth (no significant differences appear in the land per capita ratio), while yields per ha equivalent remains equivalent as far as there is enough land where to expand to compensate the permanent loss of fertility of the cultivated fields. It means however that a fully saturated situation will appear far more rapidly in he UFS than the NCFS situation (between 20 and 30 years after the end of the 60 years simulation for the UFS vs. 50 to 60 years for the NCFS). One should then question the sustainability of such an organization in the considered context, i.e. the capacity of such a system to maintain itself over time in the face of intensive stress or shock (Conway, 1985).

3.3 A hypothesis about a change in local social organization

The two scenarios do not have the same robustness. A simulated Family that has only daughters as heirs ineluctably leads to its disappearance. While the NCFS allows the continuous creation of new families, letting the related population to escape from inheritance transfers, staying in one family in the UFS involves more population to the risk of one family head death. Family concentration in big clans is then an ineluctable phenomenon in the UFS scenario (7,7 families with 103.7 persons per family on average in the UFS vs. 17.2 families with 11.3 persons per family in the NCFS at the end of the simulation) even reaching in some simulations 420 people for one clan! The social organization that we observed during field investigations and as described in the NCFS suggests that this system prevents crystallization into big clans and the absorption of small clans as observed in the UFS (Figure 28.1).

Due to the lineage advantages in marriage and land procedures, the surviving simulated families belong more to the higher lineages in the UFS than in the NCFS (57% of the families with the best lineage value in the UFS vs. 43% in the NCFS, to compare with the initial predetermined value of 25%). Moreover, the risk of disappearance for a family, represented by the coefficient of variation between the simulations (Figure 28.2), is far more important in the UFS. This scenario is more risky, leading in 25% of the simulations to a decrease in population:

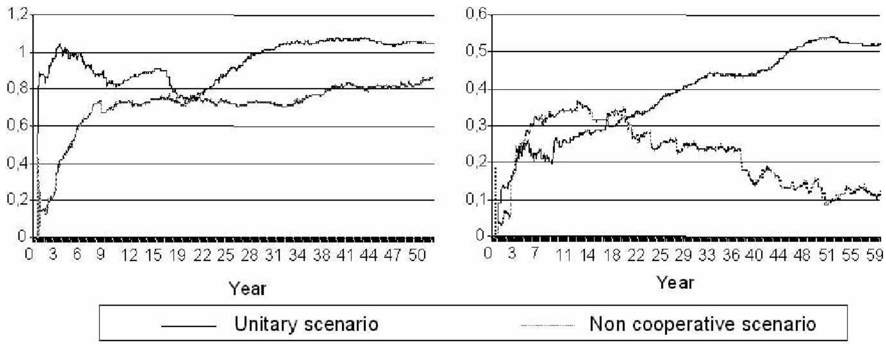


Figure 28.

28.1. Simulation results for the mean coefficients of variation between Family sizes (mean between simulations)

28.2. Simulation results for the mean coefficient of variation of family size between simulations (mean between families)

The higher demographic rate is not enough compensated by agriculture, migration and gardening incomes, all three having too strong social and economic constraints to answer the needs. Therefore, the low-cropped land/family size ratio weakens the clans in the UFS scenario. Multi-activity, by diversifying income sources, is a protection against agriculture risks. The head of the family, by concentrating the manpower on agriculture, reduces the gains from gardening and migration. Multi-decision increases the access to other activities and is by then, also a protection.

In the UFS, the concentration of the "redistribution power" in one hand creates a notion of distance between each member of the family and the head, who manages the redistribution; that distance is defined by the rank of this member. In the NCFS, this distance is very low, because it can co-exist many food distributors between one family member and the head of the family. Therefore, a bad year, for various reasons, can easily lead to the collapse of the domestic architecture in the UFS, while NCFS families are less sensitive to poor yields or poor migration gains. Moreover, the collapse of a small family has a lower impact on the village global demographic growth. Multi-decision constitutes a protection as well.

We have used the fecundity coefficients of the 2001 national census; the simulated demographic growth rate is therefore determined by the social organization. A Comparison of the two simulated scenarios suggests that the organization of each is a caricature: the real food redistribution system is actually not always so concentrated. It often happens that the father pays for his son's dowry, even though the latter left the family. It also happens that young adults own parcels without getting married, etc.
One can consider that the unitary approach is a “productive and intensive” version of the local organization: this type of organization, i.e. a village centralized in big clans, is more frequent in the southern savannas of West Africa (Reardon, 1994; Raynaut *et al.,* 1997; Gastellu & Dubois, 1997). A decentralized organization, as in the NCFS, can be considered as a less productive social organization but a more resistant one, which is far more important in Sahelian areas.

Our field data suggests that the concept of a decision-decentralized organization within families (NCFS) is valid only for recent years, while Olivier de Sardan (2003 p.246) recalls testimonies for such an evolution as far as 1914! Our investigations showed higher migration rates for 2005 than in the past: we suppose that family organization evolves, from a village where unitary families were dominant, to the mode one can observe today, in which non cooperative families are generalized, as had been assumed by Loireau-Delabre (1998). Luxereau & Roussel (1997) and Mortimore *et al.,* (2001) described this shift in the 70's for the region of Maradi and explained it with factors that we have considered (incomes bursting) and others we didn't (islamisation and capitalization, population density growth), the shock of the severe droughts of 1973 and 1984 having played a catalyst role. The fact that the average income level per head is lower in the UFS and that the income distribution is better balanced in the NCFS could have been strong incentives for the youth to escape from the enlarged family. We still have no other data yet to confirm that hypothesis.

4 Conclusion

Whatever the family organization, gardening and migration are necessary activities that simulated men and women respectively use in a village in order to not to depend totally on millet yields, particularly when incomes are not managed by the head of the family. Many development programs in the real Niger, with the rise of the gender approach, are supporting women gardens. Therefore, based on such simulation outputs but also on field investigation results, one may suggest that the same consideration should be applied to migration: this activity is actually not in competition with other activities in the dry season and procures valuable incomes for the area. Therefore, it should not be considered as an indicator of local poverty, but as a good mean of action for development in Niger: as field results have shown, the average annual migration net return is 150€ per capita for a 45€ annual investment. Therefore, allowing loans for this purpose may constitute a good support program, particularly through rainy season sheep fattening, which will be a very profitable activity for the next few years, when the Tabaski feast will be celebrated just on migration departure times.

While the economic activities distribution within families are gender predefined, actual accesses to these activities as well as income levels and distributions are strongly affected by the family organization. NCFS lowers the extension of the three activities by limiting the access to the main needed assets: cash limitations for married youngsters' migration, available manpower for gardening and agriculture. Delays in marriage slow down the demographic growth if support from parents is missing as observed in the NCFS. The UFS family organization structure, whereas it still remains in more southern Soudanian environments, seems to be less adapted to the new Sahelian context, where land availability and family protection are not the buffer they were anymore. The household approach, as a procedure that actually simplify local family structures to the UFS archetype, appears to be less appropriate for implementing development programs in the Sahelian zone.

In any case, ABM simulation outputs cannot be used to prove assertions. A complete methodology of integration between sociology, game theory and rural development is still to be built: simulating a society and building an agro-ecological model have different scientifically relevant criteria. However, there are no better tools yet than ABMs to combine qualitative information and quantitative data. In a context where the majority of development decision-makers have a technical background, ABMs are a useful interface to introduce social stakes in development projects.

The majority of the villages in Niger hold political fractures, usually strongly related to the village history, particularly regarding reputation and lineage conflicts within families, which are known to define the future attitudes of many villagers toward the project implementation. However, at the present day, development agencies have often opened these fractures within villages while operating projects. Future developments of the model will integrate these inter-village relations before bringing into contact a village population and a development agency in a simulation.

CHAPTER V: BENCHMARKING HUMANITARIAN SUPPORT: MODELING DEVELOPMENT ACTIONS IN VILLAGES OF SAHELIAN NIGER

Note: This chapter is adapted from a text that will be submitted for publication in 2008 in Agriculture, Ecosystems & Environment (Saqalli M., Gérard B., Bielders C., Defourny P. Benchmarking humanitarian support: Empirical Agent-based modeling of development action types in Nigerien villages").

1 Abstract

The purpose of this chapter is to simulate and analyze the impacts of development interventions on the population of three different sites in Sahelian millet-cropping Niger (Sahelian Africa), taking account the differentiation of social and agro-ecological constraints on the different types of villagers. The work is based on chapter 3, which have described the model & 4, which has shown that using an individual Agent-based model (ABM) is a relevant approach to integrate agro-ecological, social and economic characteristics of a system and that family internal rules have strong impacts on village and environment evolutions. Two development project interventions are simulated in a context of no land scarcity: inorganic fertilizers availability for farmers and an inventory credit technique based on millet yields that some villagers may choose to use. Two choice rationalities are tested, one upon economic values and the second upon the intra-village “reputation" gains. Our results illustrate that a village cannot be considered as a whole and project operators must take in account the precise target population rather than all adult villagers. Project involvements concern only sites where savings for securization or intensification are possible: These proposals need actually some food security and investment capacities that are largely conditioned by family manpower and size. Inorganic fertilizers have little success without any intensification process in a context of good land availability. Inventory credit intervention engages a maximum of 25% of the population in the site with medium agro-ecological conditions. Reputation has little effect on the population behavior and should be

considered more as a local wealth estimation factor between villagers. Therefore, one should consider these proposals as a potential support tool for a limited part of the population capable to go beyond the survival level, but not as a global poverty-alleviation panacea.

Key-words: farming systems, individual Agent-based model, Niger, development interventions

2 Introduction

The low impact development operators have had on rural societies in Sahelian Africa for half a century has created a huge research debate within and between scientific disciplines, but also in the development arena (Hambally, 1999; Lavigne-Delville, 1999; Batterbury & Warren, 2001; Mortimore & Adams, 2001). The debate was widely open after the food crisis[161] Niger suffered in 2005 (Loewenberg, 2005; Médecins Sans Frontières, 2005; Harragin, 2006). Therefore, an important issue of development research is to improve the relevance and the efficiency of development projects (Decoudras, 1990; de Janvry & Sadoulet, 2003; Watkins & von Braun, 2004; Dollar & Levin, 2006).

A proper understanding of the Sahelian village production system is a prerequisite for successful development actions and requires prior recognition of the inherent complexity of this system. Land tenures are various and complex (Le Bris *et al.,* 1991; Laurent *et al.,* 1994; Bruce, 1998; Lavigne-Delville, 1998; McCarthy *et al.*, 2000). However, the variables that research and/or development programs define as the most relevant to focus on are usually not determined through a prior evaluation process (Clements, 1995; McCall, 2002). They rather follow what one can call the discipline parsimony, as an extension of the scale parsimony concept used by Turner (1999a) for the same geographic area, i.e. the idea that the explanation for a phenomenon can be restricted to disciplines from which it is observed. The tendency to restrict research on few disciplines is reinforced by the scarcity of reliable, spatially and temporally continuous data, inducing researchers to focus on disciplines where data can be easily or are already collected, through remote sensing tools for instance. As a matter of fact, the identification process of rural agriculture development action types are thus usually restricted to their economic and agronomic dimensions (Olivier de Sardan *et al.,* 1995; Lambin *et al.,* 2001).

[161] Choosing between “famine” and “food shortage crisis” to describe what actually happened in 2005 reflects the political position in the development arena

However, one may consider such development actions as proposals that an institutional operator presents to the focused population. As any proposal, such procedure should thereby also integrate a "marketing" approach: who are the real focused populations of a development action in a Sahelian village and what factors condition the adoption of a proposal within a population? Because of the size and the type of this actual focused population, what is the extent of the adoption and the real impacts on environment and society of such proposals? These are the questions that the following chapter considers and analyses.

The two selected development interventions to analyze are emblematic of development strategies in the country:

- Niger having one of the lowest inorganic fertilizer use rates (0.27 kg/ha) (World Bank, 1997), inorganic fertilizers are considered by many development operators as the bottleneck for farming system intensification and income increase in Niger (Van Keulen *et al.,* 2001; de Rouw & Rajot, 2004; Ouédraogo, 2005). The purpose of these operators is to support farmers to use inorganic fertilizers in food crop fields and vegetable gardens through farmers' organizations, by increasing the availability of inorganic fertilizers at the village-level and the knowledge on their use, with an emphasis on the microdose technology (Abdoulaye & Sanders, 2005; Gérard *et al.,* 2007), thereby reducing inorganic fertilizers waste and the weed impact (Muehlig-Versen *et al.,* 2003). The promoted inorganic fertilizer is Diammonium Phosphate (DAP). Group members can buy inorganic fertilizers at market price. Groups almost entirely consist of either women or men, using inorganic fertilizers for gardens, cash crops or cereal fields.
- The second proposal is the warrantage, also named inventory credit. As described in chapter 1, it is a credit technique based on the use of farmers goods set down as a guarantee in a warehouse. Usually after harvest, farmers stock a part of the yield in a reliable warehouse as a guarantee for the credit operator. In exchange, this last provides a credit equivalent to 100% of the value of the stock at the time of the deal[162], with 10% of the initial stock value for the FA as storage and fee costs. The farmer reimburses the credit by buying back the stored millet and sells it on the market at high prices (usually during "soudure" times). The benefit due to price increase during the storage period belongs to the farmer. The objective is to provide better access to financial resources (Badamassi, 2006) and for income securization, by compensating millet price fluctuations (Pender *et al.,* 2006).

[162] It means that the credit value is the yield portion the farmer let in the warehouse, upon the price at the harvest, usually around 0.15 €/ kg.

All the elements of the system to include in the evaluation of this relationship cannot be analyzed in a systematic and/or an experimental manner (Ahrweiler & Gilbert 2005), which implies to model the system. The main purpose of such a modeling procedure is to simulate a Sahelian village society facing such development proposals without forgetting social effects on the success of these lasts.

Actually, many factors may modify the way a development proposal is considered by a village population. The relationship between a population and a development operator is intrinsically also political and social (Bonnal *et al.,* 1997). Beyond the informal but recurrent local reinterpretation of the rules of the development project itself (Laurent *et al.,* 1994; Biershenk *et al.,* 2000; Laurent, 2000), one should also easily conceive that social factors will informally affect the access to development actions: firstly, the benefit of a development intervention varies with the type of concerned villagers (Lavigne-Delville, 1999; Marou, 2005). Secondly, the way the project action types themselves are implemented can also lead the network of social powers to influence their successes (Olivier de Sardan, 1991; Olivier de Sardan & Dagobi, 2000). Social position and reputation within the village should therefore also be considered. Villager reputation as described in chapter 1 §2.3.2 and implemented in chapter 3 §2.3.2 is thus introduced in the model as a local factor of discrimination among villagers. A first scenario, named “economy”, describes a village-project relationship where the villagers' interest for a project action is only based on economic rationalities and neglects the impact of reputation. The second scenario, named the “reputation” scenario, defines reputation as the main “currency”: reputation gains and losses are the main criteria for someone to choose whether to be involved in a development program or not. However, because decision is sexually discriminated, the two scenarios should be understood as concerning each gender separately.

The ABM simSahel model on which this implementation is assessed is presented and described in chapter 3. More precisely, the assessment of the scenarios that are here compared is fully described in § 5.2 of this chapter 3. Two types of scenarios are tested, in order to test both the effects of development proposals, but also the effect of reputation. For each of these two scenarios, we test the effects of the two proposals implemented together, to compare with a situation without any of the two proposals, and combined with the reputation scenarios.

This work is based on the assumption that some factors and constraints must not be omitted in the analysis of a development project action simply because of a lack of data and/or a difficulty to integrate information from various disciplines. Assuming that development projects are *de facto* in a marketing logic regarding their relations with villagers, the model should help to better understand the villager demands, by simulating the behavior of various villagers and a range of strategies, before simulating the effects of development interventions.

3 Results

For each scenario and site, thirty simulations were run for a period of sixty years (i.e. two generations) corresponding to 3120 weekly time steps. Simulation outputs were obtained for the entire village, at family level and at gender and age group levels. Village level simulation results are compared to available data, i.e. our macro level field investigation results, literature review and the Niger national census, in order to access the consistency of the model. The two development actions are then compared individually or in combination, with the “economy” or the “reputation” scenarios. Table 26 shows the combination of scenarios and their abbreviations. As the village is founded at t= 0, the first 5 years should not be considered as part of the simulation results as they are strongly affected by the initialization process.

Table 26. Combination of scenarios and abbreviations

Sites	Scenarios	Control	Fertilizers	Warrantage	Warrantage + Fertilizers
Zermou	“Reputation”	ZRC	ZRF	ZRW	ZRFW
	“Economy”	ZEC	ZEF	ZEW	ZEFW
Gabi	“Reputation”	GRC	GRF	GRW	GRFW
	“Economy”	GEC	GEF	GEW	GEFW
Fakara	“Reputation”	FRC	FRF	FRW	FRFW

3.1 Reputation: only a quicker wealth estimation factor

Reputation did not lead to dramatic changes in the average access to the main assets (land, livestock and manpower) per inhabitant compared to economy-based scenarios. The ratio of per capita manpower between reputation & economy scenarios and the ratio of per capita land use between scenarios show no significative differences between scenarios. The ratio of per capita livestock herd units shows a declining value for the case of Fakara, a globally higher ratio in Zermou, and a globally lower one for Gabi, without any significant temporal tendency for the last two sites (results not shown).

Other output comparisons between the “reputation” and the “economy” scenarios show that shifts and evolutions in the adoption of development proposals are equivalent, except for the fact that shifts occurs 2 to 5 years earlier in the reputation case than in the economy case (results not shown): it appears that reputation between villagers is used mainly as a local way to estimate the wealth of a villager, i.e. the capacity of an Agent to sustain himself and his relatives and dependants. Greif (1989) writes a similar assertion from a very different context where merchants use mutual reputation as a confidence-building tool for future transactions. Thereby, a first point of view on such reputation results may be that it is only an insurance system of estimation of one wealth.

Meanwhile, we suppose that the reputation as implemented in the model is actually based on a too high proportion given to the level of wealth, to the detriment of social duties to fulfill and social classification criteria (family rank and family lineage). Field observations let us to integrate many wealth parameters in the reputation definition but one may simulate reputation not as a permanent and absolute value that is used by all the villagers but more as a memory of events, declining with time, that one villager apply on each other villager, as Rouchier (2000) have built between nomadic herders and sedentary farmers in Cameroon. Therefore, a second point of view is to consider that reputation should depend on the observer and should vary over time along social events.

Therefore, given the small differences between the ‘economy’ and ‘reputation’ scenarios, further results will be discussed only with respect to the “economic” scenarios.

3.2 Comparing sites

Simulation outputs are compared between sites in the case where no development projects are implemented.

3.2.1 Production assets: a structural geographic advantage

Average income (Figure 29) evolves during simulations at first in a convex curve because of the generation effect: a very high adult per capita ratio during the first 5 to 10 years has positive effects on income. But the children explosion during the 15 to 30 years period (Figure 29.2) force the slope of the income curves of the three sites to become negative.

However, the curve amplitude varies depending on the simulated site: Fakara and Gabi show equivalent declining curves, while income at Zermou is continuously significantly lower. Better conditions, both biophysical (rainfall and soil fertility) and economic factors (migration costs) as they are implemented at the Fakara and Gabi allow higher individual incomes which facilitates the access to marriage for men, reducing therefore the delay for getting children (Saqalli, 2006).

As the decision to expand fields is simulated to be conditioned by the food production and yields are very low at this site, land occupation increases faster at Zermou than at the two other sites. Therefore, the land per capita ratio is higher in this site than the two other sites (Figure 29.3) during the first half of the simulation period. But, as the manpower ratio of Zermou remains quite equivalent to the two other sites (Figure 29.2), villagers do not benefit from this rapid field expansion, as they cannot crop all of it properly.

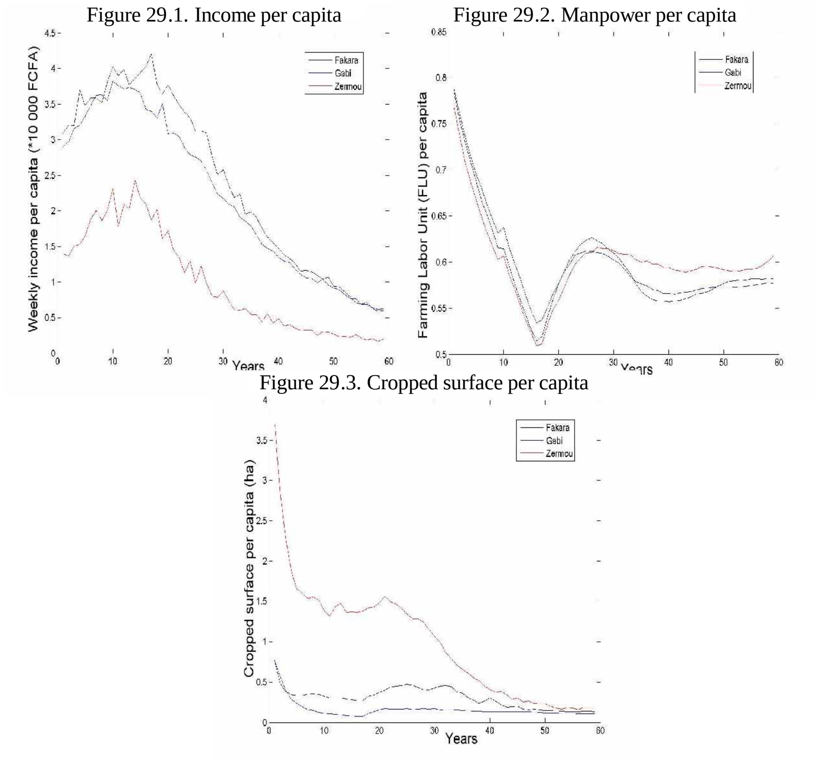


Figure 29. No project & no reputation simulation output means per capita for selected population characteristics in the three sites

As a consequence, village population growth is equivalent for the Fakara site (585 inhabitants ± 141 inhabitants at the end of the simulation) and Gabi (505 inhabitants ± 131) but is significantly lower for Zermou (321 inhabitants ± 97). The substantial differences between Zermou and the two other sites suggest that the Zermou site has exceeded a threshold resulting from the accumulation of the higher constraints we implemented.

3.2.2 Activities distribution: site specific specialization

All three activities (agriculture, migration and gardening) grow in volume along the 60 years of simulation because of the demographic growth. As shown in Figure 30, income from millet agriculture per villager varies according to the site:

Zermou shows a constant decline in the farming income and even a shift in the allocated labor for farming between the 15th and the 25th year (i.e. after the very rapid period of field extension in Zermou) (Figure 30.4). The two other sites have similar trends, both strongly affected by a generation effect due to the progressive appropriation of new lands during this period, which does not occurs in Zermou. During at least the first half of the simulation, it seems that the Fakara population is more involved in farming and has higher farming gains than in Gabi. However, this last site is the only one to maintain its farming gains per capita and sees even an increase in the farming labor until it exceeds the Fakara figures between the 35th and the 45th year.

For the gardening activity, local social and economic rules we implemented dramatically change the situation: both hausa-populated sites of Zermou and Gabi are simulated as restricting gardening to men. However, we allowed male villager Agents in the Gabi site to practice migration and gardening at the same time, while this combination is not implemented at Zermou. Actually, we implemented this difference considering that the immediate proximity of Nigeria in the case of the Gabi site (Table 2) allows this combination while it is impossible for the case of Zermou. Consequently, the use of the very few gardening places of the site stops quasi totally[163]. More land suitable for gardening (Table 15) and access to male manpower in Gabi allows a progressive increase in the gardening gain per villager. But this expansion is lower than in the Fakara, which may have benefited from the gender discrimination between gardening and migration (Table 2 & Figure 30.3). Manpower involvement ratios for the zarma-populated Fakara and in Gabi do therefore concern different populations (Figure 30.6).

---

[163] The potential acreage for gardening in Zermou is very low compared to the other sites: 0.52% (see Table 7)

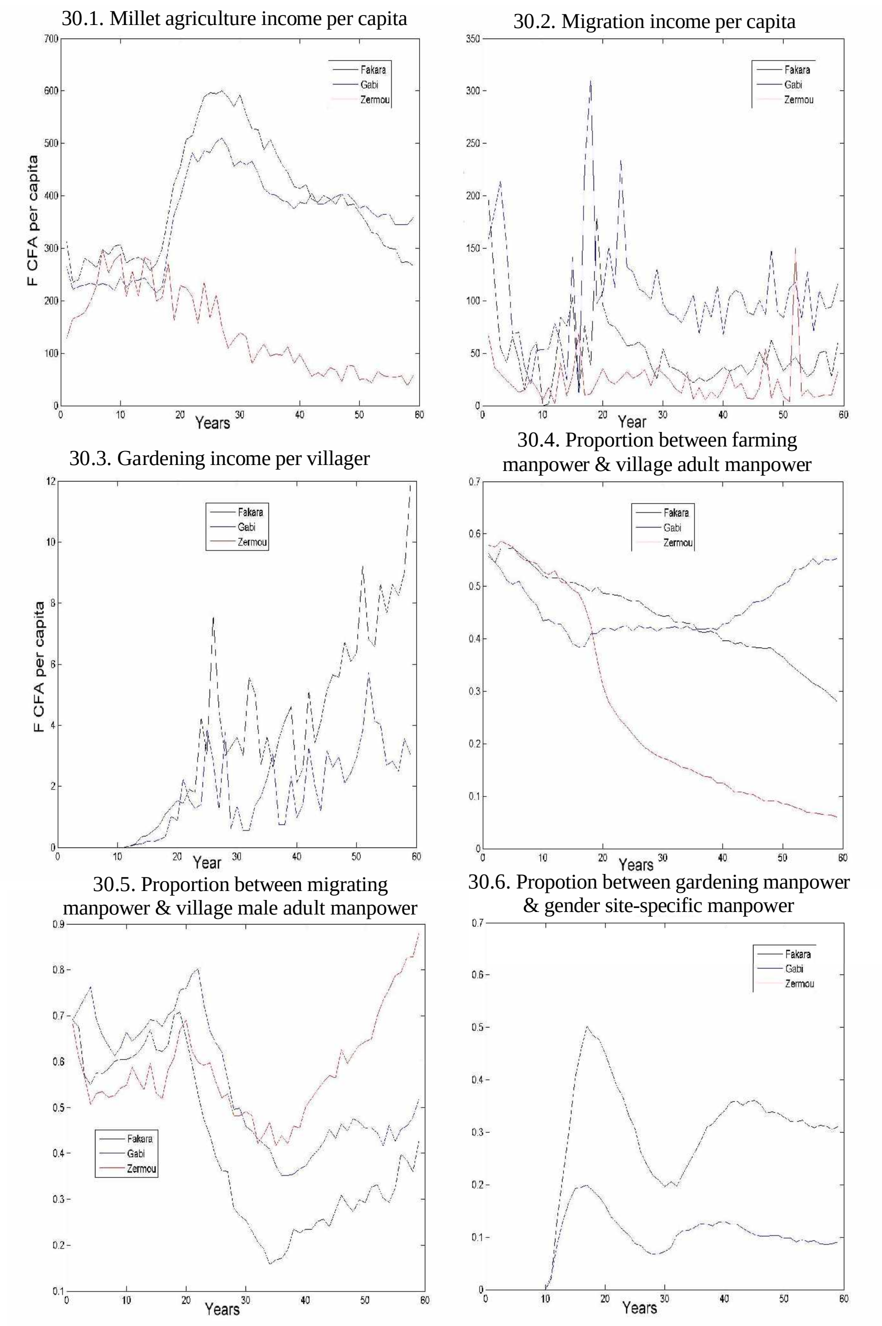


Figure 30. No project & no reputation simulation output means per capita for production activities in the three sites

For the migration activity, while the three sites show no significant differences in the manpower allocation before the generation peak (year 10 to 20[164]), migration seems to be strongly affected by the access constraints we implemented (Table 7): While the lower cost for departure for Gabi allows progressively more people to leave (Figure 30.5) and to bring back home more money (Figure 30.2) than in the Fakara, it seems that the accumulation of disadvantages for the Zermou site (higher departure costs, more risks, poor agriculture gains) limits the extension of this activity at the beginning but the very low gain of agriculture and the impossibility to garden (Figures 30.1 & 30.3) progressively forces people to reallocate their manpower on the sole available activity, i.e. migration.

3.2.3 Inequality and sustainability: producing more for how long and for whom?

One should also analyze the sustainability of the considered systems as some sites show declining figures for production efficiency or land occupation ratios (Figure 31). The sustainability is defined as the capacity of such a system to maintain itself over time in the face of intensive stress or shock (Conway, 1985). The environmental sustainability is analyzed through level indicators while social sustainability is considered through inequality indicators.

As defined by the model rules, Fakara and Gabi site population expands their cropped land taking account their manpower/population ratios. Land occupancy grows in Gabi by a temporally stable rate of 4,6% per year (Fakara, 2.4% and declining over time). Zermou villagers rapidly conquer their territory (Figure 31.1) although they do not so much involves themselves in farming (Figure 30.4), because of the far more rapid decline of the fertility of the cropped land. This assertion is compatible with the literature for various zones in Niger, including the Damagaram where Zermou is located, but also other arable places in Niger for the end of the first half and the beginning of the second half of the 20th century. This conquering behavior is usually described as a response to manpower scarcity but also as an "investment for the future" at family and village levels (Demont *et al.*, 2006; Bah *et al.*, 2006). Even with lower land occupation growths in the Gabi and Fakara sites, 60 years of continuous growth eventually led to complete occupation of arable land: it means however that further simulation results concerning sustainability and project action

[164] The generation peak affects migration before farming: migration is allowed for men after 16, even if they are not married, whereas marriage is a prerequisite to become farmers and land "owners". Getting married on the other hand stop the support from their parents for migration, which lower their financial ability to leave.

impacts cannot be compared with the present situation, particularly in Gabi where real land occupation has been complete for at least 40 years.

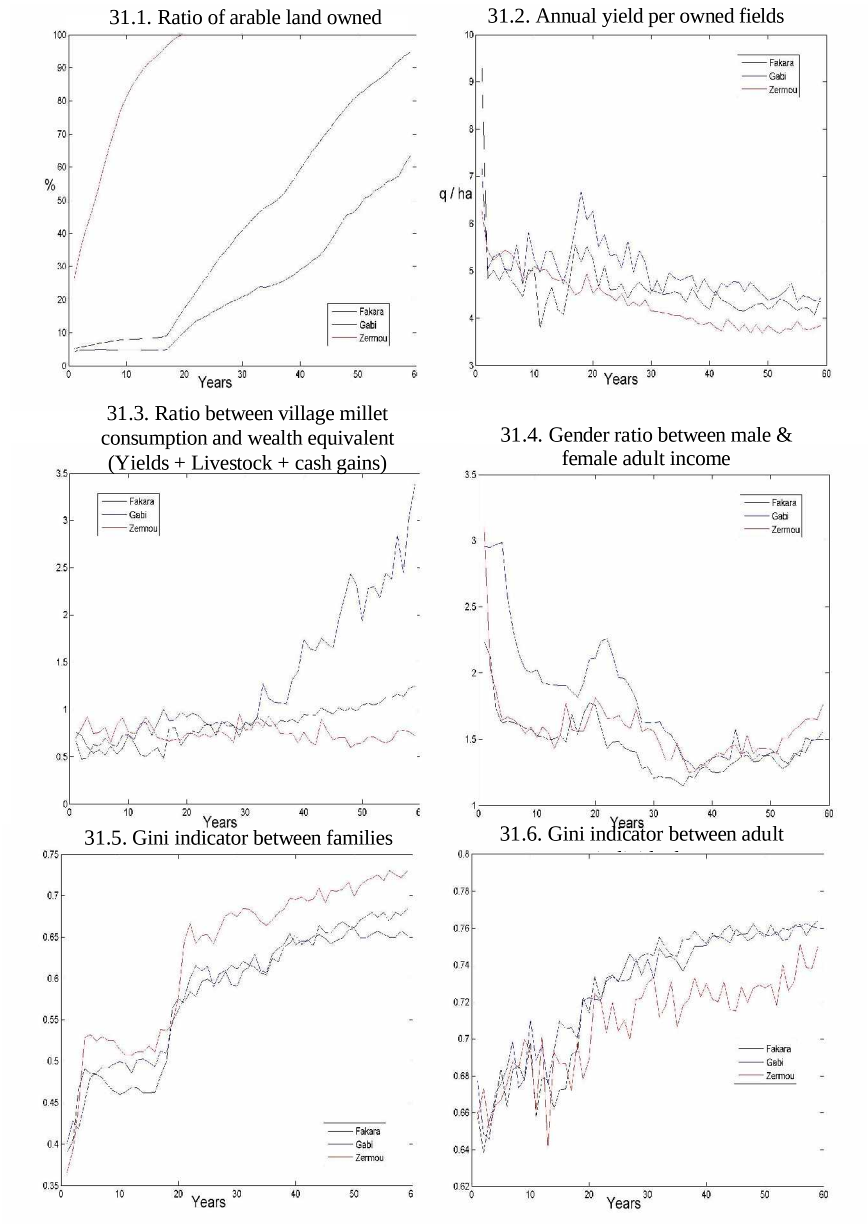


Figure 31. No project & no reputation simulation scenario output means for sustainability in the three sites

As shown in Figure 31.2, after the first cropping years, average yields are not strongly affected by land scarcity[165]. Yields are significantly different between sites as determined by the model inputs and decline slowly from 4 to 5.5 q/ha at t = 10 to 3.5 to 4.5q/ha at t = 60 [166]. This resilience cannot be explained by a permanent compensation of the old fields' fertility loss by new fertile inclusions because land is already saturated in Zermou. It means that local farming systems are resilient enough in all the three sites to maintain yields, but with low yield values. It allows the simulated population of the three sites to maintain its food security throughout the simulation period. As people already live in these sites, it gives confidence on the model realism. Figure 31.3 shows the ratio between the annual consumption per villager and the income equivalent from the three main activities and the livestock capital. While the Gabi site population food ratio even strongly increase, the consumption ratio remains stable for the Fakara and slightly declining for Zermou, making them more prone to food shortage crises.

The three last figures shows social sustainability indicators: the gender income ratio (Figure 31.4) shows the difficulty for women to sustain while having no access to economic activities for the Gabi and the Zermou sites. The Fakara site ratio slightly recovers over time due to female access to garden production gains[167]. The Gini coefficients[168] established at the family level (Figure 31.5) and the individual level (Figure 31.6) suggest another limitation of the systems: inequalities between families and within families grow, meaning that economic discrimination grows along the 60 years of simulation.

[165] The peak at t = 16 is due to the flux of new manpower allowing villagers to crop new fields with an intact fertility.

[166] The lower but not falling yield per ha for Zermou until the year t = 20 is due to the more rapid extension of new fields.

[167] For the case of Fakara, women manage the gardening activity, which explains the faster redistribution of the income after the generalization of the activity after the year 18, as shown in Figure 31.6.

[168] For *n* slices, the coefficient is obtained by the Brown formula (we have chosen n = 5 as used in demographic studies): $G = 1 - \sum_{k=0}^{k=n-1} (X_{k+1} - X_k)(Y_{k+1} + Y_k)$ X_k: the income of the k slice; Y_k: the size of the k slice (Dorfman, 1979).

3.3 Projects implementation: successes & failures

3.3.1 A low success mainly due to a poor saving capacity

The Figure 32 shows the impact of the project interventions on the population and related effects. Both Figure 32.2 and Figure 32.3 show a generation effect which suggests the strong relationship between the capacity for savings and the manpower: it supposes that having a higher manpower per capita ratio allows a household head to save more. However, Figure 32.3 suggests that the saved quantity is strongly linked to the capacity of a site to procure enough excess yield for savings: the Zermou population is unable to create enough production to both feed people and save millet. Therefore, and despite the hope of development operators to implement warrantage all over the country, these simulations suggest that success of this intervention should be considered as highly determined by the local capacity for millet production.

Fertilizers use shows strong differences between the three sites: whatever the sites, inorganic fertilizer use remains very low, with less than 10% of farmers using it (Figure 32.2) and less than 4% of the total surface (Figure 32.4). Gabi and Fakara populations show similar behavior regarding the inorganic fertilizers use, but at different levels: as far as they maintain a high manpower per capita ratio (between t=5 until t=12 for Fakara and t=20 for Gabi) allowing them to easily clear new fields and to weed cropped fields, farmers are not using inorganic fertilizers[169], suggesting that gains from activities other than farming are used for more promising purposes, such as migration. Thereafter, one can observe that the proportion of population using inorganic fertilizer and fertilized land reach a higher value in Fakara than in Gabi due to an initial lower fertility level. In a simulated context of no land saturation, the Gabi population appears less concerned by inorganic fertilizers and on fewer surfaces. One can then suppose that inorganic fertilizers are not attractive wherever free and fertile land is still easy to acquire in the simulations. Comparing with the reality, present-day figures for a full-saturated Gabi site show that ⅔ of the farmers actually use inorganic fertilizers. Therefore, simulating present time inorganic fertilizers use would require implementing a full-saturated context in Gabi.

[169] The initial high values are due to the first trials they manage to get some personal experience with the use of fertilizers.

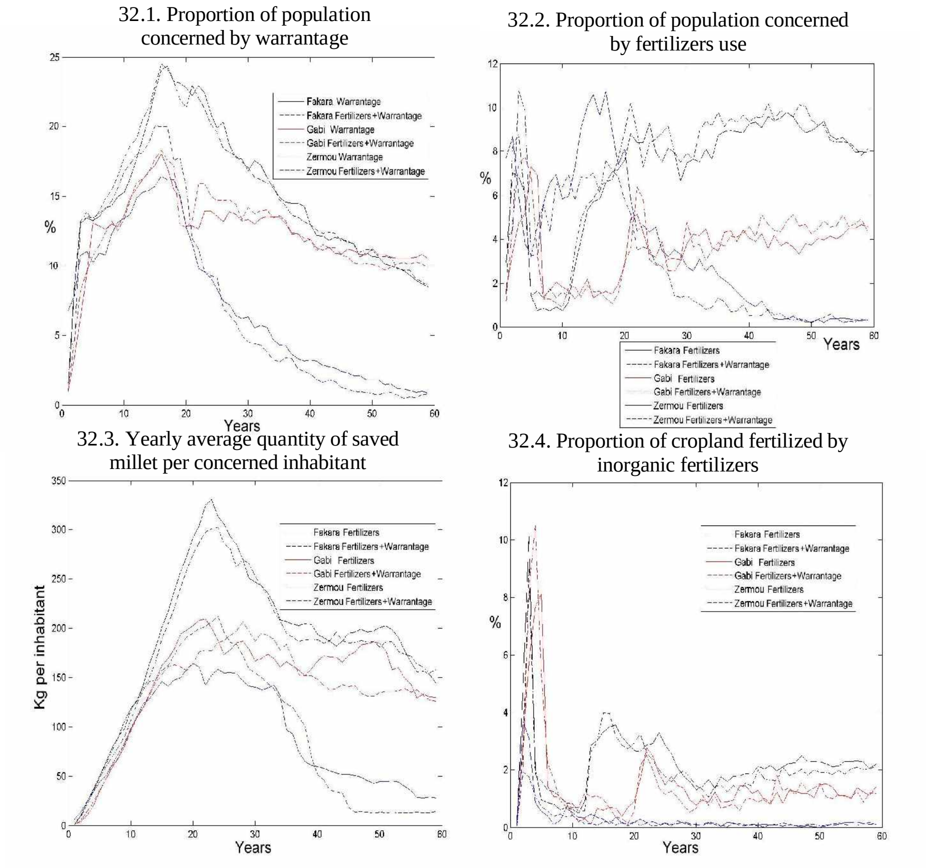


Figure 32. Comparison between the three sites of development action impact simulation output means in the no reputation scenario

Zermou farmers in the model show a different behavior at the start of simulations, largely due to their particular strategy of fields extension to compensate for their lower yields. The first 25 years shows that, as long as the manpower/population ratio remains favorable and new fields can still be cleared, one observes a growing use of inorganic fertilizers. At the time land is fully occupied, reducing drastically the interest for farming, inorganic fertilizer use declines until a quasi-zero level.

3.3.2 Two development proposals targeting different population groups

Dashed curves for the combined warrantage & inorganic fertilizers project simulation outputs shows that there is no synergy between the warrantage and inorganic fertilizers use strategy, suggesting that the logics and even the population concerned by the two activities may be distinct.

Exploring the characteristics of the simulated population that is involved in the two proposals helps to identify the most determining characteristics for involvement in projects. As inorganic fertilizer and warrantage users at Zermou are too few, the analysis of the involved population concerns only the sites of Gabi and Fakara. Inorganic fertilizers users all had in common a higher manpower per capita ratio at family level but a lower land per capita ratio and a lower livestock per land ratio than the average population. They can be split into two groups (Table 27):

Table 27. Indicators and ratio comparison between project user families and the average population

	Inorganic fertilizers using population in Gabi & Fakara				Warrantage using population in Gabi & Fakara	
Family characteristics compared to the average population	(i)	Δ	(ii)	Δ	(i)	Δ
Family head age	-	⇑	++	⇑	+	⇑
Lineage	--	⇓	/	⇒	++	⇒
Family Size	-	⇑	+	⇓	++	⇒
Manpower	-	⇒	/	⇓	++	⇒
Land size	-	⇑	++	⇒	+	⇑
Livestock	--	⇒	+	⇒	++	⇑
Income per capita	/	⇒	+	⇒	+	⇑
Livestock per capita	-	⇓	-	⇓	++	⇑
Land per capita	-	⇒	-	⇑	+	⇑
Manpower per capita	+	⇑	+	⇓	+	⇒
Manpower per cropped surface	/	⇑	-	⇓	++	⇒
Livestock per cropped surface	-	⇒	-	⇒	+	⇑

(i) --: -25% and less; -: -10 to -25%; /: ±10%; +: 10 to 25%; ++: 25% and more ⇓: - 25%; ⇒ ± 25%; ⇑: +25%

- "Small young disadvantaged but growing families": their average lineage value is low (1.6 vs. 2.8 for the whole population), suggesting that the most interested people are the ones who were disadvantaged in the land access due to social tenure discriminations. Families are small and thereby, manpower and owned land is low. The head of the family is younger than average (35 years-old vs. 43). However, the higher manpower/population ratio allows the family to sustain by diversifying income sources (millet fields, migration and after a few years, livestock sales and gardening). It also allows the use of inorganic fertilizers by succeeding in all the millet cropping cycle steps, particularly the related higher manpower requirement for weeding. Inorganic fertilizer use seems to be a way to compensate the low level of land and livestock manure. This group represents at most of 30% of inorganic fertilizer users around the 15th year and then declines, eventually disappearing around the 40th year of the simulation.

- "Large old but shrinking families": the family head is far older than average (61 years-old vs. 43). Because of the non-cooperative family organization (Saqalli 2006), elder children leave once they get married, taking with them some parts of the livestock and their manpower. The high income per capita ratio, with a high livestock per capita ratio, allows mobilizing enough funds to compensate for the declining manpower ratio. The size of this group at the start of the simulations is higher by 25% in the scenario combining both warrantage and inorganic fertilizers compared to the scenario with only inorganic fertilizers.

Anyhow, inorganic fertilizers seem to be interesting only for families in transition: they cannot be used by the poorest as it is too expensive, and the wealthiest can use other and cheaper assets, particularly manpower and livestock in a context where land is still not a constraint.

For the two implemented sites, warrantage users are members of a unique group that can be described as "large better-settled families": their average lineage value is quite high (3.2 vs. 2.8), and the family head is somewhat older than average (48 years-old vs. 43). Families are big and growing, with a higher amount of young adults than average and consequently, manpower and owned land are higher as well. Warrantage seems to be an alternative to livestock as an income saving tool, but only families that are able to maintain a saving capacity get involved.

4 Discussion & conclusion

One can then estimate that the three sites show different trajectories based on their predefined potentialities: these lasts influence the demographic growth and even more the manpower ratio, but also the involvement in farming activities: Zermou is disadvantaged in the continuous run between family needs and available manpower. Therefore, the question should concern the long-term sustainability of the settlement and colonization process, when the three sites show a decline in income per capita.

Social and environmental indicators suggest the resilience capacity but also the fragility of such systems in the simulated conditions. However, the temporal scale has to be redefined particularly regarding the case of Gabi: the present day situation shows a complete saturation of the available arable land, because of a longer and more intense period of field extension. It means that the fragility suggested by these simulated indicators should be even higher in the real situations.

As a matter of fact, the success of both proposals is strongly defined by the local biophysical capacities to sustain village populations. Involvement in warrantage and inorganic fertilizer projects do concern only sites where millet savings for securization or intensification are possible, which is not the case for Zermou. Even so, success in the last two sites is in any case limited, with a greater impact of the warrantage proposal than the inorganic fertilizer one. These proposals actually require some investment capacity that few people do have in Fakara and Gabi. This capacity is largely conditioned by each family food requirement in relation to its manpower in a context where land is still available. Only a maximum of 25% of the population engages in a project proposal: warrantage in Fakara, only during periods when enough manpower was available. In the fertile site of Gabi, a land intensification proposal does not have a large success, as long as new fertile land remains available. However, due to the limited temporal scale, simulations do not provide information upon a possible intensification process in a context of land scarcity. Therefore, one should consider these proposals as a potential support tool for a limited part of the population to go beyond the survival level, but not as a poverty-alleviation panacea.

Reputation as implemented has no particular effect on the simulation results. The problem for such a factor is that events where reputation may have an important function (marriages, inheritance, project involvement, elections, etc.) are quite rare within a village and the real negotiation arenas where such a capacity plays its part are secret. Therefore, it is difficult for an exterior observer to estimate a valuable function formula of such a fuzzy value. However, a very interesting investigation may be to analyze, with the support of more anthropological tools, whether a value such as reputation may have evolved along the 20th century in Sahelian Niger from a factor more based on social classification criteria to a more wealth and income-oriented one, based on the fact that income have played a more important part over time in such a society. Moreover, even if building such a function is difficult, one may easily observe on the field how strong such personal relationships and powers influences the functioning of a development project (Biershenk *et al.,* 2000; Laurent, 2000). Therefore, building a model of development action adoptions should integrate such a value, even if it is a fuzzy one.

Therefore, this methodology has underlined that:

- The model is realistic in the micro behaviors of the different types of villagers and reproduces correctly the macro impacts of these behaviors. Moreover, the tool gives confidence enough to discriminate sites and scenarios regarding project proposals.
- Development projects often focus on the costs/advantages of a development proposal, which can be considered as the characteristics of an offer in an economic exchange, assuming that proposing such proposal will generate its own demand. Meanwhile, modeling one

society reaction to new economic opportunities, by redefining this demand pattern, i.e. the distribution of assets within families, shows that this demand conditions the "market" size for such proposals.
- Development interventions have various successes according to the household types and to the considered area: future development proposals in Nigerien Sahel should resort to a diverse panel of proposals and never base their future planning on the assumption that a proposal, whatever its intrinsic quality, will expand all over the country. Unfortunately, this fundraiser-oriented marketing approach is in use in many development-planning programs, often suggesting that a proposal will succeed in a whole country, when data and informations are based on one local experience. This simulation tool, by suggesting the strong impact of local social and biophysical factors and their local variability and distribution, allows advocating for a new marketing approach, focusing on the local and variable population demand.

This work should be understood as a step-by-step construction. As defined from the field observations, some factors were eluded in the modeling process:
- Labor and land markets were not implemented: While land markets are still quasi totally absent in the sites of Zermou and Fakara, they do exist in Gabi, particularly for irrigable places, which is obvious in a context of land saturation that we did not implement. There are still quasi no labor markets in Zermou, but Abdoulaye & Sanders (2006) and our own observations in Fakara suggest that this activity, while quasi-absent in the 90's (Ada & Rockström, 1993; Loireau-Delabre 1998; Mounkaïla 2003), have grown very rapidly.
- While literature often defined the Fulani ratio being around 10% of the local population, figures from Barbier & Hazell (2000) suggests that they may reach around one third of the total population in the Fakara. As they have a different land and livestock use mode, including their presence on a model may transform outputs and further prospective.
- Yamba (2004) has noticed a generalization of the divorce institution. Since no data is actually available at the national level, the phenomenon was not modeled but we assume that this factor could have a strong impact as women resort to divorce at least once in a lifetime bringing with them some assets, particularly small livestock. Therefore, this institution can provide more independence to the women-driven local economy and more variability in the accumulation processes at family level (Turner, 1999b).

This model was determined by the initial hypothesis that the present time evolution of any farming system is better understood by integrating the system history and inertia[170]: To start the village simulation from its foundation is more relevant than rebuilding a general tenure or family pattern as “a copy” of an observed situation, because the past social dynamics are also included. Whereas one can find less than 60 year old villages in the Zermou or the Fakara sites, none can be found in the site of Gabi. Therefore, because their dynamics are older than the duration of the simulation period (60 years), some Nigerien areas, as Gabi, cannot be well-simulated: the simulated outputs may well represent what could have been observed at the time, but do no longer correspond to the present time. If we suppose that the fecundity are quite equivalent for the three sites, it shows that the dynamics in the latter are older and that this difference should be taken in account: the history of the land conquest should be included to understand the present time dynamics of farming systems in Niger.

As we based the 60 years simulation on a constant family organization, some divergences appeared: land is quickly occupied in the site of Zermou in the simulation whereas one can observe that there is still some land remaining in reality. Therefore, family organization historic evolution should also be taken in account, as it defines the distribution of the access to assets between and within the different households in each site (Saqalli 2006). The hypothesis of the permanence of the present day family organization in the past is shown to be false *ad absurdum*. Understanding the village evolutions on a long-term basis also should take in account the evolution of family organizations.

New phenomena may appear in simulations longer than the 60 years we implemented, as land scarcity will then operate for the different sites. However, pursuing the simulation beyond the 60 years bound may encounter practical simulation limitations as simulation time requirements are exponential. In any case, pursuing simulation by extending the scenario without offering some adaptation processes to the population will obviously show population and environmental crashes. Such simulation approaches that include social evolutions may bridge the gap between sociological and agro-economic analyses and thereby open the vision of different futures of these societies.

---

[170] I.e. the resilience of various phenomena (demography, agro-ecology) putting apart any qualitative judgement

CHAPTER VI: TESTING SOCIAL-DRIVEN FORCES ON THE EVOLUTION OF NIGER SAHELIAN RURAL FARMING SYSTEMS

Note: This chapter is adapted from a text that will be submitted for publication in 2008 in the Journal of Artificial Societies & Social Simulation (Saqalli M., Bielders C., Gérard B., Defourny P. Village Ecosystem & Society empirical Agent-based Model: testing social-driven forces on rural Nigerien Sahelian millet-cropping farming system evolutions").

1 Abstract

This chapter describes, simulates and analyzes the effects of social and agro-ecological constraints on rural farmers through the case study of three different sites in Nigerien Sahel (Sahelian Africa). The work is based on chapter 4 that has shown that family organizations and internal rules have a strong impact on village and environment evolution. Two family transition processes are tested: family organizations can evolve between a patriarchal mode and a non cooperative one through family income redistribution tensions that have strong effects on manpower and income allocations. Family inheritance systems can shift between the "customary" mode and the Muslim one through family land availability tensions, which have strong effects on land allocations. We analyze the results from two scenarios: the first one with no social-driven evolutions and a second one with the two implemented transition processes. Our results show that:

Agro-ecological and socio-economic site characteristics have a strong impact on the simulated family type distribution and consequently on the allocation of resources between the production activities.

In the simulation results for the three sites, emerging individualistic family types increase the robustness of the whole village population through different and site-specific evolutions. An intensification gradient is observed from the most favored site, where more intensive productions occurred and agro-ecological indicators are improved, to the less-favored one, where a large part of the population income is generated by migration remittances.

Key-words: integrated modeling, individual Agent-based model, Niger, Boserup paradigm

2 Introduction

Since the independence, the rural population of Nigerien Sahel has experienced major food crises (Alpha Gado, 1993), the last one having occurred as recently as 2005 (Loewenberg, 2005; Abdoulaye & Sanders, 2006; Harragin, 2006).

Actually, since the crises of the 70's and 80's, the Sahel has become the focus of strong debates on the importance of social factors in the evolution of systems of activities and farming systems. More precisely and as systems of activities in Sahelian Niger are based on small farms and families, the evolutions of this last scale are considered by several scholars (Stone *et al.*, 1990; Wiggins, 1995; Stone & Downum, 1999) as crucial determinants of the evolution of such systems, along more environmental ones that are the basis of the "desertification" concept (Aubréville, 1949; Adams & Mortimore, 1997; Reynolds *et al.*, 2003). Several scholars have acknowledged the population capacity to adapt the rules of access to production assets and thereby the organization of the systems of activities they use. In particular, the link between demography, social structure and resources has been noticed as far back as 1956 (Davis & Blake, 1956).

These anticipating adaptation processes are already taking place in Nigerien Sahel: inheritance, family organization, land tenure, social and symbolic references are evolving, because of economic pressures on individuals, families, and communities. Milleville & Serpantié (1994), Ehrlich & Luib (1997), Mathieu (1998), Lambin *et al.* (2001), Reenberg (2001), Mazzucato & Niemeijer (2001), Jouve (2004), ; Ouédraogo (2005), Raynaut (2007) and Tappan & McGahuey (2007) among others have all highlighted the major importance of social factors in farming system evolution analyses. Grégoire (1986), Luxereau & Roussel (id.), Olivier de Sardan (2003), all referring to the Sahelian part of Niger, have suggested two major, village-level social factors to consider as the main pathways for local farming system evolutions: family organizations are slowly disintegrated, shifting from patriarchal and enlarged families to mononuclear ones. The second shift concerns inheritance modes, moving from a customary mode, where one heir receives everything to a local version of the Muslim mode, where land is shared between the sons. We then adopt these two processes as the first driving media on which families may evolve in Sahelian Niger and thereby the related farming systems. Therefore, our objective is to develop answers on the following questions: What are therefore the long-term effects of such processes for the concerned families and farming systems? Do these effects are equivalent for all Nigerien Sahel?

Because such processes are conditioned and determined by both socio-economic and agro-ecological factors acting on a combined and intricate manner, it is irrelevant to focus on one side only. Therefore, for such a research, one should consider looking for a tool that can put in balance all the different economic and production activities of a Sahelian village but also all the factors that condition such activities, whatever the disciplines they belong. We consider that such a tool can be a model based on individuals, in order to avoid household oversimplifications (Saqalli, 2006). Meanwhile, a model cannot intrinsically and practically conceive all the possible evolutions of a society. Scenarios and hypotheses have to be built.
Our purpose is then to analyze the effects of such transition pathways in several rural Nigerien Sahelian villages with different levels of natural resource endowment and socio-economic opportunities and constraints. The purpose of the present chapter is to analyze the long-term impacts on village societies and farming systems of the two agro-ecologically originated but socially driven forces we described above, i.e. family organization and inheritance mode transitions. This global objective can be subdivided into three hypotheses to confirm:

- Such a model can consistently combine factors belonging to socio-anthropological and agro-ecological disciplines.
- These two evolution factors, i.e. inheritance & family organization changes, do indeed have a strong impact on resilience, efficiency and sustainability of the analyzed farming systems.
- Conceptualizing the evolution of these societies in the past and a fortiori in the future including the temporal variations of these two processes over time allows a better understanding of the dynamics of these societies.

Comparing the simulation outputs of these social change procedures with the present-day situation to determine the best theoretical “solution” is not relevant because literature shows that these transitions have already occurred, hence a poor fit between model results and reality for a given combination of factors does not invalidate the fact that this combination may have been relevant in the past. The comparison between simulation results of our model and present time situations can therefore not be used as a confidence-building step. The analysis is therefore based on a comparison of scenarios with or without evolution factors. Meanwhile, the model has successfully passed a confidence building procedure by comparing literature data on demography and land use with simulation results. Therefore, we compare the results of two scenarios:

- The first one where farming systems and populations evolve in the absence of family organization and inheritance changes as a reference level for comparative purpose (the scenario is thereafter named "No-Evolution Scenario").
- The second one where both family organization and inheritance systems can change according to the rules described above (the scenario is thereafter named "Evolution Scenario").

It is important to note that certain family types may reappear. The present-time situation of these two variables is presented in Table 7 for the three sites as derived from the literature. The calibration of these two processes has been jointly carried out for the three sites according to the collected information and literature. Twenty model runs have been realized for each scenario. All the processes and the patterns are described in chapter 1 and the whole methodology of the model development is described in chapter 3. More precisely, the assessment of the scenarios that are here compared is fully described in § 5.3 of this chapter 3.

3 Results

Simulations begin with the foundation of the village by families that belong to family customary organizations and traditional inheritance modes. The model scenarios are implemented on one-century long simulations. Apart from the initial definition of these family organizations and inheritance modes and transition processes, the model initialization is realized according to chapter 3 §4.1: at t=1 fifty villager Agents of various ages and gender-defined and 100 livestock head Objects, with one third of every species, appear in the "terroir". We first analyze the evolution of the three sites over a 100-year period according to the "No-Evolution" Scenario to compare thereafter with the results of the "Evolution" scenario. 20 simulations of each of the two scenarios have been assessed. The presented results are selected for the purpose of illustrating the main divergences between scenarios. The selected variables do not stabilize themselves over time because of the population growth that maintains itself throughout a simulation.

3.1 The "No-Evolution" Scenario: a progressive degradation because of local constraints

The results are the simulation outputs of a scenario in which no family organization or inheritance mode evolutions are considered, with only unitary and patriarchal families and a system of customary inheritance.

3.1.1 Production, global sustainability & social inequity: a structural geographic advantage

As indicated in line D of Table 28, the simulated population at the three sites strongly rises, by a factor 11 in the site of Zermou, the least agro-ecologically and socio-economically favored site, while Gabi, the most favored site, reaches a factor 32. The site characteristics have therefore a noticeable effect on the simulated population growth.

Table 28. 100 years evolution of selected indicators for the three sites in a No-Evolution Scenario (fixed unitary family & customary inheritance system) (Mean + standard deviation; n=20). (Part 1)

		Zermou					
		1	2-25	26-50	51-75	76-99	
Environ-mental sustainability	Arable land saturation (%)	29.9	79.6	94.3	100	100	A
	Pearl millet yields (quintals / ha)	5.4 ± 0.8	4.6 ± 0.7	3.8 ± 0.5	3.6 ± 0.5	3.6 ± 0.5	B
	Vegetation cover (% of the initial cover)*	80.5 ±15.8	39.7 ± 5.2	16.8 ± 4.8	10.5 ± 4.4	7.6 ± 1.7	C
Average population performances	Population size	47 ± 12	69± 24	152 ± 58	313 ± 120	495 ± 284	D
	Income per capita (in €)	18.3 ± 8.1	17.3 ± 0.4	5.7 ± 0.8	4.2 ± 1.0	3.3 ± 0.7	E
	Cropped surface per capita (in ha)	2.3± 0.6	4.2 ± 0.5	2.2 ± 0.2	1.2 ± 0.1	0.7 ± 0.1	F
	Livestock size per capita (in TLU[171])	0.4 ± 0.1	0.5 ± 0.2	0.4 ± 0.2	0.6 ± 0.2	0.4 ± 0.2	G
Social sustainability	Male/female income ratio	1.6 ± 0.2	1.7 ± 0.2	1.7 ± 0.2	2.8 ± 0.4	4.3 ± 0.5	H
	Coefficient of Gini between families	0.48 ±0.14	0.55 ±0.11	0.60 ±0.08	0.65 ±0.08	0.68±0.09	I
		Fakara					
		1	2-25	26-50	51-75	76-99	
Environ-mental sustainability	Arable land saturation (%)	04.7	13.2	59.8	94.2	97.8	A
	Pearl millet yields (quintals / ha)	5.8 ± 0.9	4.8 ± 0.6	4.4 ± 0.3	4.1 ± 0.2	4.0 ± 0.2	B
	Vegetation cover (% of the initial cover)*	93.9 ± 7.2	81.5 ± 4.1	46.4 ± 5.3	18.3 ± 3.0	12.3 ± 2.3	C
Average population performances	Population size	50 ± 2	80 ± 15	223 ± 69	639 ± 209	1246 ± 386	D
	Income per capita (in €)	39.7 ± 5.1	30.9 ± 1.5	14.3 ± 1.1	12.4 ± 0.9	10.5 ± 1.2	E
	Cropped surface per capita (in ha)	0.5 ± 0.2	0.9 ± 0.3	1.4 ± 0.2	0.8 ± 0.1	0.4 ± 0.05	F
	Livestock size per capita (in TLU.)	0.4 ± 0.1	0.5 ± 0.2	0.4 ± 0.2	0.6 ± 0.2	0.8 ± 0.2	G
Social sustainability	Male/female income ratio	1.7 ± 0.2	1.4 ± 0.1	1.3 ± 0.1	1.9 ± 0.3	2.3 ± 0.4	H
	Coefficient of Gini between families	0.50 ±0.11	0.53 ±0.06	0.61 ±0.02	0.68 ±0.02	0.74 ±0.02	I

[171] One tropical livestock unit (TLU) = 1.5 cattle = 10 sheep = 12 goats (Le Houérou & Hoste, 1977)

Table 28. 100 years evolution of selected indicators for the three sites in a No-Evolution Scenario (fixed unitary family & customary inheritance system) (Mean + standard deviation; n=20). (Part 2)

		Gabi					
		1	2-25	26-50	51-75	76-99	
Environ-mental sustainability	Arable land saturation (%)	04.3	07.1	24.3	67.1	98.4	A
	Pearl millet yields (quintals / ha)	9.3 ± 1.8	5.4 ± 0.7	4.9 ± 0.4	4.4 ± 0.3	4.2 ± 0.2	B
	Vegetation cover (% of the initial cover)*	105.2 ± 8.4	93.8 ± 4.5	63.2 ± 6.7	30.6 ± 4.9	14.9 ± 1.9	C
Average population performances	Population size	51 ± 1	75 ± 15	189 ± 53	579 ± 169	1591 ± 419	D
	Income per capita (in €)	43.8 ± 8.6	32.6 ± 4.3	17.0 ± 1.7	20.5 ± 2.2	36.3 ± 2.9	E
	Cropped surface per capita (in ha)	0.4 ± 0.2	0.5 ± 0.2	0.6 ± 0.1	0.5 ± 0.1	0.3 ± 0.08	F
	Livestock size per capita (in TLU)	0.4 ± 0.1	0.6 ± 0.2	0.7 ± 0.2	0.8 ± 0.1	1.1 ± 0.3	G
Social sustainability	Male/female income ratio	2.1 ± 0.2	1.9 ± 0.1	1.6 ± 0.1	3.5 ± 0.2	5.7 ± 0.5	H
	Coefficient of Gini between families	0.53 ±0.14	0.61 ±0.09	0.59 ±0.03	0.63 ±0.01	0.66 ±0.02	I

* Combined weed and shrub vegetation

The simulated constraints decrease along a north to south Zermou-Fakara-Gabi gradient and thereby their consequence on the related simulated societies: Wedding dowries need funds that may be found only through economic activities, all less remunerated in Zermou and even impossible to practice in the case of gardening. It explains why the delay before marriage is longer at this site.

The territory of each simulated site is progressively occupied, in less than 25 years for Zermou as opposed to nearly 100 years for the sites of the Fakara and Gabi (Table 28 line A). This difference is explained by two factors. As simulated families have to get enough millet to fulfill their growing food requirements, the lower soil fertility as implemented in Zermou (see Table 2) implies rapid yield decline forcing the population to more quickly expand their fields, in spite of the weaker growth of the population. The simulated Fakara and Gabi sites do not experience such race for land and their territories are conquered more slowly.

At the three sites, the simulated population continues to rise and there is no collapse of agricultural production even after the total occupation of arable lands, despite the decline of soil fertility and vegetation. To understand this absence of collapse, one may observe that the three simulated agro-ecological characteristics of all sites evolve according to comparable tendencies. The model does not simulate in any of the sites a yield collapse but a continued decline up to a minimum and stable level. At the end of the 100 years, yields remain higher in Gabi in comparison with the Fakara site and even more with Zermou, but the differences are small (Table 28 line B). Other non-agricultural factors that are independent from rain (migration, gardening) help to support the populations in their growths.

For agriculture, the simulated fertility-regenerating procedures are the 1-year fallow regeneration process[172] and the manure supply from herds. This last supply comes from the transfer of nutrients from fields and pastures that also declines with the growing cropland area. This process proceeds at different rates for the three sites but leads eventually to an equivalent vegetation cover as one can see for the last 25 years of the simulations (Table 28 line C).

Livestock rises very strongly in absolute value at the three sites: 1182 ± 78 Tropical Livestock Units (TLU[173]) for Gabi, 952 ± 87 for Fakara, 240 ± 39 for Zermou at t=] 75:100] to be compared with an average value of 14.17 TLU at t=0 for the three sites. The three first graphs of Figure 33 (33.1, 33.3 & 33.5) show the sizes of the herds owned by the populations and not only the ones staying in the village territory.

One can observe that simulated herds are progressively more and more cattle-dominated, that are in majority in transhumance during nine months of the year[174] and therefore with little effects on local fertility transfers but also independent from the local pasture constraints. This cattle accumulation can therefore be considered as a way of "off-shore" savings. As the model is village-based, it does not take in account the question whether outside transhumance territories can accommodate such a cattle expansion, remembering the numerous incidents between herders and farmers observed in recent times (Turner, 1999b; Lycklama, 2000; Turner *et al.*, 2005).

This absence of collapse and the gradual decline of natural resources in the simulations is accompanied by the stagnation and even the reduction of local subsistence means per inhabitant: actually, the cropped surface per inhabitant at the three sites declines over time (Table 28 line F). Only Gabi sees the average population income maintained and growing a little in this scenario (Table 28 line E). The site of Zermou maintains its livestock per inhabitant ratio, Fakara doubles it and Gabi sees it growing by a factor of 2.8

---

[172] This process is implemented only for fields that were sowed but whose sowings failed and were therefore abandoned for a one-year fallow.
[173] One tropical livestock unit (TLU) = 1.5 cattle = 10 sheep = 12 goats (Le Houérou & Hoste, 1977)
[174] Only remain at the village calves, milking cows and one or two bulls per family for pulling the cart

(Table 28 line G). These indicators altogether suggest that population and natural resources of these three sites as they are implemented jointly evolve but at a rate which depends on the initial conditions of each site.

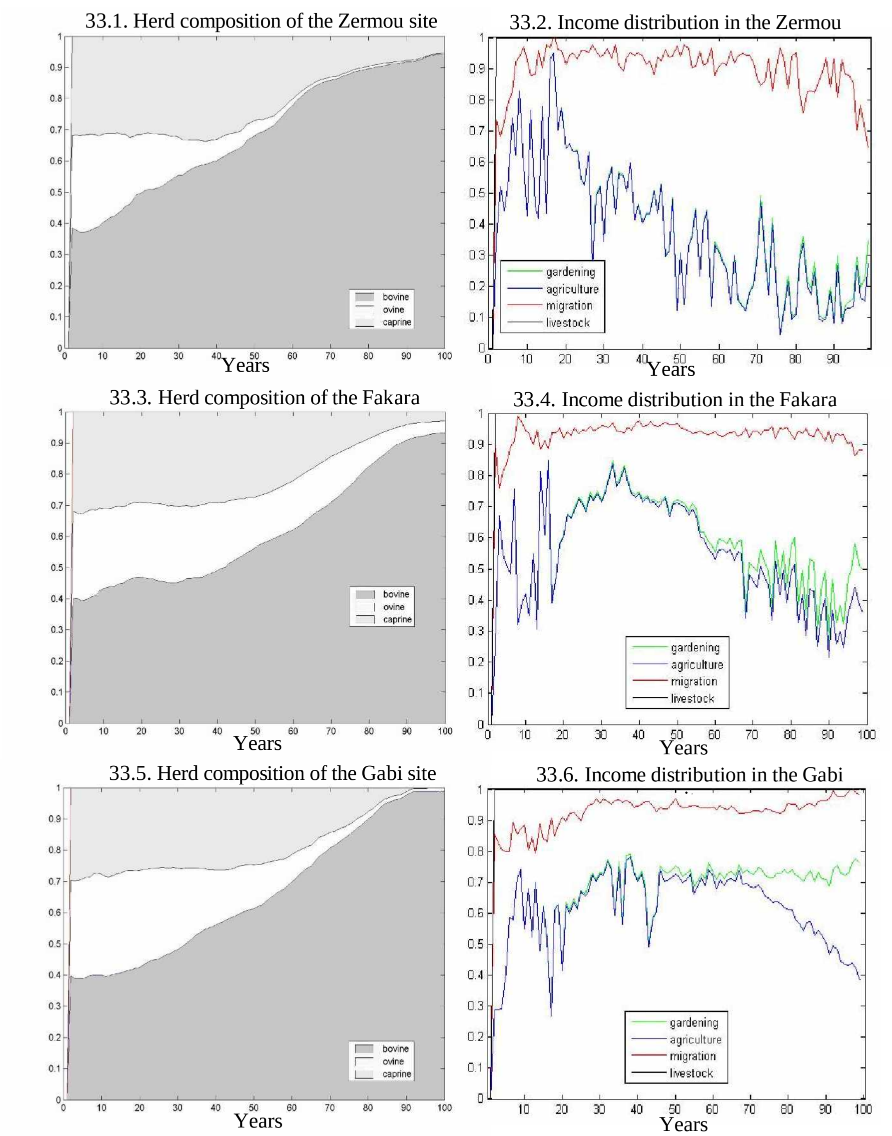


Figure 33. Proportion of species in the herds and proportion of the different activities in the village income of the three sites in the No-Evolution scenario

This village scenario induces a rise in social inequalities. The income difference between men and women grows at the three sites (Table 28 line

H). The site of Fakara presents the weakest growth of this inequality, mainly because women are the managers and the first recipients of the gardening activity. One can, however, wonder about a possible future appropriation by men of this activity if it becomes profitable, which would counter-balance the present-time male Zarma contempt for this activity.

The Gini coefficient (see chapter 4 § 3.2.3) calculated between families along the simulation from the mean values of the repetitions (Table 28 line I) underlines the social differentiation between the families, in particular in the Fakara site, as an intermediate zone where differentiation is easier between families compared to Gabi where everybody can have quite good income and to Zermou where everybody suffers from poor yields and low gains.

Finally, the standard-errors show the growing vulnerability of these simulated systems: the standard-errors between simulations of the population (Table 28 line D) increases according to the gradient Gabi-Fakara-Zermou, indicating a higher potential vulnerability of the population of Zermou facing climatic and migration risks and costs. The inter-annual coefficient of variation between simulations, calculated from the average annual figures, has an average value of 2.15 in Zermou, 1.59 for the Fakara and 0.78 for Gabi over that last 10 years (] 90: 100]). This difference underlines the fact that the yields are stabilizing over time, but shows also that the gradient Gabi-Fakara-Zermou remains applicable for the irregularity of millet yields. An equivalent gradient appears for migration, because of the highest transportation cost and the higher racketing risk in Zermou (Table 2) but not for gardening, (because it is independent from rainfall) and livestock keeping (because of the "off-shore" effect on almost the totality of the herd, and thereby its quasi–independence from local conditions).

3.1.2 Differentiation of economic activities: extra-local activities as a compensation for a local degradation

The distribution of activities explains the evolution of the simulated economic activities. Figures 33.2, 33.4 & 33.6 show the distribution between the four main economic activities at the three sites, including livestock keeping. Agriculture appears less important in terms of income share than expected according to many scholars (Affholder, 1997; Breman *et al.*, 2001; Drechsel *et al.*, 2001)[175]. This activity, as the most sensitive to the agro-climatic conditions, declines more or less rapidly at the three sites after an

[175] See Adams & Mortimore (1997), Howorth & O'Keefe (1999), Niemeijer & Mazzucato (2002), Koning & Smaling (2005) and Mortimore & Turner (2005) for a discussion on this gap.

initial peak. This peak is longer at the best site, namely Gabi (nearly for fifty years at $^{2}/_{3}$ of the village global income) in comparison with the most difficult site, namely Zermou (less than 10 years before declining). The decline extent is sensitive to the site factor as well: agriculture represents at t=] 75:100] 44% of the village income in Gabi and the Fakara but drops to 25% in Zermou. Gardening does not compensate everywhere this decrease of local agriculture: this activity is nearly absent in Zermou, because of simulated agricultural reasons (the territory simulated in Zermou is nearly totally void of irrigable parcels) but also because of social ones.

As indicated in Table 2, gardening in the Hausa zone, of which belong the sites of Zermou and Gabi, is restricted to men. The rule implemented for Zermou establishes that the distance to the Nigerian border does not allow men to practice simultaneously gardening and migration, while it is possible for men in Gabi. Gardening is therefore a very weak activity in Zermou. Meanwhile, this activity took a lot of time to develop itself at the two other sites. This delay can be explained by the need for sufficient manpower at the family level (see chapter 4), but also by the clear relation between this delayed development and land saturation (Table 28 line A). Gardening does not take off until after land saturation, implying a manpower reallocation at the family level.

Migration and livestock keeping, as extra-local activities, play therefore a role of compensators facing the local resource limitations. Livestock keeping, thanks to cattle transhumance, is free from the local pasture constraints and maintains itself all along simulations, whereas migration grows slowly at the three sites, reaching up to 45% of the total local income in the Fakara (Figure 33.4).

Thus, the unitary family organization allows the distribution of activities to evolve when local resources become limited because of land saturation and/or degradation. This evolution favors external activities, particularly for the least favored site. The villagers' economic situation is more and more limited and fragile, but does not collapse. This last point is important: it means that building a model where no cognitive and complicated rules are implemented but where combining different economic activities at the family and individual levels is possible, allows a shift of all or a part of the population from one activity to another to maintain or at least limit the decline of the income because of local resources decline. The three sites seem therefore to "specialize" themselves in one activity amongst the alternative activities from millet agriculture: migration in the Fakara, gardening for Gabi and livestock keeping in Zermou.

3.2 Introducing social evolutions: family shifts as accelerators of farming system evolutions

Results of the previous scenario are here compared with the ones from simulations of a scenario in which families, initially unitary and with a customary mode of inheritance, can evolve according to the social rules established by the modeling methodology.

3.2.1 The family Evolution Scenario: same social rules but different contexts creating specific social stratifications.

Families multiplied themselves at all sites through the "explosion" of once unitary families due to the inheritance and family organization rules we implemented, which means that the breakup of the unitary family dilutes and alleviates these tensions. Thus, we find in Zermou 104.5 families on average vs. 9.7 in the "No-Evolution" scenario at t=] 75:100], 117.4 families vs. 7.7 in Gabi and 204.5 families vs. 8.4 in the Fakara site! As the Fakara presents the particularity of restricting the gardening activity to women and thereby creating another source of "frustration", the social "frustration" indicator Tac increases more rapidly at this site. These shifts occur at different moments depending on the sites, as indicated in Figure 34.

Unitary families disappear in the Fakara five years earlier than at the two other sites (Figure 34.3 to compare with figures 34.1 & 34.5). Moreover, the extent of this shift is far more important in the Fakara, reducing the part of Unitary Families with a Customary Inheritance System (UFCIS) to less than 5% of the number of families, but 19% of the total population. The Non-Cooperative Families with a Customary Inheritance System (NCFCIS) become dominant reaching up to 59% of all families and 52% of the village population (Figure 34.4). The arable land saturation is slower than in the "No-Evolution" scenario can be seen from a comparison between lines A of Table 28 and Table 29. Consequently, the shift towards the local version of the Muslim inheritance mode remains limited. At the two other sites, with a more rapid arable land saturation, the Non-Cooperative & "local Muslim" Inheritance System Families (NCFMIS) become dominant in the number of families and even in the village population for Gabi (figures 34.5 & 34.6).

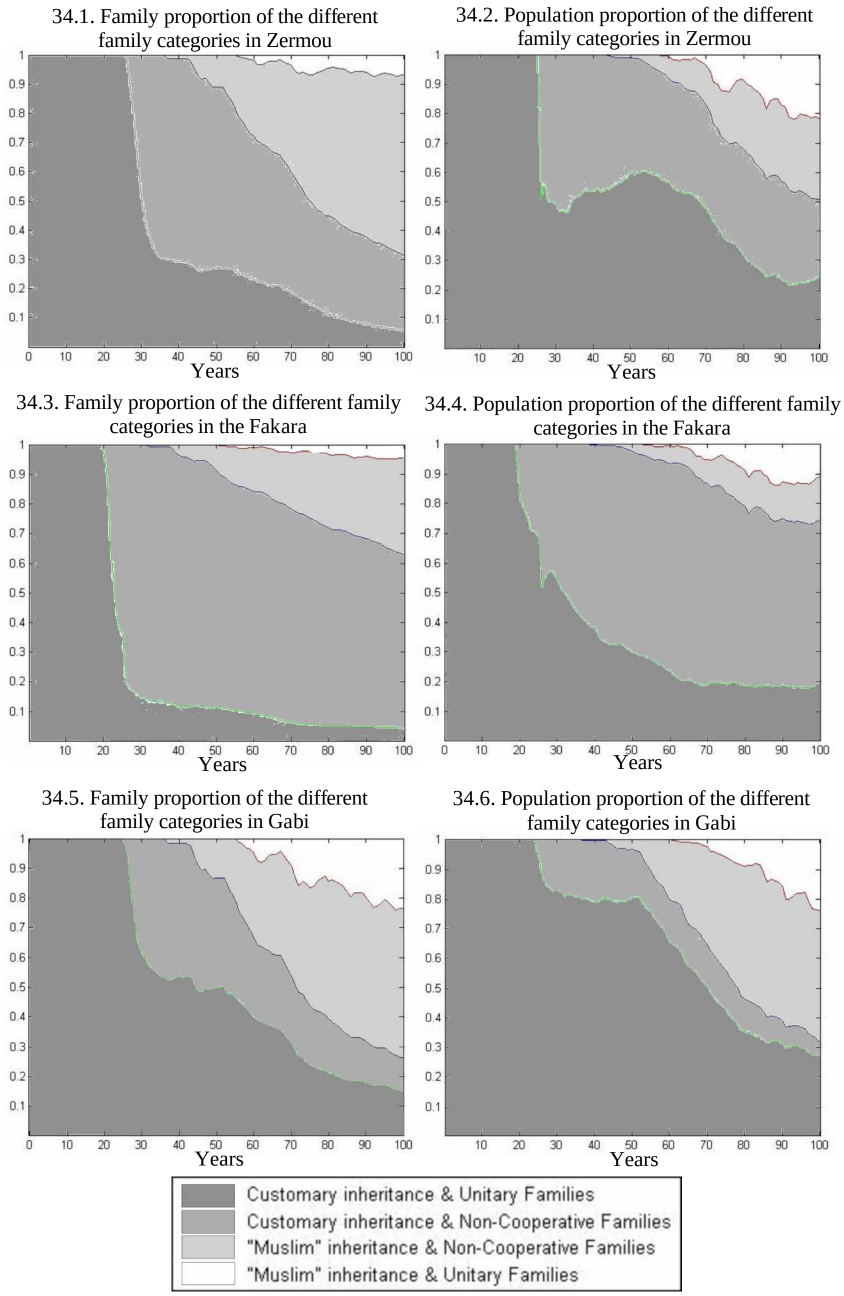


Figure 34. Proportions of the four different family categories & the different activities in each site

A family type unobserved during field investigations appears in simulations at the three sites: the Unitary Family with the "local Muslim" Inheritance System (UFMIS). It occurs in case of land-limited and little multi-active families. Paradoxically, it is the site of Gabi, with more facilities for multi-activity (large irrigable land availability and cheaper seasonal migration), that maintains a more important proportion of such unitary families, reaching more than 20% (Figure 34.4) against 6% in Zermou (Figure 34.1) and 3% in the Fakara. This development in Gabi could be explained by the fact that economic activities remain in the hands of the men, who can combine gardening and migration thanks to the proximity of the border (Table 2), which allows the unitary organization to remain.

Table 29. 100 years evolution of selected indicators for the three sites in the Evolution scenario (family organizations & inheritance systems can change) (Mean + standard deviation; n=20) (Part 1)

		Zermou					
		1	2-25	26-50	51-75	76-99	
Environ-mental sustainability	Arable land saturation (%)	28.9	83.8	100	100	100	A
	Pearl millet yields (quintals / ha)	6.2 ± 0.5	4.9 ± 0.3	4.0 ± 0.2	3.9 ± 0.2	3.8 ± 0.1	B
	Vegetation cover (% of the initial cover)*	85.6 ±11.1	42.2 ± 4.1	18.2 ± 4.9	10.9 ± 4.0	8.0 ± 1.5	C
Average population performances	Population size	50 ± 3	76 ± 11	181 ± 35	333 ± 93	545 ± 168	D
	Income per capita (in €)	21.6 ± 7.7	13.4 ±2.6	4.3 ± 0.6	4.4 ± 0.4	4.9 ± 0.4	E
	Cropped surface per capita (in ha)	2.1 ± 0.4	4.0 ± 0.5	2.0 ± 0.2	1.1 ± 0.1	0.7 ± 0.04	F
	Livestock size per capita (in TLU)	0.5 ± 0.1	0.5 ± 0.1	0.6± 0.2	1.1 ± 0.2	1.3 ± 0.4	G
Social sustainability	Male/female income ratio	1.8 ± 0.3	1.7 ± 0.1	1.7 ± 0.2	2.7 ± 0.3	3.4 ± 0.4	H
	Coefficient of Gini between families	0.51 ±0.14	0.60 ±0.10	0.64 ±0.05	0.73 ±0.02	0.71 ±0.02	I
		Fakara					
		1	2-25	26-50	51-75	76-99	
Environ-mental sustainability	Arable land saturation (%)	04.6	10.8	55.4	81.2	88.5	A
	Pearl millet yields (quintals / ha)	6.3 ± 1.1	4.7 ± 0.7	4.4 ± 0.4	4.2 ± 0.2	4.0 ± 0.2	B
	Vegetation cover (% of the initial cover)*	94.1 ± 6.4	82.5 ± 3.9	47.0 ± 4.8	20.7 ± 3.0	13.0 ± 2.3	C
Average population performances	Population size	51 ± 1	80 ± 13	198 ± 54	421 ± 159	704 ± 156	D
	Income per capita (in €)	51.8 ± 6.7	53.4 ±2.4	11.2 ± 0.6	11.3 ± 0.4	13.1 ± 0.3	E
	Cropped surface per capita (in ha)	0.5 ± 0.1	0.7 ± 0.2	1.5 ± 0.1	1.0 ± 0.1	0.7 ± 0.03	F
	Livestock size per capita (in TLU)	0.5 ± 0.1	0.6 ± 0.2	0.4 ± 0.1	0.5 ± 0.1	0.8 ± 0.2	G
Social sustainability	Male/female income ratio	1.6 ± 0.1	1.3 ± 0.1	1.2 ± 0.1	1.6 ± 0.2	1.9 ± 0.3	H
	Coefficient of Gini between families	0.50 ±0.14	0.54 ±0.05	0.60 ±0.03	0.68 ±0.02	0.68 ±0.02	I

* Combined weed and shrub vegetation

Table 29. 100 years evolution of selected indicators for the three sites in the Evolution scenario (family organizations & inheritance systems can change) (Mean + standard deviation; n=20) (Part 2)

		Gabi					
		1	2-25	26-50	51-75	76-99	
Environ-mental sustainability	Arable land saturation (%)	22.5	76.0	100	100	100	A
	Pearl millet yields (quintals / ha)	10.3 ± 0.7	5.8 ± 0.3	4.6 ± 0.2	4.4 ± 0.2	4.4 ± 0.2	B
	Vegetation cover (% of the initial cover)*	100.8 ± 9.2	47.3 ± 3.7	14.8 ± 3.4	12.3 ± 2.7	11.5 ± 2.6	C
Average population performances	Population size	51 ± 1	77 ± 12	210 ± 44	607 ± 102	1475 ± 199	D
	Income per capita (in €)	38.9 ± 7.8	26.2 ± 1.6	14.9 ± 1.0	16.7 ± 1.2	19.5 ± 3.0	E
	Cropped surface per capita (in ha)	2.1 ± 0.6	4.7 ± 0.7	2.3 ± 0.4	0.8 ± 0.1	0.3 ± 0.06	F
	Livestock size per capita (in TLU)	0.5 ± 0.1	1.0 ± 0.2	1.4 ± 0.3	2.0 ± 0.4	2.5 ± 0.6	G
Social sustainability	Male/female income ratio	2.1 ± 0.3	1.8 ± 0.1	1.6 ± 0.1	3.9 ± 0.3	6.2 ± 0.4	H
	Coefficient of Gini between families	0.54 ±0.13	0.52±0.05	0.62 ±0.04	0.70 ±0.02	0.70 ±0.02	I

* Combined weed and shrub vegetation

Paradoxically, this group appears after the NCFMIS at the three sites rather than before these. They may originate from formerly UFCIS families but also from formerly NCFMIS having evolved directly into UFMIS, in the case of the young families having many young children and being unable to develop yet some activities other than the ones managed by the head of the family.

In order to corroborate this appearance, one may notice that in urban and semi-urban areas of the Maradi region where Gabi is located, the development of a new middle-class of traders, called the "izalah", rather young families and very rigorous from a religious point of view[176], besides the old and big traders having established their fortune on clientele networks (Grégoire, id.). We thereby suppose that the main reason why we did not observe such families in the investigated villages is that they have already shift in town (i.e. in Maradi or Madarounfa, the nearest small town), even if they still have and crop (and/or make crop) their fields in the village.

We obtain thus for each simulated site a different village organization (Figures V-2.1, V-2.3 & V-2.5): the sites of the Fakara and of Zermou as they are implemented are almost totally composed of Non-Cooperative mononuclear families. They are shared in Zermou between Muslim

[176] This Islamic legitimacy allows them to limit their solidarity to the "zakat", the Muslim alms pillar, and therefore to be able to foresee their management and to free it from social and family contingencies.

inheritance families for the $^2/_3$ and customary inheritance families for $^1/_3$, while these proportions are inverted for the Fakara site. Finally, the Gabi population is shared between the two family organization types, unitary ($^1/_3$) and non-cooperative ($^2/_3$) and the two inheritance systems, customary ($^1/_4$) and Muslim ($^3/_4$). These proportions are important as they determine the proportion of "decision-makers" in the population (family heads only in the case of unitary families, a lot of adults in the case of non-cooperative families), whereas the proportions in terms of population, different from the family proportions because of the gap in family size between the family types, define the consequences of these decisions on the total population.

3.2.2 Production & sustainability at the village level: new population robustness due to family decomposition & individualization.

The new family type appearing has several impacts on the simulated village wealth: As described in Saqalli (id.), the appearance of mononuclear families in the Fakara site slows the growth of the global population and of cultivated surfaces in a similar way than harsher agro-ecological and economic conditions (Table 28 & Table 29, line A & D), because of the increased delay for marriage (no intra-family support for the dowry and thereby restriction on farm settlements). Meanwhile, the two sites of Gabi and of Zermou are largely different: the absence of a significant difference between the two scenarios on land saturation and population can be explained first because the number of families is half of that of the Fakara and second because about 50% of the population still belongs to unitary families, that favor demographic growth. Moreover, one can consider that the discriminating effect of the new family organizations does not appear so much for these two sites: In Zermou, the monetary constraint is already strong enough for the "No-Evolution" scenario (livestock and income per capita are there already the smallest figures of the three sites); therefore, new family modes do not reduce much more the growth of the population. One can suppose as well that the monetary limits in Gabi that appear along the simulation with these new families are not strong enough at the family and individual level to slow down marriages in significant way and thereby the growth of the population. The average income in the "Evolution" scenario increases in the second half of the simulation at the three sites and more particularly in Gabi (Table 28 & Table 29, line E) compared to the "No-Evolution" scenario. The cropped surface per inhabitant doubles in the Fakara site in the "Evolution" scenario because of the lower population growth, which is logically not observed in Zermou or in Gabi (Table 28 & Table 29, line F). Inversely, if the livestock herd size per inhabitant is more than three times higher in Zermou and more than two times higher in Gabi in the "Evolution" scenario compared with the "No-Evolution" one, it grows in an equivalent manner for the two scenarios in the Fakara site (Table 28 & Table 29, line G).

Therefore, considering both income and livestock altogether, the three simulated sites experience a better level of wealth per capita. However, the most-favored and the less-favored sites get this improvement through livestock savings while the intermediate get this improvement thanks to a lowering of its population, because of a quicker orientation towards non-cooperative family modes.

In terms of environmental sustainability, although the land is more slowly colonized along the simulations in the "Evolution" scenario, yields per hectare remain equivalent for both scenarios at the three implemented sites (Table 28 & Table 29, line B). The same is true for the vegetation cover in the two poorest sites, i.e. Zermou and the Fakara (Table 28 & Table 29, line C). Gabi sees a slightly stronger decline in vegetation cover, related to a larger cultivated area and a higher livestock per inhabitant ratio. In terms of social sustainability, inequalities between families and between gender reduce in two sites: if the coefficients of variation of the gender inequality are significantly reduced in Zermou and for the Fakara site, they stay equivalent in Gabi (Table 28 & Table 29, line H). The inequality between families instead is higher in the "Evolution" scenario compared to the "No-Evolution" one in Zermou and Gabi whereas it is significantly reduced in the Fakara site (Table 28 & Table 29, line I).

Finally, the coefficients of variation between repetitions of several factors (population, income & surface appropriated per capita) are significantly lower for the three sites (Table 28 & Table 29, lines D, E & F) in the "Evolution" scenario, which means that the collapse risk of the income and/or of the population, following a drought for instance, are reduced thanks to these new family types. However, the livestock per inhabitant is less stable: the new scenario plays its stabilizing part on this factor only for Gabi whereas no difference appears for the Fakara site and the variability even increases in Zermou (Table 28 & Table 29, line G).

Therefore, the populations of the three sites as they are implemented seem to be more robust to the hazards of production activities. This new robustness, together with a higher average income per capita, seems in the case of the Fakara site to come from a population reduction while it seems to be acquired by a clear increase of livestock in the case of the two other sites. However, in this case as well, it is necessary to consider the impacts of other activities (gardening & migration) in the analysis of the adaptation ways of the new families, in order to explain the economic connections between genders and between family types.

3.2.3 Activities & livestock distribution: increasing the robustness through site-specific orientations

The distribution of activities in this "Evolution" scenario is illustrated by the three graphs at the right of Figure 35:

The social differentiation does not translate into a significant change in the relative importance of the different activities at the Zermou site (Figure 35.2). Agriculture keeps declining to the benefit of livestock keeping and migration, the latter reaching about 72% of the average income, while gardening stays next to nothing.

However, Figure 35.1 shows a strong evolution at Zermou towards small livestock. This goes together with a multiplication by 3.9 of the volume of this herd (939±89 TLU vs. 240±39 in the "No-Evolution" scenario over the last 25 years). One can notice the multiplication by 28 of the number of goats (254 vs. 9 in the "No-Evolution" scenario), the caprine herd thereby representing 33% of the total livestock vs. 5% in the "No-Evolution" scenario, without a particularly strong decline of the vegetation cover (Table 28 line C). This results from the new social rules introduced by this scenario, which leads to the multiplication of individual strategies of livestock accumulation, geared towards goat and sheep that are less expensive. One may notice that the average sheep herd in Zermou increases from 2 to 18 units with the "Evolution" scenario, that is to say an evolution in the same proportion than that of the number of families. With one sheep per family to slaughter every year for the Tabaski ceremony, it means that despite the explosion of families, one family out of five can fulfill its social chores, similar to the "No-Evolution" scenario. It is an interesting indicator of the economic viability of these families. With a tripling of the number of cattle, this added livestock is nearly independent of local pastoral conditions, thanks to the transhumance.

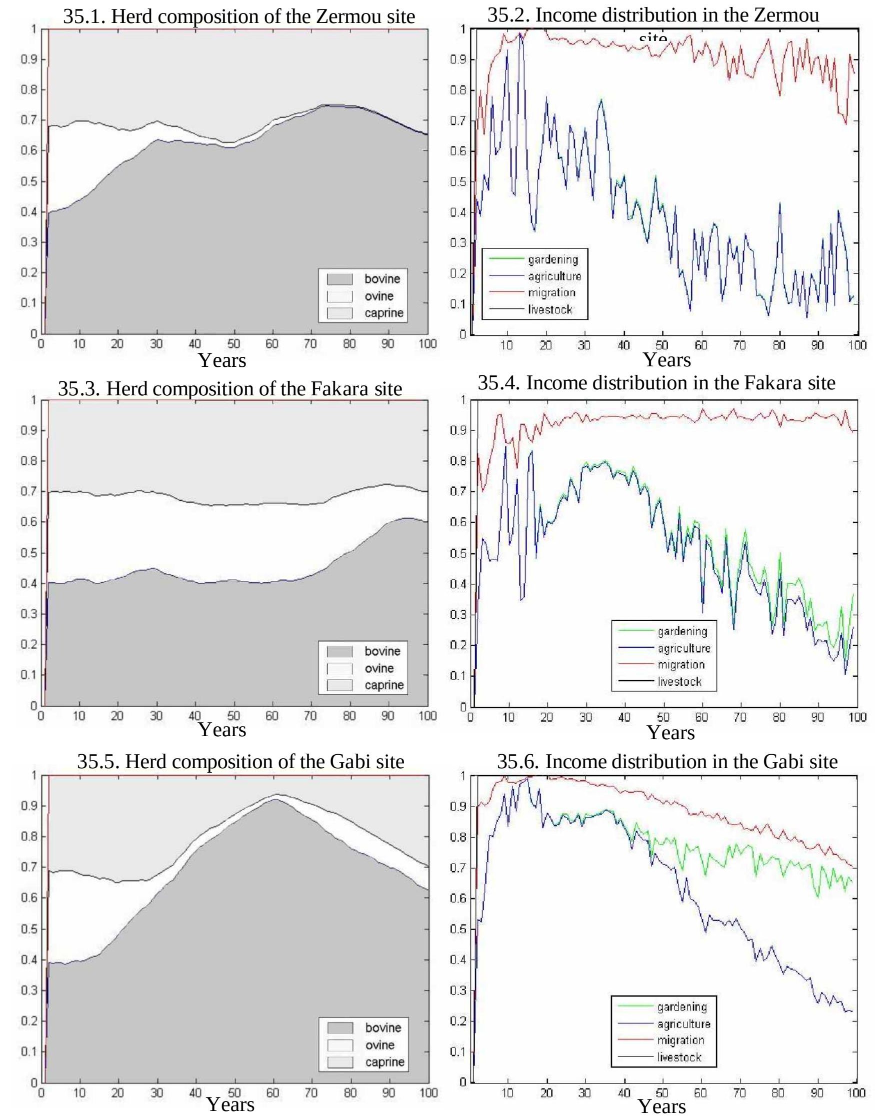


Figure 35. Proportion of species in the herds and proportion of the different activities in the village income of the three sites for the "Evolution" scenario

The site of the Fakara sees the income contribution of migration rising (66% of the average income over the last 25 years against 39% in the case of the "No-Evolution" scenario), reducing the parts of gardening, agriculture and livestock keeping (Figure 35.4). The volume of the herd stays stable (837 ± 98 TLU vs. 952 ± 87 in the case of the "No-Evolution" scenario), but the

composition evolves strongly (Figure 35.3) with a multiplication by 7.2 of the number of goats, and by 3.7 of the number of sheep.
Finally, the activities in Gabi are also affected by focusing more on local activities (Figure 35.6). Agriculture and gardening are maintained, with a slight extension of the latter. Migration passes from 26% of the average income in the "No-Evolution" scenario to less than 6%, whereas livestock keeping reaches 29% vs. 2% in the "No-Evolution" scenario. This strong growth can be explained by the same but more intense shift as observed at the two other sites, i.e. a multiplication of the small ruminants (Figure 35.5): 611 sheep and 1910 goats vs. 11 sheep and 9 goats in the "No-Evolution" scenario on average over the last 25 years, increasing the proportion of small ruminants from 1% to 37% of the total.

These small ruminants are characterized by a life cycle turnover far more rapid than that of cattle, allowing for an increase of the number of sales and of auto-consumption. As the small ruminants stay on the village territory, their higher numbers means a higher fertility transfer from grazing areas towards the cropped fields. The multiplication of families means that a more important part of the cattle herd does not leave for transhumance as well, as the model forces each family to keep in the village territory some cattle, thereby reinforcing the fertility transfer effect but also the pressure on grazing lands.

As a partial conclusion, at the three sites, livestock keeping seems to change its status from of an "off-shore" saving account in the "No-Evolution" scenario to that of a "remunerating" account used locally in the "Evolution" scenario, particularly for the most favored site of Gabi. If no evolution in terms of activity distribution appears at the least favored site of Zermou, migration becomes preponderant in the Fakara to the detriment of local activities, whereas it is livestock keeping and gardening that plays this role for the most favored site of Gabi.

3.2.4 Production & sustainability at the family levels: differentiation of the social family types according to site history & environments

Analyzing the differences in indicator values among the family types provides information on their differentiated reactions throughout the 100 years of simulation. Table 30 presents the average values over the last 25 years of several indicators for each family type. One may notice that it is not the same social types that benefit from a better income per capita depending on the sites (Table 30 line A): If the gaps between the types stays small in Zermou, with a slight advantage for the NCFCIS in a globally poor context, the UFCIS at the two other sites remains the poorest, which can be explained by a more important ratio between children and adults, as shown by the differences between Figures 35.3 & 35.5 and 35.4 & 35.6.

On the other hand, the average income per capita of the NCFMIS reaches double that of other groups for the two sites of Gabi and the Fakara. A high level of income does not imply an important availability in fields or in livestock (Table 30 line C & E), but rather more efficient orientation of the available manpower. As a matter of fact, the modeling does not introduce any cognitive process in the individual or family manpower allocation between the activities, because these are quite practically not competing for manpower in terms of time schedule (migration mainly occurs after harvesting times). It is the "natural" evolution in terms of manpower, population and land access of the various family types that determines this allocation. For example, the proportion of fields owned by the UFCIS always stays important even with a small population, because of their anteriority in the conquest of arable fields.

Table 30. Selected indicator mean values for the last quarter t=] 75-100] for the three sites for the "Evolution" scenario (Mean+standard deviation; n=20). (Part 1)

	Zermou				
	UFCIS	NCFCIS	NCFMIS	UFMIS	
Income per capita (in €)	4.7 ± 0.2	6.8 ± 0.3	5.4 ± 0.7	2.2 ± 0.3	A
Income proportion (%)	24.9 ± 0.9	33.2 ± 1.7	33.0 ± 4.2	9.0 ± 1.4	B
Livestock size per capita (TLU)	2.5 ± 0.7	0.7 ± 0.2	1.0 ± 0.4	1.2 ± 0.3	C
Livestock proportion (%)	47.6 ± 14.6	13.1 ± 2.3	22.3 ± 8.4	17.0 ± 4.7	D
Cropped surface per capita (in ha)	1.0 ± 0.02	0.9 ± 0.08	0.3 ± 0.02	0.6 ± 0.06	E
Cropped surface proportion (%)	38.8 ± 0.7	31.3 ± 2.7	11.2 ± 0.9	18.7 ± 1.7	F
Yields (q/ha)	3,4 ± 0.4	3,6 ± 0.3	4,0 ± 0.3	3,8 ± 0.2	G
Coef. Gini between families	0.75± 0.01	0.63± 0.03	0.61 ± 0.02	0.88± 0.01	H
Livestock proportion in the income (%)	13 ± 3	5 ± 0.9	11 ± 2	6 ± 1.2	I
Migration proportion in the income (%)	52 ± 5	79 ± 8	67 ± 7	89 ± 9	J
Gardening proportion in the income (%)	2 ± 0.1	1 ± 0.1	4 ± 0.1	1 ± 0.1	K
Pearl millet agriculture proportion in the income (%)	33 ± 7	15 ± 2	17 ± 2	4 ± 1	L
	Fakara				
Income per capita (in €)	7.6 ± 0.2	12.5 ± 0.2	22.8 ± 0.8	12.3 ± 0.5	A
Income proportion (%)	11.0 ± 0.2	51.6 ± 0.7	26.1 ± 0.9	11.3 ± 0.4	B
Livestock size per capita (TLU)	0.5 ± 0.1	1.0 ± 0.3	0.7 ± 0.3	0.5 ± 0.2	C
Livestock proportion (%)	13,0 ± 1.8	65.7 ± 15.0	13,1 ± 4.2	8,2 ± 2.2	D
Cropped surface per capita (in ha)	0.9 ± 0.03	0.7 ± 0.02	0.6± 0.02	0.3 ± 0.02	E
Cropped surface proportion (%)	24.4 ± 0.1	57.7 ± 1.9	12.8 ± 2.1	5.1 ± 0.4	F
Yields (q/ha)	3.6 ± 0.3	4.2 ± 0.3	3.9 ± 0.2	3.7 ± 0.2	G
Coef. Gini between families	0.73± 0.01	0.63 ± 0.02	0.62 ± 0.03	0.90± 0.04	H
Livestock proportion in the income (%)	7 ± 1	10 ± 2	10 ± 1	9 ± 2	I
Migration proportion in the income (%)	36 ± 2	52 ± 4	58 ± 4	69 ± 6	J
Gardening proportion in the income (%)	12 ± 2	8 ± 0.4	11 ± 2	6 ±0.6	K
Pearl millet agriculture proportion in the income (%)	45 ± 5	30 ± 3	21 ± 5	16 ± 2	L

* Combined weed and shrub vegetation

Table 30. Selected indicator mean values for the last quarter t=] 75-100] for the three sites for the "Evolution" scenario (Mean+standard deviation; n=20). (Part 2)

	Gabi				
	UFCIS	NCFCIS	NCFMIS	UFMIS	
Income per capita (in €)	10.6 ± 0.7	14.5 ± 1.2	25.9 ± 2.9	17.0 ± 1.6	A
Income proportion (%)	15.2 ± 1.1	2.2 ± 0.2	65.1 ± 7.3	17.4 ± 1.7	B
Livestock size per capita (TLU)	1.6 ± 0.4	1.5 ± 0.5	2.2 ± 0.9	2.4 ± 0.7	C
Livestock proportion (%)	21.3 ± 3.1	02.1 ± 0.3	53.1 ± 15.0	23.3 ± 4.8	D
Cropped surface per capita (in ha)	0.2 ± 0.04	0.7 ± 0.24	0.4 ± 0.08	0.2 ± 0.03	E
Cropped surface proportion (%)	20.3 ± 3.3	6.5 ± 2.2	62.3 ± 11.5	10.9 ± 1.6	F
Yields (q/ha)	5.8 ± 0.7	8.1 ± 0.7	3.7 ± 0.3	3.5 ± 0.2	G
Coef. Gini between families	0.73± 0.01	0.59 ± 0.02	0.60 ± 0.02	0.81± 0.04	H
Livestock proportion in the income (%)	13 ± 1.1	22 ± 2	15 ± 1.4	28 ± 3	I
Migration proportion in the income (%)	3 ± 0.4	14 ± 1	5 ± 1	17 ± 2	J
Gardening proportion in the income (%)	34 ± 2	22 ± 1	49 ± 3	21 ± 1	K
Pearl millet agriculture proportion in the income (%)	50 ± 2	42 ± 2	31 ± 2	34 ± 2	L

* Combined weed and shrub vegetation

The sites of Zermou and of the Fakara therefore present a social organization profile that can be explained by the historical succession of the family types (Figures 35.1 & 35.5), even if the simulated family change rules allow the reappearance of families of ancient type: the eldest group, the UFCIS, is the most involved in agriculture, whereas the most recent, the UFMIS, is the most involved in migration (Table 30 lines J & L). This last group can be considered as quite "absents" of the village, reducing their involvement in local activities. The Gabi population is different: it is influenced by a highest proportion of the UFMIS and by a highest field availability, and in particular garden-suitable fields: as opposed to the two other sites, the UFMIS type in Gabi see a large part of its income coming from local productions (gardening and agriculture). Also, the NCFMIS are land-limited but have a more "efficient" manpower: because they are non-cooperative, they can orient themselves in a privileged manner towards gardening.

The part of income coming from livestock keeping is hard to interpret because it is not entirely linked to the size of the herd but more likely to its turnover rate that is quicker for small ruminants. The part of these small ruminants is growing along an UFCIS-UFMIS-NCFCIS-NCFMIS gradient, which is compatible with the growing monetary constraints of these types of family (Figures 35.1, 35.3 & 35.5).

Thus, the interpretation of the relationships between family types and economic families may be uneasy to interpret because it is ruled by complex micro-interactions. However, the distribution of the chosen indicators highlights a differentiation between family types that looks like the strategies one can observe in the field: The Fakara and Zermou see their populations differentiate themselves into family groups strongly related to the succession of their appearance: the first arrived UFCIS maintain a strong agricultural involvement, as opposed to the last two groups, mainly orientated towards the external activities (migration and cattle keeping). On the other hand, higher suitable land availability in Gabi permits the maintenance of local activities for all family types, particularly thanks to gardening.

4 Conclusion

Introducing social change processes in a social model generates social groups with differentiated behaviors: New social restrictions limit the intra-family support, which has for consequence to restrain more strongly the income sharing at the individual level to his/her close family network. It let a bigger reinvestment at the local level through small livestock keeping and gardening, but also a higher level of "adequacy" to local resources, via various "strategies" (lowering of the population for the Fakara, creation of a class of "permanent" migrants for Zermou or a class of "gardeners" for Gabi). These strategies are different for every site but permit to increase the robustness of the society and to limit the degradation of the local environment. Moreover, as heads of non-cooperative families do not control their members anymore, there are more autonomous individuals in their choice of economic activities other than agriculture. As the gain from extra-agricultural activities is more important than from cropping, these groups of non-cooperative families have a higher level of income per capita. Finally, the history and the social origin of these groups do matter because it defines the final distribution of access to production assets between family types.

Thus, the introduction of social evolution factors (i.e. the inheritance mode and the family organization) induced changes that corroborate a Boserupian approach of farming transitions, but with a nuance regarding the potential extent of such changes. Even within these sites, each family and each individual does not have the same chances and strong divergences appear: the least favored site population "exports" its wealth outside the territory through cattle "off-shore" savings and does not experience any intensification; the intermediate site evolves towards a South African-style split between farming families and migrant families according to social origins. The most favored site population is the only one to intensify its practices (better integration of livestock and more gardening).

Therefore, the model results permit to confirm that:

- It is possible to combine socio-anthropological and agro-ecological factors in a model. A validation is always complex and difficult but the reconstitution of collective and differentiated behaviors based on simple and empirical behavior rules underlines the interest of such modeling methodologies for analyzing the interactions between social and farming systems.

- Beyond the methodological aspects, we have shown that social factors have an impact on farming systems at least as strong as economic or agronomic factors. However, because such social factors are different according to the villages and the sites but related to environmental ones, they have different and non-linear effects on the village evolutions[177].
- Moreover, beyond the quantitative differentiations, the integration of these factors informs on the discriminations between categories of gender and of family groups. Such informations cannot be approached with other methods and may help to increase the proportion of people benefiting from development projects in Niger and for the whole Sahel.

The present simulations take in account two factors of social differentiation. In the future, additional factors observed in the field may be important factors of emergence to be included. For instance, the transhumant Fulani herders, who had formerly an important role of fertility transfer are not simulated, as well as the high proportion of divorces (two marriages in five according to our observations) that reinforce women' autonomy through their herds and gardens. Additional social changes could be considered as the driving forces of evolution of farming systems: the progressive settlements of transhumants and nomads, the choice of activity according to the gains in terms of social reputation and economic gains, the development of communication network and in particular road and transportation networks that have allowed in the past the take-off of the seasonal migration activity. The introduction of a development project may also be an important trail from a more operational decision-support point of view.

More fundamentally, modeling social systems poses problems as underlined by Chattoe (2002): simulating individual behavior implies to postulate some reasoning, even if these are defined in the simplest possible way. Moreover, it requires parameterization of the factors that have an influence on these behaviors. Choosing such reasoning's and the related parameters are open to discussion unless based on systematic investigations still too heavy, too long-term and too costly to justify. It is difficult to establish the extent of such changes, the impacts and the "weight" of each parameter because this needs time for investigation but also because these phenomena take place over several generations.

---

[177] In the village archetypes we considered, social constraints follow a gradient equivalent to the environmental one, meaning that both constraints are overlapping. This contiguously growing constraints along the same gradient is acknowledged in the literature and is not an artifact in Nigerien Sahel. An extension of this work may be to analyze Sahelian site situations where social and environmental factors belong to different and even opposite gradients.

CONCLUSIONS AND PERSPECTIVES

This section synthesizes the main findings and the main limitations of the thesis on both thematic and methodological points of view. Finally, we present some perspectives for future research.

Assessing the evolution of farming systems in severely constrained areas in response to both internal an external factors and interventions is a complex task. Beyond the traditional mantra of multidisciplinarity, combining disciplines is a challenge that requires the integration of numerous sources of information and points of view. The census of all the factors that affect families and individuals of the rural Sahelian Niger requires building a methodology that avoids the usual omission of several factors, mainly social ones. We therefore built a methodology combining field investigations and modeling, both specifically developed for the purpose of combining social and biophysical sciences. This thesis shows that integrating different disciplines in a single research approach allows elaborating strong hypotheses regarding the hierarchy and the weight of the factors that affect in different ways the various population groups of a rural society. The thesis findings are therefore twofold: those relevant to rural Sahelian Niger societies and those related to methodological aspects.

1 Summarizing the results

The first chapter highlighted several fundamental elements needed for answering the research question proposed in the thesis introduction:

- If the rural population of the Sahelian Niger lives in harsh and erratic conditions (chap. 1 §1), such conditions have strongly evolved particularly over the last century: farming systems evolved successively from an intensive form to an extensive one, until the present-day tendency towards intensification for some of the systems, depending on factors that are both socio-political and biophysical (chap. 1 §2). The historical reconstitution of the settlement process has also shown that many farming systems in the Nigerien Sahel have already reached the limits of their extensive land use mode. These limits can be overcome only through important transitions in their organization. But the pressure on natural resources induces very different evolutions depending on the site. Finally, such historical dynamics still play their role in the present time evolution. It can therefore be concluded that a proper understanding of the present-time dynamics of a Sahelian village requires putting it back in the perspective of its historical pathway[178].

- The same chapter underlined that the family scale is a relevant level of analysis to study the evolutions of farming systems of the Nigerien Sahel (chap. 1 §2.2.1) in so far as this level is considered not as a monolithic unit but as a cluster of adult individuals (chap. 1 §2.2.3). **Social systems have evolved, particularly regarding family organization,** which conditions the access to economic activities and related gains. Family organization still evolves considerably. The juxtaposition of two evolutions (farming systems and family organizations) supports the hypothesis that both processes are linked: family organization changes may play a catalytic role and guide transition driving forces so as to increase their effect on farming systems' evolution (chap. 1 §2.4).

In chapter 2, we have shown that ZADA (chap. 2 §3) is relevant for development and research purposes because it fills an epistemological and spatial information gap at a low cost. This section has also shown that, besides agro-ecological factors that drive the living conditions of the population, socio-economic factors play a key role in the spatial differentiation of the population[179].

The ABM model development was described in chapter 3 and was part of the research process through several conceptual assumptions:

- If one focuses on the population itself (§2.1), a descriptive and empirical model is more relevant for a first analysis of the social factors we intended (§2.2).
- The individual is the most efficient unit for analyzing the potentially divergent strategies of individuals and the differentiation of the families over time (§2.3).
- As information and data are heterogeneous in quality and relevance but also to assume the difference between variables and data, we subdivide the information sources according to the disciplines and the subject: field investigations at both collective and individual levels (chap.2 § 3 & 4) define the variables on which to focus (chap.3 §2.4.2). Biophysical

[178] This dominance of the history can be found in the entire Sahel (Raynaut *et al*. 1997) and even large parts of Africa (Raison & Coniat, 1997) where political vicissitudes better explain the present-time population distribution than agro-ecological factors.

[179] Settlements can be seen to have been established according to the ethnicity and more precisely the former practice specializations of each ethnical group. Market access is very important for the population (in both senses: access to customers & access market places) and determines, together with the biophysical conditions, the commercial potentialities (livestock, straw, peanut or cowpea) of a given location.

sources provide the data that describes the agro-ecological context (rainfalls, soils, livestock) whereas socio-economic data are integrated for the socio-economic context (demography, prices). The social component of the present research was based on field investigation results whereas social-based scenarios were derived from literature but "screened out" according to field observations.

- The calibration, the tests on the sensitivity on several selected parameters and the confidence building (chap. 3 §6) were different steps that enhance confidence in the model implementation and in its results.

Having built the model, a first set of simulations was presented in chapter 4. The model showed that the differences between the two family organization types[180] have strong impacts on the performances of the social systems and related farming systems but also on their robustness. **Although the patriarchal and unitary family type appeared more productive, it was found however to be less robust in its ability to deal with climatic risks and demographic growth than the more recent and expanding mononuclear and non-cooperative family.** The same chapter suggested that the transition from the unitary organization to the non-cooperative one is a one-century-long process that may have been accelerated during the crises of the 70's and the 80's.

Chapter 5 dealt with development strategies through the analysis of development proposals and their adoption in three geographically and ethnologically different, present-day villages. These proposals are emblematic of development actions one may encounter in rural projects in Sahelian Niger. They represent two different development orientations: the inventory credit locally named "warrantage", can be viewed as a securing strategy whereas inorganic fertilizer availability at market prices corresponds to a maximization strategy for agriculture and gardening. Results suggested that **individual reputation** within the village as currently designed in the model **has little impact on villagers' adoption of a development proposal**. We supposed that the main reason of this low impact is because individual and family wealth weigh too heavily in the reputation as currently implemented, making the concept of "reputation" too close to the wealth itself. It may be that other elements such as social relationships may have more importance in the real reputation within the village arena, but elucidating the importance of reputation and social capital in the adoption process will require further detailed investigations.

[180] The patriarchal and unitary family under the rule and the control of one unique head vs. the non-cooperative where adult members keep the control, the management and the benefits of their economic activities.

Overall, adoption of the development proposals are low in the model, because they are *de facto* competing with local practices: warrantage is in competition with the livestock saving practice and inorganic fertilizer use is limited by manpower and in competition with livestock manure. Warrantage has more success than inorganic fertilization. Adoptions concern:

- **Mainly sites where the population may generate surplus** (even temporary ones) that are needed for any investment or any savings. It means that villagers in less favored sites may have no real interest in developing their agriculture and other local resource-based activities.
- **Mainly families who have enough productive fields and manpower**. Even for most favored sites, such strategies are of interest only to villagers who meet the above-mentioned surplus criterion.

The same chapter allowed introducing the notion of land saturation: **as long as there remains land to settle in, the pressure for agricultural intensification remains low**.

The last chapter corresponded to an analysis of social changes over a long period (100 years) in response to land pressure and a lesser inclination to share individual gains. Simulating societies of the same three "terroirs" **without such changes** revealed that **each population slowly "specializes" depending on its social and biophysical characteristics**[181]. Two social changes were introduced, i.e. in the family organization and in the inheritance system. These changes have important consequences on the social evolution, its speed and its rate of change. **Once these changes are made possible, each population evolves along a pattern that cannot be foreseen *ex ante*.** Societies evolve at all the three sites from a single-family type based on a unitary organization and a customary inheritance system to a mix of four types of families among which non-cooperative families become dominant at all the three sites. The model results suggested that a new social group may appear, which may be assimilated to a newly appeared social group in southern urban places of the country yet which was not observed during our field study.

[181] People of the most favored site tend to intensify their local activities whereas the intermediate site evolves towards a balance between internal and external activities and the less favored site is more oriented towards external activities.

The results of the long-term simulations suggested that:

- **The chronology is important**: the initial conditions[182] as well as the relative speed of the different factor evolutions[183] have strong impact on the final situation at the end of the 100 years simulation.
- The biophysical factors still condition the evolution of the three societies towards the different activities, but these factors have not the same impact than in the previous no-family-change scenario[184].
- **Social factors drive the evolution at the family and individual levels**: family types within each site "specialize" themselves towards specific activities. Therefore, the distribution of family types within each site defines the distribution of activities for the whole site population. All these strategies allow the populations to increase their robustness and lower the degradation of their natural environment.

2 Methodological contributions and limitations

The results of this research have underlined the capacity of the model to dynamically combine socio-anthropological and agro-ecological factors through fairly simple and empirical behavior rules. Such a model allows for the differentiation between individuals and social groups, thereby inducing social evolution processes, and can deal with emergent phenomena. Several principles listed below are, however, required as framework for such a modeling and field methodology. Therefore, one may consider that **the first specific objective is partially met, i.e. building a multidisciplinary methodology that can explore complex socio-economic and agro-ecological situations, decode its relationships and integrate field results and various literature sources into a quantitative model as a medium.**

[182] The unitary and customary inheritance family is the sole family type in the three societies at the beginning of simulations as described in the literature, which determines the importance of the family change speed factor.

[183] The gardening restriction to women that is implemented for only the intermediate site allows a quicker shift towards non-cooperative families, which induces a lower demographic growth and thereby a slower field expansion. Therefore, this population is mainly oriented towards the customary inheritance system while the two other populations are mainly based on the Muslim one.

[184] There is still a gradient towards internal activities from the less favored site to the best-endowed one but one may see that the latter site is in this scenario clearly oriented towards intensification (higher integration of livestock and more gardening) whereas the two other ones are both more oriented towards external activities.

2.1 Contributions related to the methodological objectives

A main strength of this research was to succeed in reaching a balance between anthropology-oriented fieldwork and the model design and simulation analyses. The methodology can be subdivided into three steps: information collection in the field survey sites; formalization of this information into modeling rules; model simulation and interpretation. However, there is a continuous exchange between the three steps through an iterative process of comparison and confrontation. Two main cycles of the iterative process between field surveying and modeling were found necessary to finalize the SimSahel model. Furthermore, this crucial link was insured as the same researcher carried out both works.
The fieldwork supported the search for model consistency. On the other side, the modeling process supported the field investigations by highlighting all the necessary elements required for running the model. The model itself was found consistent despite its complexity, thanks to the following calibration principle: the calibration of social parameters, which are crucial to model, was carried out at the individual level. We only checked that individual trajectories were consistent with observations. The family and village levels were thereby "free" of calibration, apart from the parameterization of several factors using external data that did not concern our research questions (human & livestock demography, rainfall, fertility). The model maintained its consistency even for the different scenarios.

2.1.1 Contributions of the field methodology

The field investigations generated several methodological contributions:

- We privileged locally defined variables and hierarchies. It forces to always question the relevance, the origin and the consistency of the model variables before calibrating them with data. The model-making process supports this rigor by forcing not to omit variables and factors[185].
- Using investigation tools such as ZADAs and semi-open interviews was found essential. They are robust and well established for such field investigations, and they are relevant for our objective, as they are at the interface of the disciplines, which allows a more balanced assessment of the situation. Our individual sample is more appropriate than a household sample: the diversity is better assessed.

[185] For instance first versions of the model crashed because of the omission of the family food redistribution system. We came back in villages to investigate this particular question.

- The sequence of research steps is important. A first exploratory step establishes the required variables. Integration tools (ZADA, ABM) are then used to force the questioning about the collected information and data and their accuracy[186]. By carrying out the variable definition step at the very beginning of the field investigations, we avoided the necessary but very complicated and time-consuming reintegrating process in the modeling tool.

2.1.2 Contributions of the modeling methodology

The modeling process concerned the elaboration of an ABM embodying an archetype of Nigerien Sahel farming systems and systems of activities as observed during the field surveys at the three sites. This kind of autonomous Agent model helps to better describe the interactions and hierarchies in such systems and to explore various hypotheses quantitatively. The modeling methodology, by confirming several epistemological positions brought several contributions. However, this modeling approach should be considered as a first step towards a complete modeling effort to integrate social dynamics and biophysical changes:

- Establishing that the population itself was the research object, rather than focusing on a resource helped in the model-making process by clearly separating the context, which was parameterized through literature and external data, and the subject, which was characterized by our own investigations.
- The calibration step, based upon literature and investigation, was crucial to design a model that is relevant concerning the local individual behaviors of the different types of villagers and that realistically simulates the consequences of these behaviors on the global population and on the related natural resources. The resulting internal consistency of the model, the comparison with external data and expert knowledge and the tests on parameter sensitivity, were the three confidence-building components supporting our model.
- The empirical approach was a necessity with so little reliable data or informations on the populations' behaviors. Moreover, this approach avoided the pitfall of model "overdetermination" through pro-optimization tools or parameter selection.
- The avoidance of overdetermination was reinforced by the methodological choice to consider the individual as the relevant modeling unit. Rebuilding *a posteriori* the complexity of a household unit could have been much more difficult to implement than integrating

[186] For instance the spatial topology for the ZADA, the rights and rules at the social level.

at the very beginning of the model implementation the complexity of activities and behaviors at the individual level.

- The most revealing complexity was more in the local combination of the different activities and behaviors than in one fully described activity or behavior.

As a conclusion, the main methodological gains from this work were linked to the epistemological choices made at the very beginning. The research process had to consider the trade-off between the time spent upstream exploring the complexity in the field and the time consumed by simulating downstream the whole extent capacity of the model. This time management dilemma remains unavoidable. We have made the choice, giving the numerous existing modeling works dealing with the complexity of one activity or one resource, to focus on the complexity of the population in an empirical manner.

2.2 Limitations of the methodology

- We clearly aimed to go as far as possible in the integration of the socio-anthropological disciplines in a modeling process thereby following the new social science concept of Moss & Edmonds (2005). We avoided the game-theory orientation as used by Janssen & Ostrom (2006) for instance: such an orientation may be considered as a further step once the main constraining factors have been highlighted for the different social groups as we have done in this work. At the level we started the thesis, we had to focus on an empirical and descriptive axis as a first exploratory step, following thereby Boero & Squazzoni (2005) who have highlighted the necessity of adaptation according to the "target characteristics". Therefore, because of the intricate characteristic of the social rules, results were often fuzzy and not obvious to interpret.
- No real confrontation with other modeling methods was carried out unlike Castella *et al.* (2007). Moreover, we lack extensive data sets as elements of comparison unlike Berger (2001) and Castella *et al.* (2005). Therefore, the validity of our methodology is restricted. However, this limitation confirms our choice of an empirical and descriptive approach as a first exploratory step: we had no access to relevant external information that may prevent this "people's perception first" paradigm and the related variable selection procedure. It was thus necessary to focus on the individual constraints people expressed during interviews.
- The major limitation is related to this empirical approach. This implied building a model with many parameters that cannot be tested and checked through a systematic and comprehensive sensitivity analysis, meaning that no full validation can be realized on such models. Therefore, these parameters have not been sorted out to eliminate

possible redundancies and crossed influences. Such a problem is discussed by Ahrweiler & Gilbert (2005), who acknowledged the unavoidable epistemological tension between local credibility and scientific validity. Sets of validation for such models still have to be built to elaborate a full decision-support tool for farming system analysis and elaboration of development proposals.

- Another problem is the genericity of the model. The methodology was essentially based on the exploratory field investigations to define the framework of model variables. It is very necessary before any extension of this model to other sites to check for any new site-specific variables to adjust or rebuild an equivalent model that can be either site-specific or more generic.
- The last problem is the quality of the predictability of such long-term prospective: As scenarios are based on few variations, such long-term simulations have no real predictive power. Meanwhile, they provide results on present-time trends.

Actually, one cannot avoid to choose between two epistemological orientations: a companion-modeling, action-oriented and situated modeling pattern, where genericity and statistical significance are not necessary but local agreement is a prerequisite (d'Aquino *et al.*, 2004; Le Page *et al.*, 2004), and a generic and sometimes game-theory-like pattern which remains too far from local implications and agreements (Bousquet *et al.*, 2001) but receives more easily the agreement from the scientific community.

In any case, simulating population behavior in such an environment may open several epistemological debates that can certainly not be settled here but that cannot be obliterated either. The main asset of such approaches is to keep these kinds of debates open. This is important for the rural population, because of the strong validation power research scientists may provide to development actions.

3 Thematic contributions & limitations

The methodology has contributed to several thematic findings, to be considered within the domain of validity of the model.

3.1 Contributions related to the thematic objectives

Reconsidering the different findings, we have shown that:

- Differences in the social organization and more precisely in the family organization as shown in chapter 4 have a tremendous effect on the village population demography, wealth and level of inequality but also on its sustainability, all other factors staying constant. These differences reduce the demographic growth level but also the gap between the demographic growth and the expansion of the cropped area. Moreover, the family rank determines crucial differentiations between the related social groups within the village whereas reputation as currently implemented in the model has no significant impact on the evolution of the populations. Therefore, one may conclude that the **second specific objective** was largely met: **some family-based differentiation factors within the present-time social structures effectively have strong impacts on the distribution of production activities, the trajectories of the individuals, the families and the populations of the villages and the sustainability of the rural populations of the Nigerien Sahel.** Individuals are the main stakeholder for decision and action because of the growing centrifuge forces that remove the labor capacity from the control of the family level. This evolution is not a Rostow-like process and is far from being generalized[187]. Moreover, the ZADA has shown that other socio-economic factors[188] may have an effect on the populations as important as biophysical ones as well.

- Testing the adoption of development proposals in three present-time geographically and ethnologically different villages has shown (chapter 5) that, even if reputation has no real effect on the adoption, other simulated factors have indeed some influence on this adoption. Actually, the main adoption-limiting factor is the population's structural pluriactivity and the social segregation regarding the access to production and economic assets. The two development proposals compete with either livestock or manpower accessibility at the individual level (head of household or "head of garden"). At the family-level, only very specific families are both able and interested in such proposals and not at all the three investigated sites. We were then able to finally conclude that the adoption of such proposals depends on each individual profile as much as on the living conditions. It therefore shows that focusing on the diversity of the individual situations is highly relevant for an evaluation of the potentialities of such development actions. This major conclusion means that, even an apparently simple implementation of a village, including all the economic activities, can highlight the critical importance of and give strong insights into the mechanisms determining the potential adoption at the village level. **Our third specific objective** is therefore also largely met: we **have estimated the effects of several factors, related**

[187] It can even shift back in the opposite direction as happened in simulations with the appearance of Muslim inheritance and unitary families as noticed in chap. 6.

[188] Access to markets, road network, new settlements, economic competition with other sites.

to the present-time family organization, on the villagers' responses to development incentives.

- Chapter 6 was dedicated to the last objective: once including family-based evolution factors, each population evolves according to a pattern that is different from the site-specific "specialization" processes observed without transition. The distribution of activities is changed, providing more access to activities for low-rank social groups but it also allows higher inequalities. Farming systems evolve but in different directions that are determined by both agro-ecological and socio-economic conditions. **Our fourth and last specific objective** can therefore be considered as largely met: we **have estimated the impacts of some social organization transitions on the evolutions of the rural populations of Sahelian Niger**.

3.2 Practical relevance of the thematic results

What do such field and modeling results mean for a development stakeholder?

- As described in Chapter 2 §2, it is not necessary to rely on very expensive data collection campaigns to focus on key factors that affect rural population. The ZADA tool may simplify and clarify the diagnosis as compared to systematic data-collection campaigns and even PRAs thanks to its more "open-minded" approach. Moreover, ZADA is a good preparatory step for the primordial and necessary selection of the variables to investigate. One may thereafter replace the data collected through the ZADA by data coming from more spatially accurate sources[189].
- More regional phenomena and structures, such as new settlements or distances to markets, have fundamental effects that can overrule all the efforts of a development agency. For instance, distance and thereby transportation costs, together with a too small and/or erratic market, but also the presence of already active gardens elsewhere, may ruin all the efforts of a garden project. A low-cost tool such as the ZADA may help to limit the risk of poorly conceived projects.
- As noticed in chapter 1, 3 & 4, pluriactivity is an essential factor to reduce the vulnerability of the populations. Therefore, one may recommend supporting extra-agricultural activities. Many development operators already do this regarding women. But what about migration? We have shown that this last activity does not really compete with agriculture, at least in Sahelian Niger. Supporting seasonal migration

[189] Such procedures already exist at lower scales. For instance, Hiernaux (1998) used first the emic description of soils with their vernacular names and only thereafter, increased the spatial accuracy of the soil limits with data coming from other sources.

may have demultiplying effects on other activities, such as gardening, livestock keeping and even agriculture, particularly in regions like in Zermou where opportunities for other economic activities are limited.

- As described in chapter 5, if only certain family categories may potentially be interested in inorganic fertilizers, it is interesting to focus the support on them. It means, for instance, that fertilizer availability should not be linked to other project-related actions[190], forcing people to use some fertilizers only to remain registered in the project[191]. Some other specific social groups, such as temporary gardeners (youngsters, women in some places) may also be good market groups to focus on.
- The main farming revolution in Europe was the full integration between livestock and crops without inorganic fertilizers during the 18th century (Mazoyer & Roudart, 1997). The Boserupians consider that a "good" farming transition in the Sahel may also be realized through an equivalent integration (Mathieu, 1998). Meanwhile, the small livestock increases its share (Turner, 1999), meaning that the interest for such a speculation is high, mainly within less-endowed persons, i.e. the ones who lack manpower and cash for sustaining a herd. A proposition could thus be to lower the prices of the food supplementation products (cowpea straws, other fodder types[192]) rather than inorganic fertilizers. Through such an action, a development operator may favor a more equal accumulation and an increase of the investment capacity of a larger proportion of the population (mainly married women and young men, i.e. 50% of the adult population) and thereby, field organic fertilization may be increased.
- As described in chapter 5, if only some family categories may be interested to get involved in inventory credit/warrantage because of its competition with livestock keeping, it may be more strategic to support the local productions or to create new financial products that combine the two elements. For instance, a development action may offer loans during the cropping cycle that are equivalent to the price of a sheep and its food. The loan should be reimbursed when money comes back, i.e. at harvesting times or even at the return from migration, with an interest level that integrates the different risks (sheep rising & migration) (Gentil *et al.*, 1993).

---

[190] For instance by not limiting the access to inorganic fertilizers to members of farmers associations only.

[191] It means also to adapt the project goal and capacity by not estimating that its purpose is that everybody should use inorganic fertilizers.

[192] It seems more interesting and less expensive to support local products rather than pellets from abroad

3.3 Domain of validity of the thematic results

The validity of the SimSahel model and some of the results can be extended to the territory where similar agro-ecological and socio-economic structures can be found. The model can thus be applied to the Zarma and the Hausa Nigerien Sahel. *A contrario*, some Sahelian societies are based on different structures or the economic activities they practice are competing[193], implying that this specific model is no longer valid. Opening new markets, roads and other ways of communication or other economic disturbances may also be strong drivers of fast change that we did consider through the ZADA but did not simulate with the model.
Even at the family level, other factors observed during field investigations are in conflict with the usual external perception of the rural society in Sahelian Niger[194]. In fact, there is infinity of combinations of social, agro-ecological and economic factors to be included in and/or deduced from the model in order to extend its validity or test scenarios. The extension of this work should thus rely more on the methodology we developed, rather than on the specific model rules.

4 Perspectives

Particular perspectives were already mentioned throughout this document. We mention for example: the ZADA integration into a GIS-based variable identification and hierarchization procedure for an *ex ante* local development diagnosis. The integration of new variables in the model for testing new scenarios based on new variables such as divorces, nomads or roads, are also interesting elements to consider to further improve the modeling effort. More general perspectives are presented here on two levels:

4.1 Extending the research relevance of the model

Beyond the improvement of the relevance of the model by including new variables and functions as suggested above, one may wish to improve the overall rationality of the model architecture. On the social side of the model, one may formalize the behavior of all Agents along a Belief-Desire-intentions (BDI) process, closer to a non-empirical mode, in order to eventually test different rationalities, such as Alam Shah *et al.* (2005) for gift exchanges and social networks. Such a BDI may be specific to each Agent

[193] For instance, migrations last several years for Mossi in Côte d'Ivoire or Kayes-originated Malian migrants in Europe, meaning that there is a permanent manpower competition between agriculture and migration that do not really occur in our study sites.
[194] For instance, divorces are very common and their effects may not be neglected considering the redistribution of herds and its effect on female autonomy.

category, based on field-originated informations. More data may be obtained from the field to improve the implemented hierarchy of social factors, especially on relative values of reputation and rank, as well as external factors such as migration costs and gains. On the biophysical side of the model, one may include more spatially and temporally accurate climate data from various sources to reconstitute the history of several representative and well-documented villages and thereby improve the simulation of this history, in order to increase the quality of the model confidence building.

An extension of the overall methodology validity may concern two dimensions: geographically, the methodology may be applied to other places in Africa or at least in the Sahelian region. Socially, other problematics may be analyzed such as urban settlements or commercial networks in Sahelian Niger. An improvement of the model may follow different directions:

- Integrating the model into a dynamic GIS may allow testing the simulated phenomena on "real" villages and to compare the results with quantitative data collected from the field.
- As described above, a better sensitivity analysis may be carried out through the selection of more parameters to test in a wider range of variability.
- A better validation may be carried out through a comparison with historical data as noted above (for instance climate or price series), but also through a model result comparison with other already validated models. Confronting the model results with development experts and operators, and even better, with the concerned population, may help improve the social and biophysical implementation. Such a confrontation may be considered as a first step for a companion-modeling approach.

4.2 Extending the practical relevance of the approach

A first step is to formalize a complete methodological diagnosis set to apply and test in an *ex ante* stage of development projects or programs. This diagnosis set comprises first a regional stage, including ZADA and transects, and then a field investigation based on individual interviews of both villagers and development operators. An ABM equivalent to SimSahel may then be used for testing *ex ante* the impact of development proposals, juridical or technical innovations in site-specific environments, as assessed by Berger (2001) or Castella *et al.* (2005).

Another possibility is to integrate such a model in a "companion-modeling approach" such as Etienne (2003), Touré *et al.* (2004) and Bah *et al.* (2006): the model is here used as a tool to support a negotiation process between divergent actors. The objective of such a model is first to be recognized as both realistic and objective by local actors. Like all political processes, it requires time and confidence, which are human criteria that are hardly measurable but essential for any collective project.

As a final note, the following example illustrates the relevance of such a multidisciplinary approach focusing on the complexity. Field investigations and the modeling process underline the potentially huge effects of "anecdotal" phenomena that has a blocking effect on a lot of villagers:
At least one million of male Nigeriens leave for migration every year, bringing back home about 52.5 kFCFA (80 €) per capita, meaning that, with 80 million € annually, it is the second source of income of the whole Nigerien nation after Uranium and surely the first "development agency" of the country. Some migration candidates in Sahelian Niger practice sheep rising during the rainy season to earn the transport fees and the necessary funds for their commercial activities. However, the sale of this sheep usually provides enough funds for the transport but not enough for the initial commercial funds, meaning that migrants have to get loans to be reimbursed with their gains. Our investigations show that about half of their gains are lost because of these loans. Meanwhile, each year, sheep prices always increase during the two-month period before the main annual religious ceremony, i.e. the Tabaski. Therefore, given that the Tabaski feast will remain between the harvesting period and the main departure period for the next seven years, sheep raising will be even more profitable for migrant candidates, meaning that they will be able to avoid loans. Supporting this "small" seasonal activity may thereby double the gains of migration, and thereby increases the support to the majority of the families living in Niger.

PUBLICATIONS RELATED TO THIS THESIS

Peer review articles

1. Saqalli M., Gérard B., Bielders C., Defourny P. 2007. *Assessing the impacts of family organization in Sahelian rural multi-activity systems using an empirical Agent-based model: A case study from Fakara, Niger*. To be submitted in *Agricultural Systems*.
2. Saqalli M. 2008. *Le pouvoir des savoirs: enjeux des conceptions sur le développement rural pour le Sahel nigérien*. Accepted in *VertigO* 8: 2 "Le désert & la désertification : impacts, adaptation et politiques".
3. Saqalli M., Defourny P., Caron P., Issaka A. 2007. *A fast & low-cost indigenous perception based regional mapping methodology in support for rural development: analysis of an experience in Niger*. Submitted in *Applied Geography*.
4. Saqalli M., Gérard B., Bielders C., Defourny P. *Benchmarking humanitarian support: Empirical Agent-based modeling of development action types in Nigerien villages*. To be submitted in *Agriculture, Ecosystems & Environment* in 2008.
5. Saqalli M., Bielders C., Gérard B., Defourny P. *Village Ecosystem & Society empirical Agent-based Model: testing social-driven forces on rural Nigerien Sahelian millet-cropping farming system evolutions*. To be submitted in the *Journal of Artificial Societies & Social Simulation* in 2008.

Conference articles

1. Saqalli M. 2006. *Multi acteurs, multi activités: Simulations multi agents pour la détection des changements dans l'Organisation sociale dans les villages de l'ouest Nigérien*. 6th Congress "Modélisation, Optimisation & Simulation des Systèmes: Défis & Opportunités" (MOSIM'06). April 2006. Rabat, Morocco.
2. Saqalli M. 2006. *Rural systems in Sahelian Niger: Rural development evolution paradigms*. 2nd International Turkish-African Congress (TACSS 2006). December 2006. Istanbul, Turkey.
3. Saqalli M. 2007. *Paysans du Niger: évolution et résilience de paradigmes sur le développement rural*. 23èmes Journées du

Développement de l'Association Tiers-Monde. "L'Etat malgré tout? Acteurs publics et développement". May 2007. Mons, Belgium.

Posters

1. Akponikpè P. B. I., Saqalli M., Marinho Filho E. de A. Bielders L. C., Defourny P., Gérard B., Gaspart F. 2005. *Development of decision-support tools for development operators in village communities in Sahel (Niger).* DGCD-DSS May 2004. Brussels, Belgium.
2. Saqalli M., Gérard B. 2006. *Understanding social constraints in Sahelian Niger communities as a decision-support tool for development operators.* International Conference on Deserts & Desertification. September 2006. Brussels, Belgium.

M. Sc. Related to this thesis

1. Hamidou N., *Analyse des activités des ménages agricoles du Fakara au Niger : cas de trois villages.* M. Sc. Tropical Agronomy & Rural development. CNEARC, Montpellier, France.
2. Ali Zene H., 2006. *Contribution de l'institution de microfinance "ADFinance Assussu Cii Gaba" dans l'amélioration des conditions de vie des femmes de la région de Zinder.* M. Sc. Rural Economy & Sociology. UCL, Louvain-la-Neuve, Belgium – Université Cheikh Anta Diop, Dakar, Sénégal.
3. Minet, J. 2007. *Influence de la dispersion du parcellaire sur la gestion du risque climatique au Fakara, Niger.* M.Sc. Agronomy. UCL, Louvain-la-Neuve, Belgium.

M. Sc. Theses

1. Saqalli, M. 2001. Limitations et conflits autour de la promotion de Moringa oleifera dans les districts de Handeni-Korogwe, Province de Tanga, Tanzanie. Optima of Africa Ltd / Sokoïne University / Dar Es-Salaam University / CNEARC /ENGREF
2. Saqalli, M. 1999. *Analyse des perspectives de développement de la zone tampon agroforestière de la réserve naturelle de U Minh Thùong, Province de Kiên Giâng, Viêt-Nam.* CARE Viêt-Nam / Hô-Chi-Minh University / CNEARC
3. Saqalli, M. 1998. Gestion des ressources et analyse des systèmes d'élevage sur les districts de Kambashe et Imiqhayi, ex-Bantoustan du Ciskei, Eastern Cape, South Africa. CIRAD–TERA / ARC / Fort Hare University, Paris X –IEDES / INA-PG

www.enge.ucl.ac.be/staff/curr/ Saqalli/

REFERENCES

Abba, S. 1985. "La chefferie traditionnelle en question". *Politique Africaine*. 38: 51-60.

Abdoulaye, T. 2002. *Farm level analysis of agricultural technological change: inorganic fertilizer use on dryland in Western Niger*. Ph.D. Economy Purdue University, USA.

Abdoulaye, T. Lowenberg-DeBoer, J. 2000. "Intensification of Sahelian farming systems: evidence from Niger". *Agricultural Systems*. 64: 1: 67-81.

Abdoulaye, T. Sanders, J. H. 2005. "Stages and determinants of fertilizer use in semiarid African agriculture: The Niger experience". *Agricultural Economics*. 32: 2: 167-179.

Abdoulaye, T. Sanders, J. H. 2006. "New technologies, marketing strategies and public policy for traditional food crops: Millet in Niger". *Agricultural Systems*. 90: 1-3: 272-292.

Ada, L. Rockström, J. 1993. *Diagnostic sur le système agraire du Zarmaganda central (Niger)*, M.Sc. Agronomy. INA-PG, Paris, France.

Adams, W. M. Mortimore, M. J. 1997. "Agricultural intensification and flexibility in the Nigerian Sahel". *The Geographical Journal* 163.

Affholder, F. 1997. "Empirically modeling the interaction between intensification and climatic risk in semiarid regions". *Field Crops Research*. 52: 1-2: 79-93.

AGRHYMET Publication Group. 2004. *Mensuel Agrhymet*, CILSS, M05.

Ahonon, D. 1994. *Etude de la régénération des ligneux dans 7 jachères sur le terroir de Banizoumbou*. M.Sc. Agronomy. Université Abdou Moumouni, Niamey, Niger.

Ahrweiler, P. Gilbert N. 2005. "Caffè Nero: the Evaluation of Social Simulation". *Journal of Artificial Societies & Social Simulation*. 8: 4.

Aide & Action. 2003. *Etude de prospection sur l'arrondissement de Mirriah dans le département de Zinder. Zinder.*

Akponikpé, P. B. I. Bielders, C. L. Gérard, B. Michels, K. 2007. "Modeling integrated fertility management strategies for pearl millet in the Sahel". Proceedings of the 16th International Symposium of the International Scientific Centre of Fertilizers (CIEC) Ghent, Belgium.

References

Alacs, P. 2004. "Complexity and uncertainty in the forecasting of complex social systems". *Journal of Interdisciplinary Description of complex systems*. 2: 1: 88-94.

Alam Shah, J. Hillebrandt, F. Schillo, M. 2005. "Sociological Implications of Gift Exchange in Multiagent Systems". *Journal of Artificial Societies & Social Simulation.* 8:3.

Ali Zene H., 2006. *Contribution de l'institution de microfinance "ADFinance Assussu Cii Gaba" dans l'amélioration des conditions de vie des femmes de la région de Zinder.* M.Sc. Rural Economy & Sociology UCL, Belgium/ Université Cheikh Anta Diop, Sénégal.

Alpha Gado, B. 1993. *Une histoire des famines au Sahel: étude des grandes crises alimentaires (19ème-20ème siècle).* L'Harmattan, Paris, France.

Alpha Gado, B. Chérif, C. Maïkoréma, Z. 2003. *Plan National d'urgence du Niger: analyse rétrospective des crises alimentaires et des réponses apportées*, Office of the Prime Minister of the Republic of Niger, Niamey, Niger.

Amblard, F. 1999. *Modèles multi-agents pour la décision collective,* M.Sc. Computer Programming. Université Montpellier 3, Montpellier, France.

Amblard, F. Phan, D. 2006. *Modélisation et simulations multi-agents: application pour les sciences de l'Homme et de la Société*. Hermès, Paris, France.

Amblard, F. Rouchier, J. Bommel, P. 2006. "Evaluation et validation de modèles multi-agents". In *Modélisation et simulations multi-agents: Application pour les sciences de l'Homme et de la Société,* Amblard F. Phan D., (Eds.), Hermès, Paris, France: 103-140.

AQUADEV 2006. "Suivi de la sécurité alimentaire; Région de Zinder : Départements de Mirriah, Tanout et Gouré; Situation octobre 2006". *Bulletin Trimestriel* 6-13. AQUADEV, Zinder, Niger.

Aubréville, A. 1949, *Climats, forêts et désertification de l'Afrique tropicale.* Société des Editions Géographiques, Maritimes et Coloniales, Paris, France.

Audinet, J. -P. Haralambous, S. 2005. "Achieving the Millennium Development Goals: Rural Investment and Enabling Policy". *IFAD Governing Council*, 28.

Augusseau, X. Cheylan, J.-P. Liehoun, E. 2006. "Dynamiques territoriales de l'agropastoralisme en zone de migration: niveaux d'organisation et interactions". *Cahiers d'études et de recherches francophones /Agricultures*. 13: 488-494.

References

Ayantunde, A. Williams, T. O. Udo, H. M. J. Fernandez-Rivera, S. Hiernaux, P. Van Keulen, H. 2000. "Herders' Perceptions, Practice, and Problems of Night Grazing in the Sahel: Case Studies from Niger". *Human Ecology*. 28: 1: 109-130.

Ayantunde, A. Fernandez-Rivera, S. Hiernaux, P. Van Keulen, H. Udo, H. M. J. 2002. "Day and night grazing by cattle in the Sahel". *Journal of Range Management*. 55: 2: 139-143.

Bacaër, N. Bah, A. Mahamane, A. "Fuelwood harvesting in Niger and a generalization of Faustmann's formula". *IRD working paper*.

Badamassi, F. 2006. *Le warrantage au Niger: Une technique de crédit pour lutter contre la pauvreté rurale? Cas des femmes de l'Union Tonougakay Ni Bonga de Saboudey Carre*. M.B. Finance, Ecole Supérieure de Commerce de Dakar, Dakar, Sénégal.

Bah, A. Touré, I. Le Page, C. Ickowicz, A. Diop, A. T. 2006. "An agent-based model to understand the multiple uses of land and resources around drillings in Sahel". *Mathematical & Computer Modeling*. 44: 513-534.

Baidu-Forson, J. 1999. "Factors influencing adoption of land-enhancing technology in the Sahel: lessons from a case study in Niger". *Agricultural Economics*. 20: 231-239.

Bailly, A. S. 2006. "Subjective distances and spatial representations". *Geoforum*. 17: 1: 81-88.

Bakam, I. Kordony, F. Le Page, C. Bousquet, F. "Formalisation de modèles multi-agents par les réseaux de Petri: Application à l'étude d'un système de gestion de la chasse à l'Est-Cameroun". CORMAS. www.cormas.cirad.fr

Balandier, G. 1955. *Sociologie actuelle de I'Afrique noire*. Point, Essais, Paris, France

Balmann, A. 1997. "Farm-based Modelling of Regional Structural Change". *European Review of Agricultural Economics*. 25: 1: 85-108.

Banoin, M. Guenguant, J. -P. 1999. "Les systèmes agraires traditionnels Nigeriens dans l'impasse face à la démographie". In *Jachères et systèmes agraires*. Floret, C. Pontanier, R. (Eds.) CORAF/Union Européenne, Dakar, Sénégal. 1: 1-14.

Banoin, M. Achard, F. 1999. "Place des jachères dans les systèmes d'élevage et comportement alimentaire du bétail (Ticko, sud-ouest Nigerien)". In *Jachères et systèmes agraires*. Floret, C. Pontanier, R. (Eds.) CORAF/Union Européenne, Dakar, Sénégal. ı: 99-110.

References

Barbier, B. Hazell, P. B. R. 2000. "Declining access to Transhumant Areas and sustainability of Agropastoral Systems in the semi-Arid Areas of Niger". In *Property Right and Collective action.* Hazell P. B. R. (Ed.). IFPRI, Washington, USA: 371-395.

Barreteau, O. Bousquet, F. Millier, C. Weber, J. 2003. "Suitability of Multi-Agent Simulations to study irrigated system viability: application to case studies in the Senegal River Valley". *Agricultural Systems*. 80: 1: 255-275.

BAD-FAD. 2006. Document de stratégie par pays axée sur les résultats 2005 – 2009.

Bassett, T. J. Blanc-Pamard, C. Boutrais, J. 2007. "Constructing Locality: The Terroir Approach in West Africa". *Africa: The Journal of the International African Institute*. 77: 1: 104-129.

Basu, K. 2004. "Gender and say: A Model of Household Behavior with Endogenously-determined Balance of Power". *Montesquieu Working Paper*. 17. Université Montesquieu, Bordeaux, France.

Bationo, A. Lompo, F. Koala, S. 1998. "Research on nutrient flows and balances in West Africa: state-of-the-art". *Agriculture, Ecosystems & Environment.* 71: 1-3: 19-35.

Batterbury, S. Warren, A. 2001. "The African Sahel 25 years after the great drought: assessing progress & moving towards new agendas and approaches". *Global Environmental Change*. 11: 1: 1-8.

Batterbury, S. Fernando, J. L. 2006. "Rescaling Governance and the Impacts of Political and Environmental Decentralization: An Introduction". *World Development*. 34: 11: 1851-1863.

Becker, C. T., Faber, M. Hertel, K. Manstetten, R. 2005. "Malthus vs. Wordsworth: Perspectives on humankind, nature and economy. A contribution to the history and the foundations of ecological economics". *Ecological Economics*. 53: 299-310.

Becker, G. S. 1974. "A Theory of Marriage: Part II: Marriage, family human capital and fertility". *The Journal of Political Economy*. 82: 2: S11-S26.

Becu, N. 2001. *Modélisation de la gestion de l'eau d'irrigation à l'échelle d'un bassin versant et exploration du système via simulations; Une approche basée sur les Systèmes Multi-Agents; Le cas du bassin versant du Mae Uam (Nord Thaïlande).* M.Sc. Water Management. ENGREF/Université Montpellier 2, Montpellier, France.

Berger, T. 2000. "Integrating approaches for natural resource management and policy analysis. Introductory remarks based on experiences with MAS".

References

Proceedings of the 24th International Conference of Agricultural Economists (IAAE), Berlin, Germany: 2-3: 1-23.

Berger, T. 2001. "Agent-based spatial models applied to agriculture: a simulation tool for technology diffusion, resource use changes and policy analysis". *Agricultural Economics*. 25: 2-3: 245-260.

Berger, T. Schreinemachers P. Woelcke J. 2006. "Multi-agent simulation for the targeting of development policies in less-favored areas". *Agricultural Systems*. 88: 28-43.

Bernus, E. 1993. "Politiques pastorales au Sahel Nigerien : bilan et perspectives". Proceedings of the International Rangelands Network, Ifrane (Morocco): 175-180.

Biershenk, T. Chauveau J.-P. Olivier de Sardan J.-P. 2000. *Courtiers en développement. Les villages africains en quête de projet.* APAD-Karthala, Paris, France.

Binswanger, H. 1986. "Evaluating research system performance and targeting research in land-abundant areas of sub-Saharan Africa". *World Development*. 14: 4: 469-475.

Blaizeau, D. Dubois J-L. 1990. "Le ménage et les unités de collecte". In *Connaître les conditions de vie des ménages dans les pays en développement. Part 2: Collecter les informations*. Min. Coop. & Dév./la Documentation française, Paris, France: 19-37.

Boero, R. Squazzoni, F. 2005. "Does Empirical Embeddedness Matter? Methodological Issues on Agent-Based Models for Analytical Social Science". *Journal of Artificial Societies & Social Simulation*. 8: 4.

Boissier, O. 2001. "Modèles et architectures d'agents". In *Systèmes Multi-Agents Principes et architectures.* Briot, J.P. Demazeau, Y. (Eds.). Hermes, Paris, France.

Bonaudo, T. 2005. *La gestion environnementale sur un front pionnier amazonien.* Ph.D. Geography. Institut National Agronomique Paris-Grignon, Paris, France.

Bonin, M. Caron, P. Cheylan, J. -P. Clouet, Y. Thinon, P. 2001. "Territoire, zonage et modélisation graphique: recherche action et apprentissage". *Geocarrefour*. 73: 3: 241-252.

Bonnal, J. Chauveau, J. -P. Lebas, P. Lavigne-Delville, P. 1997. *La dynamique des sociétés rurales face aux projets participatifs de développement rural: Réflexions et propositions d'action à partir* *d'expériences d'Afrique de l'Ouest*. Food & Agriculture Organisation (FAO), Rome, Italy: 11.

Boserup, E. 1965. *The conditions of agricultural growth; the economics of agrarian change under population pressure*. George Allen & Unwin L^{td} Ruskin House Museum S^{t}. London, U.K.

Boserup, E. 1989. "Population, the Status of Women, and Rural Development". *Population & Development Review*. 15: 45-60.

Boulier, F. Jouve, P. 1990. "Evolution des systèmes de production sahéliens et leur adaptation à la sécheresse". R3S & CIRAD report.

Bousquet, F. 1994. *Des milieux, des poissons, des hommes: étude par simulations multi-agents. Le cas de la pêche dans le delta central du Niger*. Ph.D. Ecology. Université de Lyon 1, Lyon, France.

Bousquet, F. Bakam, I, Proton, H. Le Page, C. 1998. "CORMAS: Common-Pool Resources and Multi-Agent Systems". *Lecture Notes in Artificial Intelligence*. 1416: 826-837.

Bousquet, F. Gautier, D. 1999. "Comparaison de deux approches de modélisation des dynamiques spatiales par simulation multi-agents : les approches "spatiale" et "acteurs". CyberGeo. 89: 1-10.

Bousquet, F. Barreteau, O., d'Aquino, P. Etienne, M. Boisseau, S. Aubert, S. Le Page C. Babin D. Castella J.-C. 2002. "Multi-agent systems and role games: an approach for ecosystem co-management". In *Complexity and ecosystem management: the theory and practice of multi-agent approaches*. Janssen, M. A. (Ed.). Elgar Publishers, Northampton. U.K.

Bousquet, F. Le Page, C. 2004. "Multi-agent simulations and ecosystem management: a review". *Ecological Modeling*. 176: 3-4: 313-332.

Bousquet, F. Lifran, R. Tidball, M. Thoyer, S. Antona, M. 2001. "Agent-based modelling, game theory and natural resource management issues". *Journal of Artificial Societies & Social Simulation*. 4: 2.

Boutrais, J. 2007. "Crises écologiques et mobilités pastorales au Sahel : les Peuls du Dallol Bosso (Niger)". *Sécheresse* 18: 1: 5-12.

Bouzou, M. 2000. "Gestion des ressources naturelles et évolution des systèmes agraires dans la région de Maradi". *Drylands Research*. Crewkerne. U.K.

Breman, H. Groot, R. J. J. Van Keulen, H. 2001. "Resource limitations in Sahelian agriculture". *Global Environmental Change*. 11: 1: 59-68.

Bruce, J. W. 1998. *Country profile of land tenures 1996*. Land Tenure center, University of Wisconsin-Madison. *LTC Research papers*. 130-289.

References

Buresh, R. J. Smithson, P. C. Heliums, D. T. 1997. "Building Soil Phosphorus Capital in Africa". Proceedings of the 51st ICRAF / American Society of Agronomy / Soil Science Society of America Conference on "Replenishing Soil Fertility in Africa" 81-96. Indianapolis, Indiana, USA.

Campo, P. C. 2003. *Multi-agent systems modeling integrating geographic information systems and remote sensing: Tools for Participatory Natural Resource Management (Prototype for Loon in Bohol, Philippines).* M.Sc. Remote Sensing. College of Engineering, University of the Philippines, the Philippines.

CARE 2002. *Household Lifestyle inquiries result for Niger.* CARE Project, Niamey.

Caron, P. 1998. *Espaces, Elevage et Dynamique du changement : analyse, niveaux d'organisation et action : Le cas du Nordeste semi-aride du Brésil.* Ph.D. Geography. Université Paris 10, Paris, France.

Caron, P. 2001a. "Zonage à dires d'acteurs: des représentations spatiales pour comprendre, formaliser et décider. Le cas de Juazeiro, au Brésil". In *Représentations spatiales et développement territorial*. Lardon, S. Maurel, P. Piveteau, V. (Eds.). Hermès, Paris, France. 343-357.

Caron, P. 2001b. "Modélisation graphique et chorèmes: la gestion des parcours collectifs à Massaroca (Brésil)". *Mappemonde*. 62: 2: 1-21.

Castella, J. -C. Boisseau, S. Tran Ngoc, T. Dang Dinh, Q. 2005. "Agrarian transition and lowland-upland interactions in mountain areas in northern Vietnam: application of a multi-agent simulation model". *Agricultural Systems*. 86: 3: 312-332.

Castella, J. –C. Suan, P. K. Chu, T. H. Dang, D. Q. Verburg, P. H. 2007. "Combining top-down and bottom-up modelling approaches of land use/cover change to support public policies: Application to sustainable management of natural resources in northern Vietnam". *Land Use Policy*. 24: 3: 531-545.

Castella, J. –C. Verburg, P. H. 2007. " Combination of process-oriented and pattern-oriented models of land-use change in a mountain area of Vietnam". *Ecological Modelling*. 202: 3-4: 410-420.

Chambers, R. 1994. "Participatory rural appraisal (PRA): Analysis of experience". *World Development*. 22: 9: 1253-1268.

Chattoe, E. 2002. "Building Empirically Plausible Multi-Agent Systems: A Case Study of Innovation Diffusion". In *Multi-Agent Systems, Artificial Societies, and Simulated Organizations*. Dautenhahn, K. Bond, A. Cañamero, L. Edmonds, B. (Eds.). Springer US, Oxford, U.K. 109-116.

References

Chevrier, V. Huget, M. -P. 2006. *Système multi-agents: articulation entre l'individuel et le collectif.* Hermès, Paris, France.

CIRAD, IRD, BDPA-SCETAGRI, GRET. 1991. *Manuel de l'agronome*. Paris, France.

Clements, P. 1995. "A Poverty-Oriented Cost-Benefit Approach to the Analysis of Development Projects". *World Development*. 23: 4: 571-592.

Conelly, T. W. 1994. "Population pressure, labor availability, and agricultural disintensification: The decline of farming on Rusinga Island, Kenya". *Human Ecology* 22: 2: 145-175.

Conway, G.R. 1985. Agro-ecosystem analysis. *Agriculture Administration* 20: 31-55.

Coquery-Vidrovitch, C. Moniot, H. 1974, *L'Afrique Noire de 1800 à nos jours*. Presses Universitaires de France, Paris, France.

Courade, G. 1989. "Le risque d'insécurité alimentaire : de l'imprudence écologique au démantèlement de l'Etat-providence". In *Le risque en agriculture*. Eldin, M. Milleville, P. (Eds.). INRA-SAD, Paris, France. 575-597.

Crosetto, M. Tarantola, S. Saltelli, A. 2006. "Sensitivity and uncertainty analysis in spatial modeling based on GIS". *Agriculture, Ecosystems & Environment*. 81: 71-79.

Crozier, M. Friedberg, E. 1977. *L'acteur et le système.*, Seuil, Paris, France.

d'Aquino, P. Barreteau, O. Etienne, M. Le Page, C. Bousquet, F. 2004. "Jeu de rôles et simulation multi-agents". In *Modélisation des agro-écosystèmes et aide à la décision.* Malézieux, E. Trébuil, G. Jaeger, M. (Eds.). Edition Repères CIRAD-INRA, Paris, France. 373-391.

Daré, W. 2005. *Comportements des acteurs dans le jeu et dans la réalité: indépendance ou correspondance? Analyse sociologique de l'utilisation de jeux de rôles en aide à la concertation.* Ph.D. Environment Sciences. ENGREF, Montpellier, France.

d'Herbès, J.-M. Ambouta, K. J.M. Peltier, R. 1997. *Fonctionnement et gestion des écosystèmes forestiers contractés sahéliens.* John Libbey, Paris, France.

Davis, K. Blake, J. 1956. "Social structure and fertility: An analytical framework". *Economic Development &Cultural Change.* 4: 3: 211-235.

Davis, K. 1990. "Population and resources: Fact and interpretation". *Population & Development Review. Supplement: Resources, environment and population, present knowledge, future options*. 16: 1-21.

de Janvry, A. Sadoulet, E. 2003a. "Progress in the modeling of rural households' behavior under market failures". In *Poverty, Inequality and Development, Essays in Honor of Erik Thorbecke.* de Janvry, A. Kanbur, R. (Eds.). Kluwer Publishing, Los Angeles, USA.

de Janvry, A. Sadoulet, E. 2003b. "Dépasser Bono: Comment rendre plus efficiente l'aide au développement". *Revue d'Économie du Développement*. 63-76.

de Reffye, P. Houllier, F. Blaise, F. Barthélémy, D. Dauzat, J. Auclair, D. 1995. "A model simulating above-and below-ground tree architecture with agroforestry applications". *Agroforestry Systems.* 30: 175-197.

de Ridder, N. Breman, H. Van Keulen, H. Stomph, T. J. 2004. "Revisiting a 'cure against land hunger': soil fertility management and farming systems dynamics in the West African Sahel". *Agricultural Systems.* 80: 2: 109-131.

de Rouw, A. 1998. "Comment assurer la production de mil: jachère ou parcage?" In *Jachères et systèmes agraires.* Floret, C. Pontanier, R. (Eds.) CORAF/Union Européenne, Dakar, Sénégal. 1: 139-152.

de Rouw, A. 2004. "Improving yields and reducing risks in pearl millet farming in the African Sahel". *Agricultural Systems*. 81: 1: 73-93.

de Rouw, A. Rajot, J.-L. 2004. "Nutrient availability and pearl millet production in Sahelian farming systems based on manuring or fallowing". *Agriculture, Ecosystems & Environment*. 104: 2: 249-262.

Decoudras, P. -M. 1990. "L'aide internationale au Niger". *Politique Africaine. 38:* 87-96.

Deffontaines, J. -P. Cheylan, J. –P. Lardon, S. 1990. "Gestion de l'espace rural, des pratiques aux modèles". *Mappemonde.* 4: 1-48.

Deffuant, G. Amblard, F. Duboz, R. Ramat, E. 2002. "Une démarche expérimentale pour la simulation individu-centrée". Proceedings of the 10th "Rochebrune days" interdisciplinary meetings on complex natural & artificial systems. ENST LISC. Megève, France.

Delabre, E. 1993. *Une typologie structurale des jachères à Guiera senegalensis du sud-ouest Nigerien*. M. Sc. Forestry. ENGREF -FRT.

Delabre, E. 1998. *Caractérisation et évolution d'écosystèmes anthropisés sahéliens: les milieux post-culturaux du sud-ouest Nigerien.* Ph.D. Ecology. Université Paris 6, Paris, France.

Demont, M. Jouve, P. Stessens, J. Tollens, E. 2007. "Boserup versus Malthus revisited: Evolution of farming systems in northern Côte d'Ivoire". *Agricultural Systems.* 93: 1-3: 215-228.

Dollar, D. Levin, V. 2006. "The Increasing Selectivity of Foreign Aid, 1984-2003". *World Development*. 34: 12: 2034-2046.

Donni, O. 2004. "La théorie des modèles non coopératifs d'offre de travail et ses applications empiriques". Université du Québec en Outaouais / CNRS / ENS. *Working Paper*. 4: 3-21.

Dorfman, R. 1979. "A Formula for the Gini Coefficient". *The Review of Economics and Statistics*. 61: 1: 146-149.

Drechsel, P. Gyiele, L. Kunze, D. Cofie, O. 2001. "Population density, soil nutrient depletion, and economic growth in sub-Saharan Africa". *Ecological Economics*. 38: 2: 251-258.

Drogoul, A. Vanbergue, D. Meurisse, T. 2000. *Simulation Orientée Agent: où sont les agents?* LIRMM, Paris, France

Dunn, T. 1994. "Rapid Rural Appraisal: A description of the methodology and its application in teaching & research at Charles Sturt University". *Rural Society*. 4: 3/4.

Egg, J. Michels, D. Blein, R. Alby-Flores, V. 2006. *Evaluation du dispositif de prévention et de gestion pendant les crises alimentaires de 2004-2005.* IRAM, Paris, France.

Ehrlich, I. Luib, F. 1997. "The problem of population and growth: A review of the literature from Malthus to contemporary models of endogenous population and endogenous growth". *Journal of Economic Dynamics and Control*. 21: 205-242.

Erenstein, O. 2006. "Intensification or extensification? Factors affecting technology use in peri-urban lowlands along an agro-ecological gradient in West Africa". *Agricultural Systems*. 90: 1-3: 132-158.

Etienne, M. 2003. "SYLVOPAST: a multiple target role-playing game to assess negotiation processes in sylvopastoral management planning". *Journal of Artificial Societies & Social Simulation*. 6: 2.

Fafchamps, M. 1993. "Sequential Labor Decisions Under Uncertainty: An Estimable Household Model of West-African Farmers". *Econometrica*. 61**:** 5: 1173-1197.

FAO. 2006. *Food Security Statistics: Niger.* FAO, Rome, Italy.

FAO, CEDEAO. 2006. *Stratégie régionale de promotion des engrais en Afrique de l'Ouest, préparée dans le cadre du Sommet Africain sur les Engrais.* FAO, Abuja, Nigeria.

Fauquet, F. 2005. *Dynamiques des ressources environnementales et mutations des systèmes agro-sylvo pastoraux en milieu tropical semi-aride:*

le cas de la vallée d'Arewa, Niger Central. Ph.D. Geography. Université Joseph-Fourier, Grenoble, France.

Faure, J. -F. 1997. *Logiques de l'utilisation de l'espace pastoral dans le Sahel Nigerien, Modélisation et spatialisation des interactions ressources-usages dans la zone de Banizoumbou (Sud-Ouest du Niger).* M.Sc. Geography. Université Montpellier 2, Montpellier, France.

Ferber, J. 1999. *Multi-Agent Systems. An Introduction to Distributive Artificial Intelligence* Addison-Wesley Longman, London. U.K.

Ferrand, N. 1998. "Modèles et systèmes multi-agents pour la gestion de l'environnement et des territoires." Proceedings of the "Séminaire sur les Multi-Agents pour la Gestion de l'Environnement & des Territoires (SMAGET) 1998". Clermont-Ferrand, France.

Feuillette, S. 2001. *Towards a demand management on a free-accessible watertable: exploring interactions between water resource and uses by multi-agent systems. Application to the Kairouan watertable, Center of Tunisia.* Ph.D. Agronomy, ENGREF, Montpellier, France.

Franqueville, A. 1973. "Réflexions méthodologiques sur l'étude des migrations actuelles en Afrique". *Cahiers de l'ORSTOM / Sciences Humaines*. 10: 2-3: 143-149.

Fraslin, J.-H. Doucet, G. Binet J. 2005. *Mission de capitalisation des expériences de crédits garantis par le warrantage de produits agricoles.* ICAR.

Galtier, F. 2000. "Dispersion de l'information et efficacité des marchés, La commercialisation des céréales au Mali et au Bénin". Proceedings of "Journées des Jeunes Chercheurs de l'INRA". Montpellier, France.

Garneau, T. Delisle, S. 2002. "Programmation orientée-agent: évaluation comparative d'outils et environnements". Proceedings of the "Journées sur l'Intelligence Artificielle & le Développement des Systèmes Multi-Agents (JFIADSMA). Lille, France.

Gastellu, J. -M. 1980. "Mais où sont donc ces unités économiques que nos amis cherchent tant en Afrique? Note Méthodologique." *Cahiers de l'ORSTOM / Sciences Humaines*. 17: 1-6: 1-9.

Gastellu, J. -M. Dubois, J. -L. 1997. "En économie: l'unité retrouvée, la théorie revisitée". *Les Etudes du CEPED.* 1997: 75-97.

Gavian, S. Fafchamps, M. 1996. "Land tenure and allocative Efficiency in Niger". *American Journal of Agricultural Economics*. 78: 2: 460-471.

Gentil, D. Fournier, Y. Doligez, F. 1993. *Les paysans peuvent-ils devenir banquiers? Epargne et crédit en Afrique*. Syros, Paris, France.

Geist, H. J. Lambin, E. F. 2004. "Dynamic causal patterns of desertification". *Bioscience*. 54: 9: 817-829.

Gérard, B. Buerkert, A. 2001. "Estimation of spatial variability in pearl millet growth with non-destructive methods". *Explanatory in Agriculture*. 37: 373-389.

Gérard, B. 2002. *Projet Aide à la décision: full proposal for the DGCD*. Bruxelles, Belgium.

Gérard, B. 2005. *ICRISAT agronomic results from the global linear modelization of demonstration tests fields' data. ICRISAT report.* Niamey, Niger.

Gérard, B., Fatondji, D. Dandois, C. Manyame, C. Bielders, C. 2007. "Toward farm specific recommendations for the use of mineral fertilizers in Sahelian crop-livestock systems". Proceedings of the 16th International Symposium of the International Scientific Centre of Fertilizers (CIEC) Ghent, Belgium.

Gilbert, N. 2006. "Sciences sociales computationnelles: simulation sociale multi-agents". In *Modélisation et simulations multi-agents: Application pour les sciences de l'Homme et de la Société*. Amblard, F. Phan, D. (Eds.). 141-159.

Gimblett, R. 2005. Modeling human-landscape interactions in spatially complex settings: Where are we and where are we going? *Journal of Artificial Societies & Social Simulation*. 2: 6.

Gladwin, C. H. 1989, *Ethnographic decision tree modeling* Newbury Park, California, USA.

Glättli, S. 2005. *Méthodes et outils pour faciliter l'échange de savoir entre spécialistes de conservation des eaux et sols et agriculteurs sur la gestion durable des sols au Niger, Afrique de l'Ouest. Une analyse ethno-pédologique pour démontrer les différentes perceptions du sol.* Ph.D. Environment. Fakultät der Universität Bern, Center for Development & Environment (CDE), Switzerland.

Graef, F. Haigis, J. 2001. "Spatial and temporal rainfall variability in the Sahel and its effects on farmers' management strategies". *Journal of Arid Environments*. 48: 2: 221-231.

Greif, A. 1989. "Reputation and coalitions in medieval trade: evidence on the Maghribi traders". *The Journal of Economic History*. 49: 4: 857-882.

References

Grégoire, E. 1986, *Les Alhazai de Maradi, Niger: Histoire d'un groupe de riches marchands sahéliens.* Éditions de l'ORSTOM Paris, France.

Guenguant, J. -P. Banoin, M. Quesnel, A. 2002. "Dynamique des populations, disponibilités en terres et adaptation des régimes fonciers: le cas du Niger". In F. Gendreau, & M. Lututala, (Eds.). *Développement durable*. (Chapter 3). Food & Agriculture Organisation (FAO). Rome, Italy.

Gurung, T. R. Bousquet, F. Trébuil, G. 2006. "Companion modeling, conflict resolution, and institution building: sharing irrigation water in the Lingmuteychu Watershed, Bhutan". *Ecology & Society*. 11: 2.

Halfacree, K. H. 1993. "Locality and social representation: Space, discourse and alternative definitions of the rural". *Journal of Rural Studies*. 9: 1: 23-37.

Hama Beïdi, B. 1993. *Les Peuls du Dallol Bosso, coutumes et modes de vie.* SEPIA, Paris, France.

Hambally, Y. 1999. Mode d'intervention et pratiques paysannes au Niger, Ph.D. Geography. EDHESS, Paris, France.

Hamidou, N. 2005. *Analyse des activités des ménages agricoles du Fakara au Niger: cas de trois villages.* MSc Agronomy CNEARC, Montpellier, France.

Hammel, R. 2000. "Terroirs d'attache des pasteurs au Niger". Proceedings of the 1st Symposium on "Elevage et gestion de parcours au Sahel, implications pour le développement", Niamey, Niger.

Happe, K. Kellermann, K. Balmann, A. 2006. "Agent-based analysis of agricultural policies: an illustration of the agricultural policy simulator AgriPoliS, its adaptation, and behavior." *Ecology & Society*. 11: 1: 825-837.

Hardin, G. 1968. "The Tragedy of the Commons". *Science*. 162: 1243-1248.

Harragin, S. 2006. *The Cost of being Poor: Markets, mistrust and malnutrition in southern Niger 2005-2006.* Save the Children, London, U. K.

Harris, F. M. A. 1998. "Farm-level assessment of the nutrient balance in northern Nigeria ". *Agriculture, Ecosystems & Environment*. 71: 1-3: 201-214.

Henry, S. Boyle, P. Lambin, E. F. 2003. "Modeling inter-provincial migration in Burkina Faso, West Africa: the role of socio-demographic and environmental factors". *Applied Geography*. 23: 115-136.

Herrmann, S. M. Hutchinson, C. F. 2005. "The changing contexts of the desertification debate". *Journal of Arid Environments*. 63: 3: 538-555.

References

Hiernaux, P. 1998. *The soils in villages' lands in western Niger, opportunities and constraints for rural development.* ICRISAT report. Niamey, Niger.

Hill, P. 1972, *Rural Hausa, a village and a setting*, Cambridge University Press, Cambridge. U.K.

Howorth, C. O'Keefe, P. 1999. "Farmers do it better: local management of change in southern Burkina Faso". *Land Degradation & Development*. 10: 2: 93-109.

Huigen, M. G. A. Overmars, K. P. de Groot, W. T. 2006. "Multi-actor modeling of settling decisions and behavior in the San Mariano watershed, the Philippines: a first application with the MameLuke framework." *Ecology & Society*.11: 2: 38-53.

IRD. 1974. *Pedomorphological maps of Niger: 1/ 100,000.* IRD, Paris, France.

Jackson, C. 1993. *La gestion d'équipes de recherches interdisciplinaires: l'expérience de l'ICRA.* CTA-ICRA, Wageningen-Montpellier, The Netherlands-France.

Janssen, M. A. Ostrom E. 2006. "Empirically Based, Agent-based models". *Ecology & Society*. 11: 2: 24-37.

Jouve, P. 1991. "Sécheresse au Sahel et stratégies paysannes". *Sécheresse* 2: 1: 61-69.

Jouve, P. 2003. "Typologie des agrosystèmes villageois du département de Maradi (Niger) propositions pour un programme de recherche-développement". Département DSA CIRAD, *Collection Documents Systèmes Agraires*. 3.

Jouve, P. 2004. "Transition agraire et résilience des sociétés rurales; La croissance démographique, frein ou opportunité pour une intensification agricole durable en Afrique subsaharienne?" *Courrier de l'environnement de l'INRA*. 52: 101-106.

Jouve, P. 2006. "Croissance démographique, transitions agraires et intensification agricole en Afrique sub-saharienne". Proceedings of the "Journées sur les Systèmes Agraires". Ouagadougou, Burkina Faso. 53-59.

Jouve, P. Tallec, M. 1994. "Une méthode d'étude des systèmes agraires par l'analyse de la diversité et de la dynamique des agrosystèmes villageois". *Cahiers de la Recherche & du Développement*. 39.

Ki-Zerbo, J. 1972, *Histoire de l'Afrique noire.* Hatier, Paris, France.

References

Kilani, M. Waziri Mato, M. 2001. *Gomba Hausa: Dynamique du changement dans un village sahélien du Niger*. Payot, Lausanne, Switzerland.

Kobchai, W. 2006. *Companion Modelling for razor clam Solen regularis Conservation at Don Hoi Lord, Samut SongKhram Province, Thailand*. M.Sc. Zoology. Chulalongkorn University, Thailand.

Koning, N. Smaling, E. 2005. "Environmental crisis or 'lie of the land'? The debate on soil degradation in Africa". *Land Use Policy*. 22: 1: 3-11.

La Rovere, R. 2001. *Livestock roles and agro-environmental sustainability of Sahelian Niger mixed crop-livestock systems under intensification*. Ph.D. Geography. International Livestock Research Institute, University of Hohenheim, Germany.

La Rovere, R. Hiernaux, P. Van Keulen, H. Schiere, J. B. Szonyi, J. A. 2005. "Co-evolutionary scenarios of intensification and privatization of resource use in rural communities of south-western Niger". *Agricultural Systems*. 83: 3: 251-276.

La Rovere, R. Van Keulen, H. Hiernaux, P. Szonyi, J. A. 2007. "Intensification scenarios in southwestern Niger: Implications for revisiting fertilizer policy". *Food Policy*. In Press, corrected proof.

Lambert, S. Sindzingre, A. 1995. "Droits de propriété et modes d'accès à la terre en Afrique : une revue critique". *Cahiers d'économie et sociologie rurales*. 36: 3: 95-128.

Lambin, E. F. Rounsevell, M. D.A. Geist H. J. 2000. "Are agricultural land-use models able to predict changes in land-use intensity?" *Agriculture, Ecosystems & Environment*. 82: 1-3: 321-331.

Lambin, E. F. Turner, B. L. Geist, H.J. Agbola, S. B. Angelsen, A. Bruce, J. W. Coomes, O. T. Dirzo, R. Fischer, G. Folke, C. Goerge, P.S. Homewood, K. Imbernon, J. Leemans, R. Xiubin, L. Moran, E. F. Mortimore, M. J. Ramakrishnan, P.S. Richards, J. F. Skanes, H. Steffen, W. Stone, G. D. Svedin, U. Veldkamp, T. A. Vogel, C. Jianchu, X. 2001. "The causes of land-use and land-cover change: moving beyond the myths". *Global Environmental Change*. 11: 261-269.

Landais, É. 1992. "Principes de modélisation des systèmes d'élevage. Approches graphiques". *Les Cahiers de la recherche-développement*. 32: 82-95.

Landais, É. Deffontaines, J. -P. 1987. "Les pratiques des agriculteurs. Point de vue sur un courant nouveau de la recherche agronomique". *Etudes rurales*. 109.

Lardon, S. Baron, C. Bommel, P. Bousquet, F. Le Page, C. Lifran, R. Monestier, P. Reitz, P. 1998. "Modéliser les configurations et les stratégies spatiales dans un système multi-agents pour la maîtrise de dynamiques d'embroussaillement". Proceedings of the "Séminaire sur les Multi-Agents pour la Gestion de l'Environnement & des Territoires (SMAGET) 1998". Clermont-Ferrand, France.

Lassina, O. 1992. *Etude des relations pluviométrie-phénologie-production dans la zone sud-ouest du Sahel Nigerien.* M.Sc. Agronomy. Université Abdou Moumouni, Niamey, Niger.

Laurent, P. -J. 2000. "Le big man local ou la «gestion coup d'État» de l'espace public". *Politique Africaine*. 80: 169-181.

Laurent, P. -J. Mathieu P. Totté M. 1994. "Migration et accès à la terre au Burkina Faso". *Cahiers du CIDEP*. 20: 15-131.

Lavigne-Delville, P. 1998. "Harmonising formal law & customary land rights In French-speaking West Africa". Proceedings of "Politique des structures et action foncière au service du développement agricole et rural". CNASEA, La Réunion, France, 32.

Lavigne-Delville, P. 1999. "Impasses cognitives et expertise en sciences sociales : réflexions à propos du développement rural en Afrique". GRET. *Coopérer aujourd'hui*. 9.

Lavigne-Delville, P. 2001. "Regards sur les enquêtes et diagnostics participatifs: la situation d'enquête comme interface". GRET. *Coopérer aujourd'hui*. 17.

Lavigne-Delville, P. Mathieu, M. Sellamna, N. –E. 2001. "Living up to ambitions : for a more rigorous practice of participatory appraisals and enquiries. GRET. *Coopérer aujourd'hui*. 28.

Lavigne-Delville, P. Broutin, C. Castellanet, C. 2001. "Jachères, fertilité, dynamiques agraires, innovations paysannes et collaborations chercheurs/paysans: Fondements pour des recherches-actions en milieu paysan sur la fertilité des terres". GRET. *Coopérer aujourd'hui*. 36.

Lazarev, G. Arab, M. 2000. *Développement local et communautés rurales: approches et instruments pour une dynamique de concertation.* Réseau Interdisciplinaire de Soutien au Développement Participatif. Paris, France.

Le Barbé, L. Lebel, T. 1997. "Rainfall climatology of the HAPEX-Sahel region during the years 1950-1990". *Journal of Hydrology*. 188-189**:** 43-73.

Le Bars, M. 2003. *Un Simulateur Multi-Agents pour l'Aide à la Décision d'un Collectif: Application à la gestion d'une ressource limitée agri-*

environnementale. Ph.D. Computer Programming. Université Paris 9-Dauphine, Paris, France.

Le Bris, E. Le Roy, E. Mathieu, P. 1991. L'appropriation de la terre en Afrique Noire, Manuel d'analyse, de décision et de gestion foncières, KARTHALA, Paris, France.

Le Houérou, H. N. Hoste, C. H. 1977. "Rangeland Production and Annual Rainfall Relations in the Mediterranean Basin and in the African Sahelo-Soudanian Zone". *The Journal of Range Management*. 30: 3: 181-189.

Le Page, C. d'Aquino, P. Etienne, M. Bousquet, F. 2004. "Processus participatifs de conception et d'usage de simulations multi-agents: Application à la gestion des ressources renouvelables". Proceedings of the "Journées sur les Systèmes Multi-Agents (JFSMA)". 33-46.

Lebel, T. Taupin, J. –D. d'Amato, N. 1997 "Rainfall monitoring during HAPEX-Sahel. 1. General rainfall conditions and climatology". *Journal of Hydrology* 188-189: 74-96.

Lesnoff, M. 2005. "Informations simplifiées sur les taux de mortalité et de reproduction des ruminants d'élevage en Afrique de l'Ouest". Communication in process.

Lewis, J. L. Sheppard, S. R. J. 2005. "Culture and communication: Can landscape visualization improve forest management consultation with indigenous communities?" *Landscape and Urban Planning*. 77, 3, 291-313.

Lieurain, E. 1998. *Simulations Distribuées et Multi-Agents*, M. Sc. Computer Programming. CIRAD Tera. Université Montpellier 2, Montpellier, France.

Loader, R. Amartiya, L. 1999. "Participatory Rural Appraisal: extending the research methods base". *Agricultural Systems*. 62: 1-3: 73-85.

Loewenberg, S. 2005. "Why did helping Niger take so long?" *The Lancet*. 366: 1067-1068.

Loireau-Delabre, M. 1998. *Espaces Ressources Usages: Spatialisation des interactions dynamiques entre les systèmes sociaux et écologiques au Sahel Nigerien, site de Banizoumbou, Niger*. Ph.D. Geography. Université Montpellier 3.

Loireau-Delabre, M. 2000. *Observatoire de Banizoumbou: un SIE local*. CIRAD/ OSS-ROSELT.

Lund, C. 2001. "Precarious Democratization and Local Dynamics in Niger: Micro-Politics in Zinder". *Development & Change*. 32: 5: 845-869.

Luxereau, A. Roussel, B. 1997. *Changements écologiques et sociaux au Niger*. L'Harmattan. Paris, France.

Lycklama, R. 2000. *Des champs qui ont des pieds et des vaches qui veulent marcher, conflits liés aux ressources naturelles au Niger*. AFVP Internal report, Niamey, Niger.

Mahamane, A. 2001. "Usages des terres et évolutions végétales dans le Département de Maradi". *Drylands Research*. Crewkerne, U.K.

Mainguet, M. Da Silva G. 1998. "Desertification and drylands development: what can be done?" *Land Degradation & Development*. 9: 375-382.

Marou, D. M. 2005. *Etude des effets et impacts des initiatives et innovations paysannes améliorant le revenu des ménages dans la zone d'Aguié*. M. Sc. Development. Université Catholique de Louvain, Louvain-la-Neuve, Belgium.

Mathieu, P. 1998. "Population pauvreté et dégradation de l'environnement en Afrique: fatale attraction ou liaisons hasardeuses?" *Nature Sciences & Sociétés*. 6: 3: 27-34.

Matthews, R. B. 2006. "The People and Landscape Model (PALM): Towards full integration of human decision-making and biophysical simulation models". *Ecological Modeling*. 194: 4: 329-343.

Mauss, M. 1924. "Essai sur le don: Forme et raison de l'échange dans les sociétés archaïques". *Sociologie et anthropologie*. 58: 143-279.

Mazoyer, M. Roudart, L. 1997. *Histoire des Agricultures du monde, du néolithique à la crise contemporaine*. Seuil, Paris, France.

Mazzucato, V. Niemeijer, D. 2001. "Overestimating land degradation, underestimating farmers in the Sahel" *IIED Dry Area program*. 101.

M'Bokolo, E. 2004. *Afrique noire. Histoire et civilisations, tome 2*. Hatier, Pars, France.

McCall, M. K. 2002. "Seeking good governance in participatory-GIS: a review of processes and governance dimensions in applying GIS to participatory spatial planning". *Habitat International*. 27: 549-573.

McCarthy, N. Swallow, B. Kirk, M. Hazell, P. B. R. 2000. *Property Rights, Risk, and Livestock Development in Africa* IFPRI. Nairobi, Kenya.

McCarthy, N. Dutilly-Diané, C. Drabo, B. 2004. "Cooperation, collective action and natural resources management in Burkina Faso". *Agricultural Systems*. 82: 3: 233-255.

McDonald, R. I. Urban, D. L. 2006. "Spatially varying rules of landscape change: lessons from a case study". *Landscape and Urban Planning*. 74: 7-20.

McNamara, T. P. 1992. "Spatial representation". *Geoforum*. 23: 2: 139-150.

Mechoud, S., Hill, D. R.C. Campos, A. 1998. "Simulation Multi-Agents de l'entretien du paysage par des herbivores en moyenne montagne"". Proceedings of the "Séminaire sur les Multi-Agents pour la Gestion de l'Environnement & des Territoires (SMAGET) 1998". Clermont-Ferrand, France.

Médecins Sans Frontières. 2005. *Urgence Niger : Payer ou Mourir. Chiffres remis à jour le 28 juillet 2005*. 19.

Meignel, S. 1997. "Ménages, crise et bien-être dans les pays en développement: quelques enseignements de la littérature récente". *Montesquieu Working Paper*. 14. Université Montesquieu, Bordeaux, France.

Mettrick, H. 1994. *Recherche Agricole orientée vers le développement, le cours ICRA*. ICRA, Wageningen, The Netherlands.

Meurisse, T. Vanbergue, D. 2001. "Et maintenant, à qui le tour? Aperçu de Problématiques de Conception de Simulations Multi-Agents": *LIRMM Working Paper*. Paris. 21.

Milleville, P. 1989a. "Risques et pratiques paysannes : diversité des réponses, disparité des effets". In *Le risque en agriculture*. Eldin, M. Milleville, P. (Eds.). INRA-SAD, Paris, France. 179-186.

Milleville, P. 1989b. "Activités agropastorales et aléa climatique en région sahélienne". In *Le risque en agriculture*. Eldin, M. Milleville, P. (Eds.). INRA-SAD, Paris, France. 233-241.

Milleville, P. Serpantié, G. 1994. "Agrarian dynamics and the question of the intensification of farming in the Sahelian and savanna zones of Africa". *Comptes Rendus de l'Académie d'Agriculture de France*. 80: 8: 149-161.

Minet, J. 2007. *Influence de la dispersion du parcellaire sur la gestion du risque climatique au Fakara, Niger*, M. Sc. Environnement, Université catholique de Louvain, Louvain-la-Neuve, Belgium.

Montagne, P. Housseini, M. 1998. "Gestion des ressources ligneuses dans les jachères de l'Ouest Nigerien". In *Jachères et systèmes agraires*. Floret, C. Pontanier, R. (Eds.) CORAF/Union Européenne, Dakar, Sénégal. 1: 161-170.

Mortimore, M. J. Adams, W. M. 2001. "Farmer adaptation, change and 'crisis' in the Sahel". *Global Environmental Change*. 11: 1: 49-57.

Mortimore, M. J. Tiffen, M. Yamba, B. Nelson, J. 2001. "Synthèse sur les évolutions à long terme dans le département de Maradi, Niger 1960-2000". *Drylands Research*. Crewkerne. U.K.

Mortimore, M. J. Harris, F. M. A. 2005. "Do small farmers' achievements contradict the nutrient depletion scenarios for Africa?" *Land Use Policy*. 22: 1: 43-56.

Mortimore, M. J. Turner, B. L. 2005. " Does the Sahelian smallholder's management of woodland, farm trees, rangeland support the hypothesis of human-induced desertification?" *Journal of Arid Environment*. 63: 3: 567-595.

Moss S. Edmonds, B. 2005. "Sociology and Simulation: Statistical and Qualitative Cross-Validation". *American Journal of Sociology*. 110: 4: 1095-1131.

Mounkaïla, H. 2003. "De la migration circulaire à l'abandon du territoire local dans le Zarmaganda (Niger)". *Revue Européenne des Migrations Internationales*. 18: 2: 161-187.

Muehlig-Versen, B. Buerkert, A. Bationo, A. Roemheld, V. 2003. "Phosphorus placement on acid arenosols of the West African Sahel". *Explanatory in Agriculture*. 39: 307-325.

Müller, J.-P. 2006. "Les modèles actuels de l'émergence". Présentation aux sessions de formation aux Multi-Agents. Caen, France.

Nederlof, S. E. Dangbégnon, C. 2007. " Lessons for farmer-oriented research: Experiences from a West African soil fertility management project". *Agriculture & Human Values*. 24: 3: 369-387.

Newell, B. Crumley, C. L. Hassan, N. Lambin, E. F. Pahl-Wostle, C. Underdal, A. Wasson, R. 2005. "A conceptual template for integrative human-environment research". *Global Environmental Change*. 15: 299-307.

Niemeijer, D. Mazzucato, V. 2002. "Soil degradation in the West African Sahel: how serious is it?" *Environment (Washington DC)*. 44: 3: 20-31.

Nikolopoulos, K. 2003. "Book Review of *Simplicity, Inference and Modeling: Keeping It Sophisticatedly Simple*. Zellner, A. Keuzenkamp, H. A. McAleer, M. (Eds.). Cambridge University Press 2001. *International Journal of Forecasting*. 19: 2: 333-335.

Olivier de Sardan, J. -P. 1991. *D'un savoir à l'autre. Les agents de développement comme médiateurs.* EHESS. Marseille/Paris, France.

References

Olivier de Sardan, J.-P. Boiral, P. Lanteri, J.-F. 1995. *Paysans, experts et chercheurs en Afrique noire, sciences sociales et développement rural.* CIFACE KARTHALA, Paris, France.

Olivier de Sardan, J.-P. Dagobi, A. E. 2000. "La gestion communautaire sert-elle l'intérêt public? Le cas de l'hydraulique villageoise au Niger". *Politique Africaine.* 80: 153-168.

Olivier de Sardan, J. -P. 2003a. *Anthropologie & développement, essai en socio-anthropologie du changement social.* APAD KARTHALA, Marseille Paris, France.

Olivier de Sardan, J. -P. 2003b. "L'enquête socio-anthropologique de terrain: synthèse méthodologique et recommandations à usage des étudiants". *Etudes et travaux du LASDEL.* Niamey, Niger. 13.

Olivier de Sardan, J. -P. 2003c. *Les sociétés Songhay - Zarma (Niger - Mali) Chefs, guerriers, esclaves, paysans.* KARTHALA, Paris, France.

Olivier de Sardan, J. –P. 2006. "Chefs et projets au Village (Niger)". *Bulletin de l'APAD.* 15.

Osbahr, H. Allan, C. 2003. "Indigenous knowledge of soil fertility management in southwest Niger". *Geoderma.* 457-479.

OSS-ROSELT-Niger. 2001. *Etat d'avancement des activités de l'observatoire de Torodi - Dantiandou - Tondikandia.* Niamey, Ministère de l'hydraulique, de l'environnement et de lutte contre la désertification.

OSS-ROSELT-Niger. 2006. *Guide pour l'évaluation et le suivi des pratiques d'exploitation des ressources naturelles.*

Ouédraogo, S. 2005. *Intensification de l'agriculture dans le plateau central du Burkina Faso: Une analyse des possibilités à partir des nouvelles technologies.* Ph.D. Economy. Rijksuniversiteit Groningen. Nederlands.

Parker, D. C. Berger, T. Manson, S. M. 2001. *Agent-Based Models of Land-Use and Land-Cover Change: Report and Review of an International Workshop.* LUCC Report Series.

Parker, D. C. Manson, S. M. Janssen, M. A. Hoffmann, M. J. Deadman, P. 2001. "Multi-Agent Systems for the Simulation of Land-Use and Land-Cover Change: A Review". In *Multi Agents in Land Use.* LUCC Report Series.

Paul, J. -L. Bory, A; Bellande, A. Fabri, A. Garganta, E. 1994. "Quel système de référence pour la prise en compte de la rationalité de l'agriculteur: du système de production agricole au système d'activité".

References

Proceedings of the "Symposium international INRA-CIRAD:Recherches-système en agriculture et développement rural. 46-52. Montpellier, France,

Pender, J. Abdoulaye, T. Ndjeungua, J. Gérard, B. Kato, E. 2006. "Impacts of inventory credit, input supply shops and fertilizer micro-dosing in the dryland of Niger." Proceedings of the 26th Conference of the International Association of Agricultural Economists. Brisbane, Australia.

Perrot, C. Landais, É. 1993. "Comment modéliser la diversité des exploitations agricoles? Méthodes d'études en milieu paysan". *Les Cahiers de la recherche-développement*. 33: 24-40.

Peyre de Fabrègues, B. 2001. "Les grandes étapes de l'élevage en zone pastorale au Niger et leurs conséquences majeures". Proceedings of the 1st Symposium on "Elevage et gestion de parcours au Sahel, implications pour le développement", Niamey, Niger.

Phan, D. Beugnard, A. 2003. "Moduleco: Un prototype de plate-forme multi-agents fondé sur un modèle informatique original, conçu pour simuler les marchés, les phénomènes sociaux et la dynamique des populations". *CIRAD Working paper*, Montpellier, France.

Phillips, E. L. 2007. *How do Households in Niger maintain their livelihoods after a production shock? A comparative study of coping strategies used by two Nigerien villages.* M. Sc. International Agriculture and Rural Development, Cornell University, Ithaca, U.S.A.

Pierret, S. 1999. *Logique de l'utilisation de l'espace pastoral Nigerien, modélisation et spatialisation des interactions entre animaux et ressources à partir de suivis de troupeaux* M.Sc Université Montpellier 2, Montpellier, France.

Poix, C. Michelin, Y. 2000. "Simulation paysagère: Un modèle multi-agents pour prendre en compte les relations sociales". *CyberGeo*. 116.

Poncet, Y. 1973. *Ethno-demographic maps of Niger: 1/ 100,000.* Études Nigeriennes n°32. IRD-Centre Nigerien de recherches en sciences humaines.,, Niamey, Niger.

Popper, K. R. 1985. *Conjectures et réfutations. La croissance du savoir scientifique*. Payot, Paris, France.

Pujol, J. M. Flache, A. Delgado, J. Sangüesa, R. 2005. "How Can Social Networks Ever Become Complex? Modeling the Emergence of Complex Networks from Local Social Exchanges". *Journal of Artificial Societies & Social Simulation.* 8: 4.

Quin'ones, M. A. Borlaug, N. E. Dowswell, C. R. 1996. "A Fertilizer-Based Green Revolution for Africa". Proceedings of the 51st ICRAF / American Society of Agronomy / Soil Science Society of America Conference on "Replenishing Soil Fertility in Africa" 81-96. Indianapolis, Indiana, USA.

Radja, K. 2003. La famille dans l'analyse économique: modélisation et représentations théoriques de la famille. *Montesquieu Working Paper*. 25. Université Montesquieu, Bordeaux, France.

Rain, D. 1999. *Eaters of the dry season: Circular labor migration in the West African Sahel.* West View Press, Oxford, U.K.

Raison, J. -P. Coniat, D. 1997. *Essais sur les montagnes de Tanzanie* KARTHALA, Paris, France.

Raynaut, C. Koecklin, J. Brasset, P. Cheung, C. Stigliano, M. 1988. *Le développement rural de la région au village: analyser et comprendre la diversité. Projet de développement rural de Maradi.* GRID, Bordeaux, France.

Raynaut, C. 1989. "La culture irriguée en pays haoussa Nigerien: Aspects historiques, sociaux et techniques". *Etudes Rurales*: 115-116.

Raynaut, C. Grégoire, E. Janin, P. Koecklin, J. Lavigne-Delville, P. Bradley, P. 1997. *Societies & Nature in the Sahel.* Translated by *Simon, D. Koziol, H.*, Routledge London. U.K.

Raynaut, C. 2007. "L'opération de développement et les logiques de changement : la nécessité d'une approche holistique, l'exemple d'un cas Nigerien". *Revue de l'Institut Universitaire d'Etudes du Développement et de la société suisse d'études africaines*. 27: 2: 9-38.

Read, D. W. 2003. "Kinship based demographic simulation of societal processes". *Journal of Artificial Societies & Social Simulation.* 6: 3.

Reardon, T. 1994. "La diversification des revenus au Sahel et ses liens éventuels avec la gestion des ressources naturelles par les agriculteurs". In *Promotion de systèmes agricoles durables dans les pays d'Afrique soudano sahélienne*. Benoît-Cattin, M. (Ed.). FAO CTA CIRAD. 65-77.

Reenberg, A. Paarup-Larsen, B. 1997. "Determinants for land use strategies in a Sahelian agro-ecosystem; anthropological and ecological geographical aspects of natural resource management". *Agricultural Systems*. 53: 2-3: 209-229.

Reenberg, A. 2001. "Agricultural land use pattern dynamics in the Sudan-Sahel-towards an event-driven framework". *Land Use Policy*. 18: 4: 309-319.

Renfrew, C. A. 1987. "Problems in the modeling of socio-cultural systems ". *European Journal of Operational Research*. 30: 2: 179-192.

Requier-Desjardins, M. 2000. *Elevage, transhumance, Appropriation et contrat d'accès aux pâturages au Nord-Cameroun*. PhD Geography. Université Paris X, Paris, France.

Reynolds, J. F. Stafford-Smith, D. M. Lambin, E. F. 2003. "Do humans cause deserts? An old problem through the lens of a new framework: The Dahlem Desertification paradigm". Proceedings of the 7th International Rangelands Congress, Durban, South Africa. 2041-2048.

RGP, 2001. Recensement Général de la Population du Niger. Gouvernement du Niger, Niamey, Niger.

Ronnenberg-Moller, M. 1998. *The changing roles of non-agricultural activities in the livelihoods of Nigerian peasants*. CDR. *Ibiscus-Regards-* DF.9: 27.

Rouchier, J. Requier-Desjardins, M. 1998. "L'Interdisciplinarité pour la modélisation dans la recherche-développement : compte-rendu d'une expérience en cours, une application au pastoralisme soudano-sahélien". Proceedings of the "Séminaire sur les Multi-Agents pour la Gestion de l'Environnement & des Territoires (SMAGET) 1998". Clermont-Ferrand, France.

Rouchier, J. 2000. *La confiance à travers l'échange: Accès aux pâturages du Nord-Cameroun et échanges non-marchands: des simulations dans des systèmes multi-agents*. Ph.D. Computer Programming. Université d'Orléans, Orléans, France.

Rouchier, J. O'Connor, M. Bousquet, F. 2001. "The creation of a reputation in an artificial society organised by a gift system". *Journal of Artificial Societies & Social Simulation*. 4: 2.

Roy, B. 1992. "Science de la décision ou science de l'aide à la décision?" *Revue Internationale de systémique*. 6: 497-529.

Sangaré, M. Fernández-Rivera, S. Bationo, A. Hiernaux, P. Pandey, V. S. 2001. "Effets de différents types d'amendements sur le rendement du mil et la fertilité du sol au Sahel". *Cahiers d'études et de recherches francophones / Agricultures*. 10: 5: 319-325.

Saqalli, M. 2002. *Diagnostic comparatif sur 2 sites circum-sahariens de suivi de la désertification*. OSS-ROSELT/ IRD/ MATE, Montpellier, France.

Saqalli, M. 2006. "Multi acteurs, multi activités: Simulations multi-agents pour la détection des changements dans l'Organisation sociale dans les villages de l'Ouest Nigerien". Proceedings of the "Conférence Francophone de Modélisation et de Simulation (MOSIM'06)". Casablanca, Morocco. 253-263

Schlect, E. Buerkert, A. 2004. "Organic inputs and farmers' management strategies in millet fields of western Niger". *Geoderma*. 121: 271-289.

Schlect, E. Hiernaux, P. Kadaoure, I. Hülsebusch, C. Mahler, F. 2006. "A spatio-temporal analysis of forage availability and grazing and excretion behaviour of herded and free grazing cattle, sheep and goats in Western Niger". *Agriculture, Ecosystems & Environment*. 113: 1-4: 226-242.

Schmidt, C. Rounsevell, M. D.A. 2006. "Are agricultural land use patterns influenced by farmer imitation?" *Agriculture, Ecosystems & Environment*. 115: 1-4: 113-127.

Seidl, I. Tisdell, C. A. 1999. "Carrying capacity reconsidered: from Malthus population theory to cultural carrying capacity". *Ecological Economics*. 31: 395-408.

Sévila, F. 2001. "La conception d'outils d'aide à la décision". In *Modélisation des agro-écosystèmes et aide à la décision*. Malézieux, E. Trébuil, G. Jaeger, M. (Eds.). Edition Repères CIRAD-INRA, Paris, France. 75-91.

Seybou, H. 1993. *Enquête sur les systèmes de culture, cas du terroir de Banizoumbou*, M.Sc. Agronomy. Université Abdou Moumouni, Niamey, Niger.

Shiawoya, E. L. 2006. "Sheep fattening enterprise as a strategy for poverty reduction: A case study of some key local government areas (LGAs) of Niger State". *Journal of Human Ecology*. 20: 1: 11-14.

Sicot, M. 1989. "Contraintes et risques hydriques encourus par l'activité agropastorale au Sahel". In *Le risque en agriculture*. Eldin, M. Milleville, P. (Eds.). INRA-SAD, Paris, France. 131-141.

SIM Céréales. *Evolution des prix des céréales et leurs impacts sur les revenus des populations issus de la vente de bétail. 1-11. 2002.* Union européenne auprès des SIM céréales et bétail au Niger, Systèmes d'Information sur les Marchés des céréales, du Niébé et du Bétail.

Simon, H. A. 1955. "A Behavioral Model of Rational Choice". *Quarterly Journal of Economics*. 69: 1: 99-118.

Sirven, N. 2003. "Capital social et développement : quelques éléments d'analyse". *Montesquieu Working Paper*. 20. Université Montesquieu, Bordeaux, France.

Small, C. 1999. "Finding invisible history: a computer simulation experiment in virtual Polynesia". *Journal of Artificial Societies and Social Simulation* 2: 3.

Soini, K. 2001. "Exploring human dimensions of multifunctional landscapes through mapping and map-making". *Landscape and Urban Planning*. 57: 225-239.

Sontheimer, S. Callens, K. Seiffert, B. 1999. "Conducting a PRA training & modifying PRA tools to your needs. An example from a participatory household food security & nutrition project in Ethiopia. FAO. Rome, Italy.

Stone, G. D. Downum, C. E. 1999. "Non-Boserupian ecology & agricultural risk: ethnic politics & land control in the arid southwest Nigeria". *American Anthropologist* 101: 1: 113-128.

Stone, G. D. McC.Netting, R. Stone, M. P. 1990. "Seasonality, Labor Scheduling, and Agricultural Intensification in the Nigerian Savanna". *American Anthropologist.* 92: 1: 7-23.

Stone, M. P. Stone, G. D. McC.Netting, R. 1995. "The Sexual Division of Labor in Kofyar Agriculture". *American Ethnologist*. 22: 1: 165-186.

Tandia, M. 1991. *Utilisation de l'espace et des ressources pastorales dans quelques terroirs villageois Banizoumbou (Niger)*, M.Sc. Management of agro-sylvo-pastoral tropical Systems. Université Paris 12, Paris, France.

Tappan, G. McGahuey, M. 2007. "Tracking environmental dynamics and agricultural intensification in southern Mali". *Agricultural Systems*. 94: 1: 38-51.

Thébaud, B. 1996. *Gestion de l'espace et crise pastorale au Sahel, Etudes comparatives du Niger Oriental et du Yagba Burkinabé.* Ph.D. Geography. EDHESS. Paris, France.

Thébaud, B. Batterbury, S. 2001. "Sahel pastoralists: opportunism, struggle, conflict and negotiation. A case study from eastern Niger". *Global Environmental Change*. 11: 1: 69-78.

Tiffen, M. 2001. Profile of Demographic Change in the Kano-Maradi region, 1960-2000. *Drylands Research*. Crewkerne, U.K.

Tiffen, M. 2003. Transition in Sub-Saharan Africa: Agriculture, Urbanization and Income Growth. *World Development.* 31: 8: 1343-1366.

Tillion, G. 1982, *Le harem et les cousins.* Point, Paris, France.

Timera, M. 2001. "Les migrations des jeunes sahéliens: Affirmation de soi et émancipation". In Collignon, R. Diouf M. (Eds.). *Les jeunes: hantise de l'espace public dans les sociétés du Sud?* KARTHALA, Paris, France 37-49.

References

Touré, I. Bah, A. d'Aquino, P. Dia, I. 2004. "Savoirs experts et savoirs locaux pour la coélaboration d'outils cartographiques d'aide à la décision". *Cahiers d'études et de recherches francophones/ Agricultures*. 13: 546-553.

Turner, M. E. 1999a. "Merging local and regional analyses of land use change: the case of livestock in the Sahel". *Annals of the Association of American geographers*. 89: 2: 191-219.

Turner, M. E. 1999b. "No space for participation: pastoralist narratives and the etiology of park-herder conflict in southeastern Niger". *Land Degradation & Development*. 10: 345-363.

Turner, M. E. Patterson, D. Patterson, K. P. 2005. *Conflict management for improved livestock productivity and sustainable natural resource use in Niger, West Africa*. Final report, ILRI, Niamey, Niger.

Turner, M. E. Hiernaux, P. Schlect, E. 2005. "The distribution of grazing pressure in relation to vegetation resources in semi-arid West Africa: The role of herding". *Ecosystems* 8: 6: 668-681.

Turner, M. E. Williams, T. O. 2006. "Livestock market dynamics and local vulnerabilities in the Sahel". *World Development.* 30: 4: 683-705.

UNCCD 2003. *What is desertification?* New York, USA.

UNDP 2005. *Human Development Report 2005.* International Cooperation at a crossroads. Aid, trade and security in an unequal world. New York, USA.

UNDP 2007. *Human Development Data: Niger* http://www.hdrstats.undp.org/countries/ data_sheets /cty_ds_NER.html

UNEP 1991. Stop Deserts Growing. Save Soils. Nairobi, Kenya.

UNICEF. Gouvernement du Niger. 2000. *Enquête de base du programme services de base intégré.* Niamey, Niger.

Vanderlinden, J.-P. 1998. "The Niger case study," *The African Policy*. 350-370.

Van Dyck, V. 2007. *L'impact de la migration sur les inégalités : Le cas du Niger*. M. Sc. Economy, Université catholique de Louvain, Louvain-la-Neuve, Belgium.

Vaugelade, J. 1997. "Les unités collectives dans les enquêtes statistiques africaines : pour la traduction et pour l'utilisation du concept de ménage agricole". *Cahiers de l'ORSTOM / Sciences Humaines*. 27: 3-4: 389-394.

Veldkamp, T. Lambin, E. F. 2001. "Editorial: Predicting land use change". *Agriculture, Ecosystems & Environment*. 85: 1-6.

References

Verhagen, H. Smit, R. 2003. "Multi-agent system as simulation tools for social theory testing". *Erasmus Working Paper*. Erasmus University Rotterdam. Nederland.

Warren, A. 2005. "The policy implications of Sahelian change". *Journal of Arid Environments*. 63: 3: 660-670.

Watkins, K. von Braun, J. 2004. *Time to stop dumping on the world's poor*. OXFAM–IFPRI. U.K.

Waziri Mato, M. 2000. *Les cultures de contre-saison dans le sud de la région de Zinder (Niger)*, Ph.D. Geography. Université de Lausanne, Switzerland.

Wesel, A. Rajot, J. -L. Herbrig, C. 2000. "Influence of shrubs on soil characteristics and their function in Sahelian agro-ecosystems in semi-arid Niger". *Journal of Arid Environments*. 44: 4: 383-398.

White, D. R. 1999. "Controlled Simulation of Marriage Systems". *Journal of Artificial Societies & Social Simulation*. 2: 3.

Wiggins, S. 1995. "Change in African farming systems between the mid-1970s and the mid-1980s". *Journal of International Development*. 7: 6: 807-828.

Yamba, B. 2004. "Les mutations des systèmes agraires et des modes d'usage des ressources naturelles dans la zone centrale du Niger". *Revue de géographie alpine*. 92: 1: 97-110.

Yamba, B. 2005. *Observatoire de Maradi-Mayahi-Dakoro, Rapport de caractérisation*, Min. de l'Hydraulique, de l'Environnement et de la Lutte contre la Désertification, Rép. Du Niger, Niamey, Niger.

Yamoah, C. F. Bationo, A. Shapiro, B. Koala, S. 2002. "Trend and stability analyses of millet yields treated with fertilizer and crop residues in the Sahel". *Field Crops Research*. 75: 53-62.

Yépez del Castillo, I. Charlier, S. Ryckmans, H. 2001. "Relations de genre, stratégies des femmes rurales du Sud et développement durable". In *Savoirs et jeux d'acteurs pour des développements durables*. Debuyst, F. Defourny, P. Gérard, Hubert (Eds.), UCL CIDEP, Louvain-la-Neuve, Belgium. 483-500.

TITRES RECENTS DE LA COLLECTION (2005, 2006, 2007)

2005

Département de biologie appliquée et des productions agricoles

N°53. Nkunzimana, Tharcisse: Une filière agro-industrielle en mutation. Cas de la filière théicole au Burundi.

N°55. Meunier, Alexandre: Detection of rhizomania in Belgium: Diversity & characterization of Beet necrotic yellow vein virus RNAs-2 & –3.

N°56. Grissa, Kaouthar: Étude de la dynamique des populations et du contrôle des acariens ravageurs dans les vergers de pommiers tunisiens.

N°62. Rubayiza, Aloys: Authentification & quality control of coffee by fluorescence & Raman spectroscopy.

N°68. Odjo, Sunday Pierre: Modélisation en équilibre général non séparable et analyse de réformes agricoles et commerciales au Bénin.

N°69. Célestin, Dario Styve: Stabilisation du secteur caféier en Haïti par la promotion de la concurrence et la mise en œuvre d'un plan d'assurance pour la gestion des risques agricoles.

Département de chimie appliquée et des bio-industries

N° 57. Vermeulen, Catherine: Synthèse et caractérisation organoleptique de thiols polyfonctionnels ~ Recherche de leur présence dans la bière.

N°58. Van Wilder, Valérie: Phosphorylation des aquaporines de la membrane plasmique de maïs.

N°64. Bertinchamps, Fabrice: Total oxidation of chlorinated VOCs on supported oxide catalysts.

N°65. Demoulin, Olivier: Dynamic aspects of the surface of a palladium on alumina catalyst used in combustion of methane.

N°67. Trincal, Mathieu: Grx5p, a mitochondrial glutaredoxin required for mitochondrial DNA maintenance.

N°70. Dury, Frédéric: Coupling of the deoxygenation of benzoic acid with the oxidation of propylene as a new tool to elucidate the architecture of Mo-based oxide catalysts.

Département des sciences du milieu et de l'aménagement du territoire

N°54. Romanowicz, Agnieszka Aleksandra: The impacts of environmental change on water resources: A case study in the Dyle catchment (Belgium) in support of the implementation of the Water Framework Directive.

N°59. Delfosse, Thomas: Acid Neutralisation & Sulphur Retention in S-Impacted Andosols

N°60. Titeux, Hugues: Transfert de carbone organique dissous et de métaux dans des sols forestiers acides: influence du fonctionnement de la litière et des réserves minérales du sol.

N°61. Blaes, Xavier: Crop monitoring by advanced SAR remote sensing techniques: modelling & experimental analysis.
N°63. Farcy, Christine: L'aménagement forestier à la croisée des chemins. Éléments de réponse au défi posé par les nouvelles attentes d'une société en mutation.
N°66. Jonard, Mathieu: Dynamique des litières foliaires en peuplements purs et mélangés de chêne et de hêtre : Retombées foliaires et premières étapes de la décomposition.
2006
Département de biologie appliquée et des productions agricoles
N°71. Muratori, Frédéric: Reconnaissance des facteurs cuticulaires de l'hôte et conséquences sur l'exploitation des colonies par le parasitoïde de pucerons, *Aphidius rhopalosiphi* (Hymenoptera: Aphidiinae).
N°72. Condori Ali, Paulino Bruno: Analyse comparative et modélisation de la croissance et du développement de tubercules andins dans les Andes en Bolivie.
N°75. Doucet, Diane: Development of a model & similarities with a benyvirus.
N°76. Nkwembe Unsital, Guy-Bernard: La problématique de la pauvreté des ménages agricoles ruraux et urbains dans la périphérie de la ville de Kinshasa. Essai d'analyse du phénomène et de ses implications sur la sécurité alimentaire.
N°78. Ndayiragjie, Alexis: Relations entre métabolisme des polyamines et la résistance au stress salin chez le riz (*Oryza sativa* L.).
N°80. Secheli Ringot, Diana: Risk analysis of ochratoxin A & developpement of a decontamination procedure based on the biosorption of ochratoxin A onto yeast industry derivatives.
N°82. Abboudi, Tarik: The indispensable amino acid requirements for maintenance in Atlantic salmon fry.
N°83. Martins da Silva, Evaldo: Polyphenols from the Amazonian plant *Inga edulis*: process optimization for the production of purified extracts with high antioxidant capacity.
N°84. Fadlaoui, Aziz: Modélisation bioéconomique de la conservation des ressources génétiques animales.
N°85. Kambale Valimunzigha, Charles: Étude du comportement physiologique et agronomique de la tomate (*Solanum lycopersicum* L.) en réponse à un stress hydrique précoce.
N°86. Lepoint, Pascale: Speciation within the African Coffee Wilt Pathogen.
N°88. Mushagalusa Nachigera, Gustave: Competitive relationships in potato/maize intercropping: involvement of root system architecture
N°89. Nyamangyoku Ishibwela, Obedi: Ferrous iron toxicity: Mechanisms of resistance & impact on nutrient elements at the vegetative stage in

cultivated rices (*Oryza sativa* L., *Oryza glaberrima* Steud & interspecific hybrids)

Département de chimie appliquée et des bio-industries

N°73. Pety de Thozée, Cédric: Implication of the ER quality control in the degradation of the yeast plasma membrane Pdr5 ^{L183P} ABC transporter.

N°79. Gurdak, Elzbieta: Supramolecular organization of collagen layers adsorbed on polymers.

N°87. Janssens, Xavier: Monitoring & predicting elusive species colonisation: Application to the otter in the Cévennes National Park (France).

Département des sciences du milieu et de l'aménagement du territoire

N°74. Kayitakire, François: Forest stand characterisation using very high resolutions satellite remote sensing

N°77. Van der Velde, Marijn: Agricultural & climatic impacts on the groundwater resources of a small island: measuring & modelling water & solute transport in soil & groundwater on Tongatapu.

N°81. Degen, Thomas: Dynamique initiale de la végétation herbacée et de la régénération ligneuse dans le cas de trouées, au sein d'une hêtraie (*Luzulo-Fagetum*).

2007

Département de biologie appliquée et des productions agricoles

N°97, De Dorlodot, Sophie: Root system architecture: a genetic analysis in rice.

N°99, Daoui, Khalid: Recherche de stratégies d'amélioration de l'efficience d'utilisation du phosphore chez la fève (*Vicia faba* L.) dans les conditions d'agriculture pluviale au Maroc.

N°101, Vanloqueren, Gaëtan: Penser et gérer l'innovation en agriculture à l'heure du génie génétique. Contribution d'une approche systémique d'innovations scientifiques dans deux filières agroalimentaires wallonnes pour l'évaluation, la gestion et les politiques d'innovation.

N°109, Pairon, Marie: Ecology & population genetics of an invasive forest tree species: *Prunus serotina* Ehrh.

N°111, Manyonga, Madika: Modelling the competition for light in maize (*Zea mays* L.)/bean (*Phaseolus vulgaris* L.) intercropping with three-dimensional approach.

Département de chimie appliquée et des bio-industries

N°90. Eyers, Laurent: Characterization of bacterial populations of 2,4,6-trinitrotoluene (TNT) contaminated soils & isolation of a *Pseudomonas aeruginosa* strain with TNT denitration activities.

N°91. Dupré de Boulois, Hervé: Role of arbuscular mycorrhizal fungi on the accumulation of radiocaesium by plants.

N°92. Crouzet, Jérôme: Expression pattern, ectopic expression & gene silencing of two *Nicotiana* Pleiotropic Drug Resistance transporters.

N°93, Drugmand, Jean-Christophe: Characterization of Insect Cell Lines Is Required for Appropriate Industrial Processes.
N°94, De La Providencia, Ivan Enrique: Contribution of Anastomosis & Hyphal Healing Mechanism to the Extraradical Mycelium Architecture of Arbuscular Mycorrhizal Fungi.
N°95, Sebari, Karima: Optimisation de la gestion conjointe des ressources en eau de surface et des ressources en eau souterraines dans une région semi-aride: la Vallée du Drâa.
N°100, Vandermeeren, Caroline: Quaternary Structure & Regulation of the *Nicotiana plumbaginifolia* Plasma Membrane Proton Pump ATPase.
N°102, Morales Belpaire Isabel: Fate of the active form of proteins in selected environmental matrices. Investigation with green fluorescent protein, β-glucosidase, & amyloid fibrils in wastewater sludges, biofilms & soils.
N°103, Trombik Tomasz: Characterization of two Pleiotropic Drug Resistance transporters from *Nicotiana plumbaginifolia*.
N°104, Callemien, Delphine: Use of new methodologies to study phenolic compounds through beer storage.
N°106, Van der Auwera, Géraldine: pAW63: A molecular wanderer in the *Bacillus cereus* gene pool.
N°107, Mateos Pedrero, Cecilia: Synthesis & characterization of Rh supported on Ti-modified oxides: catalytic activity in the partial oxidation of methane.
N°108, Voets, Liesbeth: Role of arbuscular mycorrhizal networks on plant interconnection & carbon transfer.
N°110, Jerkovic, Vesna: Découverte du resvératrol dans les houblons. Impact de la variété, de l’année de récolte et du conditionnement en vue de la préparation d’extraits polyphénoliques enrichis en stilbènes.
N°112, Dekeyser, Caroline: Elaboration & evaluation of nanostructured surfaces for the control of cell behavior.
N°113, Nonckreman, Cristèle: Design of materials with nanostructured surface to improve hemocompatibility.
Département des sciences du milieu et de l'aménagement du territoire
N°96, Lefèvre, Isabelle: Investigation of three Mediterranean plant species suspected to accumulate & tolerate high cadmium & zinc levels: morphological, physiological & biochemical characterization under controlled conditions.
N°98, Desclée, Baudouin: Automated object-based change detection for forest monitoring by satellite remote sensing: applications in temperate & tropical regions.
N°105, André, Frédéric: Influence of the heterogeneity of canopy structure on the spatio-temporal variability of atmospheric deposition within a mixed oak-beech stand.