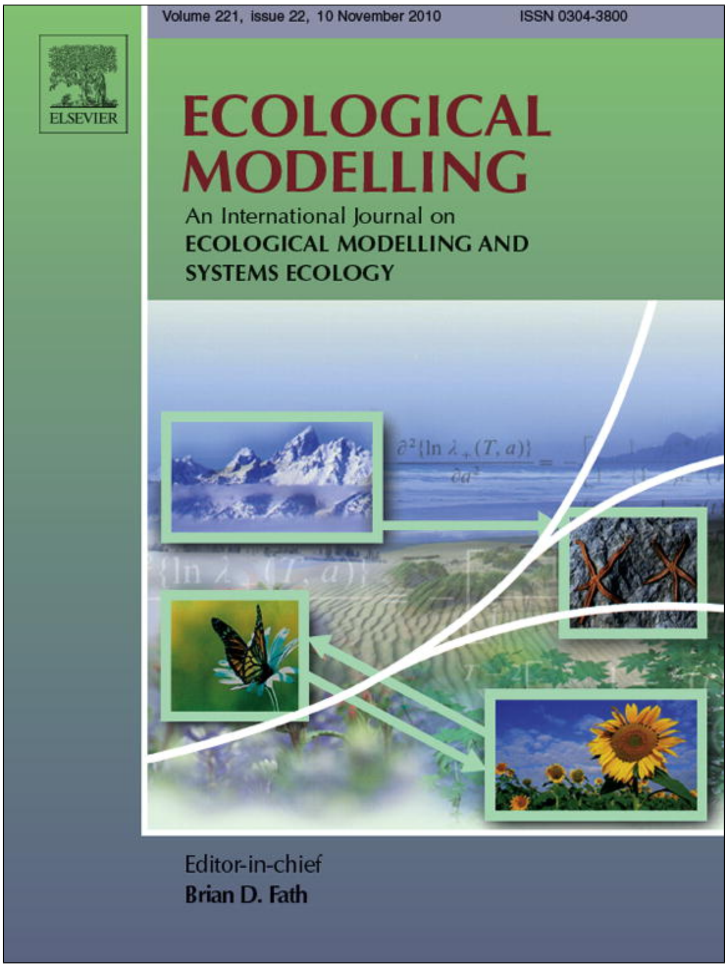
Volume 221, issue 22, 10 November 2010
ISSN 0304-3800
ELSEVIER
ECOLOGICAL MODELLING
An International Journal on
ECOLOGICAL MODELLING AND SYSTEMS ECOLOGY
Editor-in-chief
Brian D. Fath

Ecological Modelling 221 (2010) 2714–2727

Contents lists available at ScienceDirect

Ecological Modelling

journal homepage: www.elsevier.com/locate/ecolmodel

Testing the impact of social forces on the evolution of Sahelian farming systems: A combined agent-based modeling and anthropological approach

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ARTICLE INFO

Article history:
Received 6 October 2009
Received in revised form 7 May 2010
Accepted 4 August 2010
Available online 7 September 2010

Keywords:
Individual agent-based modeling
Social distribution of economic assets
Family transition processes
Inheritance
Family organization

ABSTRACT

This article presents the results of a methodology based on an extensive sociological fieldwork in three different sites settled along a gradient of aridity in Nigerien Sahel. This fieldwork led to build a set of rules for the behaviour of individuals in non-pastoralist villages. We implemented these rules into an agent-based model simulating three village archetypes. Each archetype includes biophysical, economical, social agricultural and livestock modules. Results from simulations with no social transition processes show that villages specialize themselves into different economic activities according to natural resource specificities: A decreasing intensification gradient is observed from the most favoured site, with more local productions and good ecological indicators, to the less-favoured site, with a growing proportion of the population wealth coming from migration remittances and "off-shore" livestock. Two family transition processes were implemented, following field observations and literature-based hypotheses: family organizations evolve between a patriarchal mode and a non-cooperative mode following tensions due to income redistribution. Family inheritance systems evolve from a "customary" one-heir mode to a "local Muslim" mode in which all males inherits land. This evolution depends on family tensions due to land availability. Once introducing these processes, the population of each site differentiates itself into specialized groups according to size, assets and social status. Meanwhile, the group proportions and specializations strongly vary according to the sites but they are all characterized by the emergence of individualistic family types and the increase of the village populations' robustness.

1. Introduction

1.1. The main drivers of Sahelian agro-ecosystems are social

Since the crises of the 1970s and 1980s, 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. As systems of activities in Sahelian Niger are based on small farms and families, the evolutions of this family level are considered by several scholars as one of the most crucial determinants of the evolution of such systems (Stone et al., 1990; Wiggins, 1995; Stone and Downum, 1999), along more environmental ones that are the basis of the "desertification" concept (Aubréville, 1949; Adams and Mortimore, 1997; Reynolds et al., 2003). These 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 and Blake, 1956).

The social patterns governing the dynamics of societies in Nigérien Sahel are already changing: inheritance, family organization, land tenure, social and symbolic references are evolving, because of economic pressures on individuals, families, and communities. Milleville and Serpantié (1994), Mathieu (1998), Lambin et al. (2001), Reenberg and Paarup-Larsen (1997) and Tappan and McGahuey (2007) among others have all highlighted the major importance of social factors when analysing farming system evolutions. Grégoire (1986), Luxereau and Roussel (1997), Olivier de Sardan (2003), all referring to the Sahelian part of Niger, have suggested two major, village-level social factors as the main pathways for local farming system evolutions.

1.2. Family organizations

All the investigated literature that concerns local family evolutions described the average sedentary family at the end of the 19th century as enlarged and under a quite strict hierarchy: the family head, usually the father, was ruling the whole family, including

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doi:10.1016/j.ecolmodel.2010.08.004

servants and slaves, as one single consistent exploitation, management and decision unit. Such families may be qualified 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). Actually, insecurity was forcing these enlarged families to stand together facing often threatening foreigners, usually under the rule of aristocrats or rising warlords. Meanwhile, the French political pacification at the beginning of the 20th century opened both the access to land and to external jobs in the Gulf of Guinea. Migrations and more individualistic behaviors trajectories multiplied (Timera, 2001) and undermined the hierarchy foundations, rendering 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 hypothesize that this led to an explosion of the family organization as theorized by Boserup (1965, pp. 316–346): The formerly dominant unitary patriarchal family archetype was replaced by a mononuclear, multi-activity and multi-decision-led family type (each adult member plays its part individually without referring to the official family head), better adapted to economic, agro-ecological and social shocks as described in Saqalli (2008a) and simulated in Saqalli (2006). Actually, our census in three sites of the Nigérien Sahel reports the presence of both types but in different proportions depending on the site: 76% of our sample in Fakara (Tillabery region, southwestern Niger) belongs to the non-cooperative mononuclear type, 59% for Gabi (Maradi region, south central Niger), 69% for Zermou (Zinder region, southeastern Niger). It means that such a shift was not absolute but variable depending on site characteristics, but also that this shift has occurred in all Nigérien Sahel. Such a dismantlement of the family structure is actually described by an extensive literature regarding various sites in Nigérien Sahel or the neighboring countries: The disintegration of the enlarged family was noticed as far back as 1914 for the Zarmaganda (Olivier de Sardan, 2003, p. 246)! We thereby consider that the individual is a more relevant unit for analyzing family evolutions than the family or the household level, because the lasts imply many simplifications of the diversification and the decision-making processes within the family (Saqalli, 2008a).

1.3. Inheritance modes

In the 19th century and because of the need for powerful and enlarged families at that time, practices were tending to maintain the power of lineage. The legitimacy was then based on the "custom" (Islam values were less strong in Niger at the beginning of the 20th century and animist values, references and ceremonies remain until now, even declined and hidden as for instance the *bori* or possession by djinns (Rouch, 1989). Therefore, the so-called "customary" inheritance mode was based on the entire transfer of the usufruct right on all the land and assets from 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 the beginning of the 20th century (Raynaut et al., 1997). It remains dominant in large parts of Nigérien Sahel, mostly in northern and less densely populated zones and where land pressure is still low (Vanderlinden, 1998). As described by Luxereau and Roussel (1997), Mortimore et al. (2001), Tiffen (2003) and Yamba (2004), due to the decrease of available land, this inheritance mode has shifted in several densely populated and land-saturated areas of Niger to a local version of the Muslim inheritance system (Religion is the only counterforce to allow one modification of this very strategic rule of inheritance): land and livestock are here equally shared between direct 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 in the case of no living adult children. One should notice that the main difference between the written Muslim law and the local adapted Muslim-claimed practices 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 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 Muslim Africa (Cf. "harem and cousins" by Tillon, 1982). This adaptation can therefore be considered as a transition pathway for farming systems because of its catalytic reduction effect on average available land per family, without blatantly confronting the Muslim official principles that are even stronger in the present time than one century ago. We 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 that families are more rapidly forced to choose whether to involve more in agriculture 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 then consider these two processes as the 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 the long-term effects of these two processes on the concerned families and farming systems? Do these two processes affect the villages of the whole Nigérien Sahel with the same orientation and magnitude?

1.4. Building an adapted methodology

The complex structure of Nigérien farming systems cannot be considered as "traditional" but as the result of political and historical evolving stakes. Farming systems should be set on a timescale reference. The starting point of the timescale should not be determined on the present-time situation but on the initial conditions, i.e. the date of the village foundation.

Because such processes are conditioned by both socio-economic and agro-ecological factors acting on a combined and intricate manner, it is irrelevant to focus on one side only. One should then look for a tool that can put in balance all the activities of a village but also all the factors that condition such activities, whatever the scientific disciplines they are related to. This tool is a model based on individuals, included in their social and family networks.

Actually, these sites lack the necessary amount of reliable, checkable data and information, while these very constraining factors determine the populations' evolutions. Not enough data means no selection of the relevant variables to introduce in the model along a statistical analysis. Before a game-theory model that leads to a premature selection of the relevant variables (such models are exploring the space of a small set of variables, meaning these variables have to be selected previously along a clear methodology), a first KIDS-oriented (Keep It Descriptive, Stupid! Edmonds and Moss, 2005; Janssen and Ostrom, 2006), and multidisciplinary model should be assessed. Variables and rules are selected according to their repeated notification as crucial during natives' interviews and field observations and are integrated in the model, even in a simplified way. The model-building methodology is thereby crucial: the interviewing process provided the behaviour/social rules and criteria while the context, i.e. the economic, demographic and agro-ecological environment is described following published or unpublished literature. Saqalli et al. (2010) built a model focusing on the villagers' differential accesses to economic and production activities according to social rules and norms. The model is mainly driven by social criteria from which gender and rank within the family are the most important, as they were observed and registered during interviews. All the necessary formula and schemes concerning the model are provided in the cited article. An even more detailed description and justification of the model are given in Saqalli (2008b, chapter 3). Thanks to a sensitivity analysis on several selected parameters, the model appears fairly robust and sensitive enough. The confidence-building simulation outputs reasonably reproduce the dynamics of local situations and are consistent with three authors having investigated the sites (Saqalli et al., 2010).

Thanks to its empirical approach and its balanced conception between sociology and agro-ecology at the relevant scale, i.e. the individual tied to social relations, limitations and obligations and connected with his/her biophysical and economic environment, the model can be considered as an efficient "trend provider" but not an absolute "figure provider" for simulating rural societies of the Nigérien Sahel and testing scenarios on the same context. Such ABMs can be a useful interface to analyze social stakes in development projects.

Meanwhile, a model cannot simulate all the possible evolutions of a society, because it means too many combinations of hypotheses to explore. We consider that exploring all the variations of the parameters means considering potentially inconsistent situations. Differences between these virtual contexts and real situations are likely to overcome "real" differences. Each of the three sites we studied may be seen as specific combinations of values of several parameters (see Table 1) but these combinations are not randomized: field anthropology and farming system scholars (Yamba, 2004) enhance the consistency of the connections between parameters when one wants to model real situations. The SimSahel model is used to explore in a combined way two theories that are proposed by scholars but need to be tested within an already agro-ecologically and socio-economically settled and consistent environment, i.e. three sites in which field investigations have been assessed. We then focus on a comparison of rural Nigérien Sahelian village archetypes, each one representing observed sites with different levels of natural resource endowment and socio-economic opportunities and constraints, through the introduction of consistent scenarios and hypotheses we developed during field investigations and already underlined by literature. The purpose of the present article is to analyze the long-term impacts on village societies and farming systems of the two agro-ecologically originated but socially driven transition pathways we described above, i.e. family organization and inheritance mode transitions.

2. Methodology

2.1. A field and modeling process

The model construction was achieved by 'there and back' iterations between field working and modeling as exposed by Drogoul et al. (2000), applied by Rouchier and Requier-Desjardins (1998). The selected Agent-based Model (ABM) platform is CORMAS (Common Resources Management Agent-based System: Bousquet et al., 1998). The SimSahel model includes a biophysical environment simulated through a grid of cellular automata with objects as livestock and agents as humans, as shown in the following UML (Unified Modeling Language) diagram (Fig. 1). Each human of the village is described along attributes belonging either to the economic part either to the social part of the life of this individual. The modeling methodology, including the parametering functions and related sources for the agro-ecological and village socio-economic modules is fully described in the cited article, as well as the individual-centered model itself called SimSahel, with relationships and dependencies between villagers (gender and rank as main factors of hierarchy in the family; lineage and individual and family wealth as the main factors at the village level) as well as their differentiated accesses to economic activities (agriculture,

Table 1
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 Variability: [70–525 mm]			Mean: 450 mm Variability: [180–675 mm]			Mean: 550 mm Variability: [275–775 mm]		
Soil arability proportion (%)	Valley: good	Plain: average	Stony hills: unsuitable	Valley: good	Plain: average	Plateaus: unsuitable	Valley: good	Plain: average	Hills: poor
	0.1	69.9	30.0	3.9	79.6	16.5	18.1	60.0	21.9
Migration impact on other activities	Gardening incompatible with migration			No competition between gardening and migration because of gender differentiation			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		
Present time family type	Mononuclear			Mononuclear			Mononuclear		
Women activity	Sheep raising			Sheep raising and gardening			Sheep raising		
Men activity	Farming, migration and gardening			Farming and migration			Farming, migration and gardening		
Present time inheritance system[a]	Local traditional			Local traditional			Local Muslim		

[a] The customary so-called traditional mode is considered as favoring one of the male descents, usually the elder, by giving him quite all the concerned assets, leaving symbolic elements and some small livestock to the others. The local adaptation of the Muslim inheritance system shares the assets between all the male heirs, splitting half of the leg to the brothers of the dead and half to his sons.

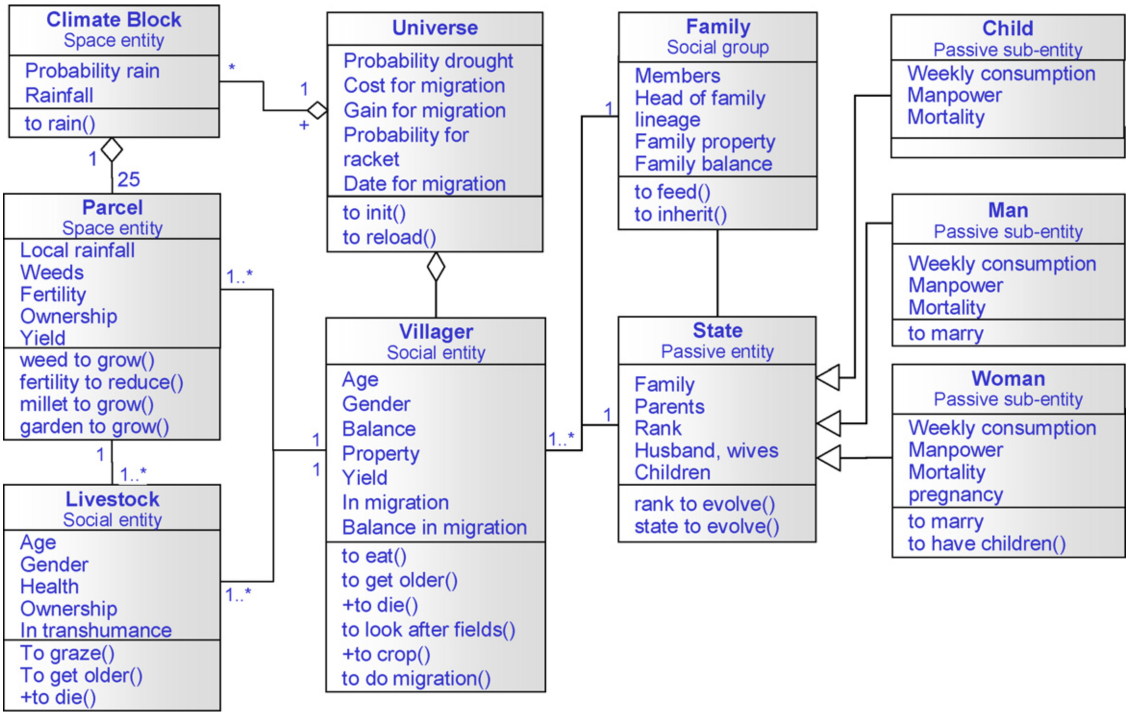

Fig. 1. UML representation of the SimSahel model.

livestock keeping, seasonal migration, dry-season gardening). The behavior rules are based upon the translation of the investigations that were done on the three survey sites, according to an interpretation process similar to that of Gladwin (1989) as cited by Huigen et al. (2006). The different modules of the model are sequenced along the following sequence diagram (Fig. 2).

The parameterization of the model was assessed by using the available published or unpublished literature for all the functions that do not correspond to individual logics of production means management: It concerns the whole biophysical module (climatology, pedology and phyto-ecology) and social factors such as demography, price evolutions of non-local products. The available grey literature (reports and documents from development or research agencies, M.Sc. and Ph.D. dissertations) comes from the research program that had collected extensive literature and data sets during the last 20 years in the three sites.

These sites are namely Zermou in the region of Zinder, Fakara in the region of Tillabery and Gabi in the region of Maradi. They represent three contrasted situations of the Sahelian Niger where rainfed agriculture is possible, along a gradient of aridity from the best-endowed site of Gabi, the medium site of Fakara to the worst endowed Zermou (Table 1). The SimSahel model was tested successfully through a comparison of simulation outputs with data from Loireau-Delabre (1998), La Rovere (2001) and Tahirou (2002), but also through a sensitivity analysis on several selected parameters (Saqalli et al., 2010). The model was already used to assess the impacts of family organizations (Saqalli, 2006) and development proposals on these village populations (Saqalli et al., 2008).

2.2. *Building a model on family evolutions based on rural transition social driven pressures*

The calibration of the model, i.e. the parameterization of these already settled rules, is carried out in the following purpose: the simulated individual behaviours should match with those observed on the ground: "simulated people do what we have seen their avatars do in the reality in specific circumstances", meaning villagers behave according to a sequential process.

This first transition we implemented is related to the family organization: We built a family characteristic called the "AntiClan tension" attribute or Tac, initially equal to zero at the family creation step. Tac has no measurement unit as it is a relative value. It then evolves according to two effects. All the adult family members who are not family heads or first heirs have to give back part of the monetary gains from the activity he/she manages (off farm, gardening activity) to the family head. This "forced" gift increases the member's Tac. Tac also rises at every new land extension, underlining the impact of this extension in the explosion of families as we noticed during investigations on many village histories: Nearly all the villages have witnessed a conflict during the 1920–1940s era between brothers or cousins within the village "reigning" family; at this time, the new colonial power have settled "peace" opening by then the whole territory to settlers and reducing the need for villagers to stand together facing raiders: A possibility to settle alone on newly accessible empty lands can be considered as an irresistible attraction for many not well endowed villagers; this attraction was regularly observed during interviews. We included this attraction at the family level because a family 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. In the two cases, the evolution is simulated as follows: for each event at time step t having an impact on family organization (money given by an adult child apart from the heir to the head of the family) as described above:

$$Tac(t+1) = Tac(t) + 5 \quad (1)$$

The family can shift from the unitary mode towards the non-cooperative one if:

$$Tac(t) > 100 * MoF(t) \quad (2)$$

only at the death of the head of the household. If this case occurs, following marriages of sons create new families (see Table 2) inheriting the family structure of the elders.

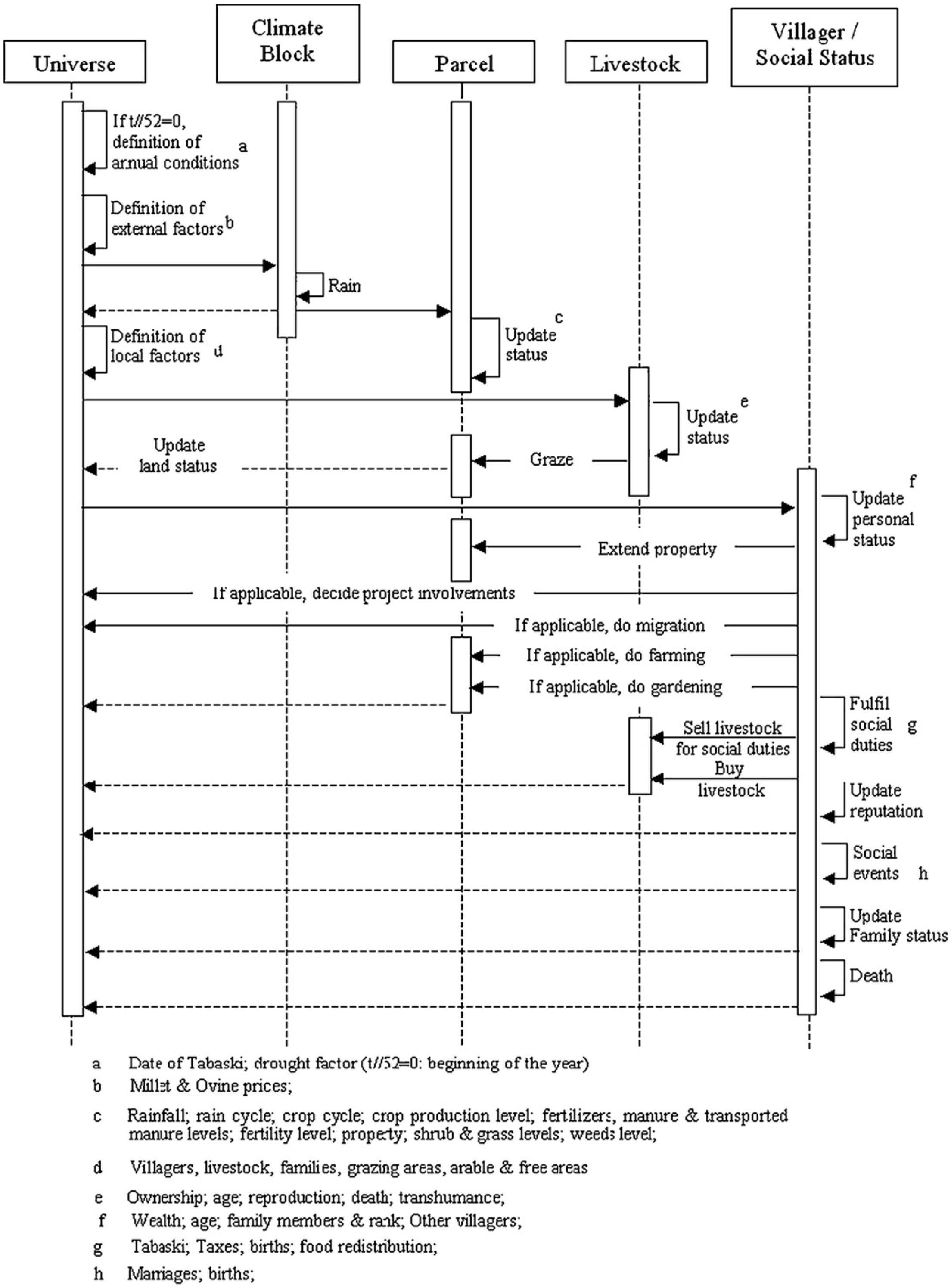

Fig. 2. The sequence diagram of one time step of the SimSahel model.

With *MoF*(t): the family manpower at t (in adult equivalents: female and male manpower are considered as equal). 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 2.

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*. As for *Tac*, *Tf* has no measurement unit as it is a relative value., Initially equal to zero at the family creation, it evolves at every failure in the search of new empty lands, as follows: for each event at time step t having an impact as described

Table 2
The simulated characteristics of the two simulated family organization 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 "fiancé' pay the dowry
Sharing food	All income is given to the head of the family, who shares them among members[a]. Therefore, the family balance is equal to zero when he dies	The "family granary" is open to all adult members who need to fulfill family askers depending on him/her[b]. 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 him 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

[a] Therefore, all gardening incomes remain in 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.

[b] 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 he family or any person with a higher rank within the family for support, only for that particular time step.

above:

$$Tf(t+1) = Tf(t) + 5. \quad (3)$$

This value can grow rapidly according to the number of attempts: the more the family is big and grows rapidly, the more this Tf value increase quickly. The family can adopt a "Muslim" inheritance mode if:

$$Tf(t) > 200 * MoF(t) \quad (4)$$

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 Muslim" rules, i.e. all fields are equally shared between the male heirs of the head of the family (brothers and sons). We observed that livestock inheritance follows the "written" Muslim rules, meaning it is shared between male heirs for two thirds and female heirs for one third. If the head of the family dies, sons' following marriages create new families (see Table 2) that inherit the family inheritance mode of the elders.

The definition of these two processes was established by making connections between variables (for instance land tenure Tension with land prospecting and family manpower) from results from field anthropological interviews. The parameterization, i.e. the establishment of the figures (5, 100, 200) was determined in order to see families behaving as we have observed. We remind the readers that the purpose of this simulation is to analyze the effects of these micro-level calibrated hypotheses, as the virtual transcription of micro-level observations, meaning their long-term consequences at the macro level. Testing small variations around these obtained values showed that micro level results does not vary significantly as far as they do not go over a limit of twice the values we introduce.

Comparing the simulation outputs of these social changes with the present-day situation to determine the best theoretical "solution" is not relevant because of the following point: We have selected these two evolution processes because field investigations and relevant literature considered them as the main social drivenforces. Meanwhile, in anthropology, "real" social evolutions are considered as a connected system. We should consider these two evolutions as a block meaning that considering them separately is as irrelevant as exploring an astrophysical model with electromagnetism but no gravity. Descriptive models as we built are used to investigate the effects of observed evolution factors we question and not to explore all the parameters of the universe. The analysis is therefore based on a comparison of scenarios with or without evolution factors. 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").
- The second one where both family organization and inheritance systems can change according to the rules described above (the scenario is thereafter named "Evolution").

Simulations begin with the foundation of the village by families with customary organizations and traditional inheritance modes. The model is initiated as follows: at $t=1$ fifty villager Agents of various ages and gender-defined and one hundred livestock entities, with one third of every species, appear in the village territory. Twenty model runs have been assessed for each scenario. It is important to note that the two simulated social transition processes are reversible and that certain family types may reappear. 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. We first present the evolution of the three sites over one-century according to "No-Evolution" to compare thereafter with the results of "Evolution". The choice of one century is based on the fact that nine villages out of ten in present-day Nigérien Sahel are less than 100 years old (Raynaut et al., 1997; Vanderlinden, 1998). 100 years of simulation is a good balance between simulation time and detection of trends over three generations.

3. Results

3.1. No-evolution scenarios: a progressive degradation depending on local agro-ecological and economical conditions

The results are the simulation outputs of a scenario with only unitary and patriarchal families and a system of customary inheritance.

The site characteristics have a noticeable effect on the simulated population growth: The three populations strongly raise, by a factor 11 in the site of Zermou, the least agro-ecologically and socio-economically favoured site, while Gabi, the most favoured site, reaches a factor 32 (Table 3, line D). The territory of each simulated site is progressively occupied, in less than 25 years for Zermou as opposed to nearly 100 years for the Fakara and Gabi sites (Table 3, line A), because the lower soil fertility in Zermou (see Table 2) implies rapid yield decline forcing the population to more quickly expand their fields, while Fakara and Gabi do not experience such race for land. At the three sites, there is no collapse of agricultural production, despite the progressive occupation of all arable lands and the related decline of soil fertility and vegetation levels. Yields see a continued decline up to a minimum and stable level. Actually, two fertility-regenerating procedures are simulated in the model,

Table 3
100 years evolution of selected indicators for the three sites in a no-evolution scenario (fixed unitary family and customary inheritance system) (mean + standard deviation; $n = 20$).

		Zermou					
		1	2–25	26–50	51–75	76–99	
Environmental 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 (% of the initial cover)[a]	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 (€)	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 (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 (L.S.U.**)	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
	Gini coefficient between families	0.48 ± 0.14	0.55 ± 0.11	0.60 ± 0.08	0.65 ± 0.08	0.68 ± 0.09	I
Tensions	Anti-clan tension	/	550/X	1150/X	2050/X	2650/X	
	Land tenure tension	/					
		Fakara					
		1	2–25	26–50	51–75	76–99	
Environmental 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 (% of the initial cover)[a]	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 (€)	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 (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 (L.S.U.[b])	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
	Gini coefficient between families	0.50 ± 0.11	0.53 ± 0.06	0.61 ± 0.02	0.68 ± 0.02	0.74 ± 0.02	I
Tensions	Anti-clan tension	/	1800/X	7100/X	10,900/X	12,000/X	
	Land tenure tension	/					
		Gabi					
		1	2–25	26–50	51–75	76–99	
Environmental 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 (% of the initial cover)[a]	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 (€)	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 (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 (L.S.U.[b])	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
	Gini coefficient between families	0.53 ± 0.14	0.61 ± 0.09	0.59 ± 0.03	0.63 ± 0.01	0.66 ± 0.02	I
Tensions	Anti-clan tension	/	1450/X	5200/X	14,200/X	26,000/X	
	Land tenure tension	/					

[a] Combined weed and shrub vegetation.
[b] Tropical Large Stock Unit equivalent.

i.e. a 1-year fallow regeneration process (this process is implemented only for fields that were sowed but whose sowings failed and were abandoned for a one-year fallow) and manure supply from herds. These two processes play a genuine effect on the fertility decline. Other non-agricultural and thereby rain-independent factors (migration, gardening but also partly livestock) help to support the populations' growths.

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). We recommend the consultation of Adams and Mortimore (1997), Howorth and O'Keefe (1999), Niemeijer and Mazzucato (2002), Koning and Smaling (2005) or Mortimore and Turner (2005) for a discussion on this gap, i.e. the difficulty to apprehend the importance of agriculture for food security. This activity, as the most sensitive to agro-climatic conditions, declines more or less rapidly at the three sites after an 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 harshest site of 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 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: see Table 1 line 4) but also because of social ones: As indicated in Table 2, gardening in the Hausa sites of Zermou and Gabi is restricted to men, but the implemented impact of the distance to the Nigerian border for Zermou does not allow men to practice simultaneously gardening and migration, while it is possible for men in Gabi (gardening means the capacity to mobilize child manpower to water vegetables even while absent of the village, for instance for migration purposes). Gardening does not take off until after land saturation, implying a manpower reallocation at the family level.

Simulated herds are progressively more and more cattle-dominated. Cattle herds are actually in majority in transhumance during nine months of the year and therefore with little effects on local fertility transfers but also independent from the local pasture constraints. This cattle accumulation can 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, 1999; Turner et al., 2005). Livestock keeping maintains itself all along simulations, whereas migration grows slowly at the three sites, reaching up to 45% of the total local income in Fakara. The gradient Gabi-Fakara-Zermou remains applicable for the irregularity of millet yields. An equivalent gradient appears for migration, because of the implemented 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). Migration and livestock keeping, as extra-local activities, play a role of compensators facing the local resource limitations.

This absence of collapse and the gradual decline of natural resources in the simulations are 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 3 line F). Only Gabi average population income is maintained and grows a little in this scenario (Table 3 line E). The site of Zermou maintains its ratio of livestock per inhabitant; Fakara doubles it; the Gabi ratio grows by a factor of 2.8 (Table 3 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.

This village scenario induces a rise in social inequalities. The income difference between men and women grows at the three sites (Table 3 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 is an indicator that shows inequalities among one population. It is defined as follows: For n slices, the coefficient is obtained by the Brown formula (Dorfman, 1979) (we have chosen $n = 5$ as used in demographic studies):

$$G = 1 - \sum_{k=0}^{k=n-1} (X_{k+1} - X_k)(Y_{k+1} + Y_k); \qquad (5)$$

with X_k is the income of the k slice and Y_k is the size of the k slice.

The coefficient calculated between families along the simulation from the mean values of the repetitions (Table 3 line I) underlines the social differentiation between the families, in particular in Fakara, 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 of the population size between simulations (Table 3 line D), because it indicates the variability between simulations, increase along time and even more along the Gabi-Fakara-Zermou gradient. The more simulations are different, the more it means that perturbations within the system have important effects on this population indicator. It means the Zermou population is more sensitive and vulnerable 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 Fakara and 0.78 for Gabi over that last 10 years (]90:100]).

3.2. Introducing social evolutions: family shifts as accelerators of farming system evolutions

3.2.1. Family evolutions: the environment-originated differentiation of social stratifications

Families multiplied themselves at all sites through the "explosion" of once unitary families due to inheritance and family organization rules we implemented: the breakup of the unitary family dilutes and alleviates the related tensions. We find in Zermou 104.5 families on average vs. 9.7 in "No-Evolution" at t =]75:100], 117.4 families vs. 7.7 in Gabi and 204.5 families vs. 8.4 in Fakara! As 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 and Unitary families disappear in Fakara five years earlier than at the two other sites (Fig.3.3 to compare with Figs. 3.1 and 3.5). Moreover, the extent of this shift is far more important in Fakara, reducing the part of Unitary Families with a Customary Inheritance (UFCIS) to less than 5% of the number of families, but 19% of the total population. The Non-Cooperative Families with a Customary Inheritance (NCFCIS) become dominant reaching up to 59% of all families and 52% of the village population (Fig. 3.4).

The Fakara arable land saturation is slower than in "No-Evolution" can be seen from a comparison between lines A of Tables 3 and 4. Consequently, the shift towards local Muslim inheritance remains limited. A more rapid arable land saturation in the two other sites helps the Non-Cooperative and "local Muslim" Inheritance Families (NCFMIS) to become dominant in terms of family numbers and even village population for Gabi (Figs. 3.5 and 3.6).

A family type unobserved during field investigations appears in simulations at the three sites: the Unitary Family with "local Muslim" Inheritance (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% (Fig. 3.4) against 6% in Zermou (Fig. 3.1) and 3% in Fakara. This is a surprise of the model that is questioned in Section 4.

We obtain thus for each simulated site a different village organization (Figs. 3.1, 3.3 and 3.5): the sites of Fakara and Zermou as they are implemented are almost totally composed of Non-Cooperative mononuclear families, meaning a slightly bigger shift than in reality (see Section 1.1). They are shared in Zermou between Muslim inheritance families for the 2/3 and customary inheritance families for 1/3, while these proportions are inverted for Fakara. Finally, the Gabi population is shared between the two family types, unitary (1/3) and non-cooperative (2/3, as in reality) 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 and sustainability at the village level

The new family distribution has several impacts on the village wealth (Table 4): As described in Saqalli (2006), the appearance of

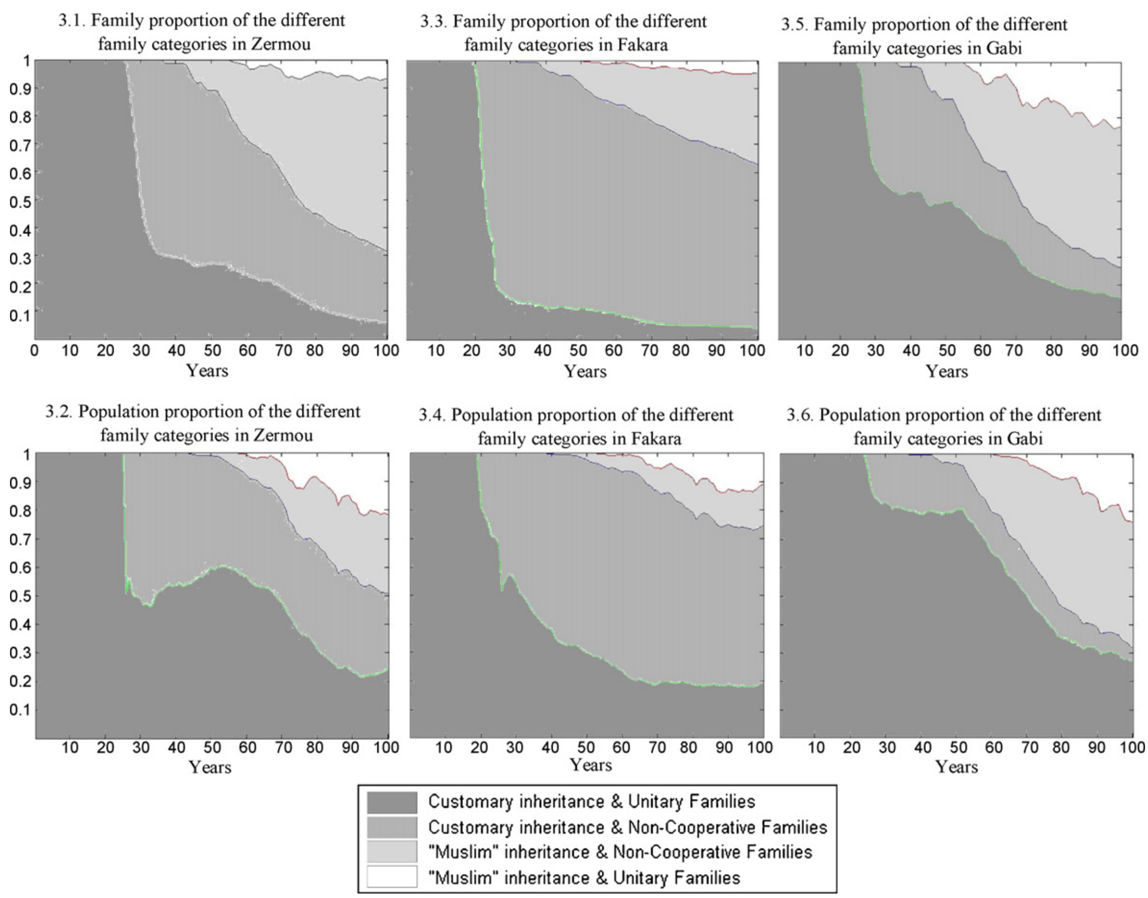

Fig. 3. Proportions of the four different family categories in the population and the number of families in each site.

mononuclear families in Fakara slows the growth of population and cropped surfaces in a similar way than harsher agro-ecological and economic conditions (Tables 3 and 4, lines A and 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 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 "No-Evolution" (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. The monetary limits in Gabi within these new families are not strong enough at family and individual levels to slow down marriages in significant way and thereby the population growth.

The average income in "Evolution" increases in the second half of the simulation at the three sites and more particularly in Gabi (Tables 3 and 4, line E) compared to "No-Evolution". The cropped surface per inhabitant doubles in Fakara in "Evolution" because of the lower population growth, which is logically not observed in Zermou or in Gabi (Tables 3 and 4, 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 "Evolution" compared with "No-Evolution", it grows in an equivalent manner for the two scenarios in Fakara (Tables 3 and 4, line G).

In terms of environmental sustainability, although the land is more slowly colonized in "Evolution", yields per hectare remain equivalent for both scenarios at the three sites (Tables 3 and 4, line B). The same is true for vegetation cover in the two poorest sites, i.e. Zermou and Fakara (Tables 3 and 4, line C). Gabi vegetation cover declines slightly strongly, related to a larger cultivated area and a higher livestock per inhabitant ratio.

In terms of social sustainability, inequalities between families and genders reduce in two sites: if the coefficients of variation of the gender inequality are significantly reduced in Zermou and Fakara, they stay equivalent in Gabi (Tables 3 and 4, line H). The inequality between families instead is higher in "Evolution" in Zermou and Gabi whereas it is significantly reduced in Fakara (Tables 3 and 4, line I).

Finally, the coefficients of variation between repetitions of several factors (population, income and surface appropriated per capita) are significantly lower for the three sites (Tables 3 and 4, lines D, E and F) in "Evolution", which means, along with higher absolute values for Fakara and Zermou, that the risk of a collapse 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 Fakara and the variability even increases in Zermou (Tables 3 and 4, line G).

3.2.3. Activities and livestock distribution

The social differentiation does not translate into a significant change in the relative importance of the different activities at Zermou. Agriculture keeps declining to the benefit of livestock keeping

Table 4
100 years evolution of selected indicators for the three sites in the Evolution scenario (family organizations and inheritance systems can change) (mean + standard deviation; $n = 20$).

		Zermou					
		1	2–25	26–50	51–75	76–99	
Environmental 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 (% of the initial cover)[a]	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 (€)	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 (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 (L.S.U.[b])	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
	Gini coefficient between families	0.51 ± 0.14	0.60 ± 0.10	0.64 ± 0.05	0.73 ± 0.02	0.71 ± 0.02	I
Tensions	Anti-clan tension	/	250/X	950 /X	1950/X	2600/X	
	Land tenure tension	/					
		Fakara					
		1	2–25	26–50	51–75	76–99	
Environmental 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 (% of the initial cover)[a]	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 (€)	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 (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 (L.S.U.[b])	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
	Gini coefficient between families	0.50 ± 0.14	0.54 ± 0.05	0.60 ± 0.03	0.68 ± 0.02	0.68 ± 0.02	I
Tensions	Anti-clan tension	/	350/X	1850/X	5800/	12,700/X	
	Land tenure tension	/					
		Gabi					
		1	2–25	26–50	51–75	76–99	
Environmental 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 (% of the initial cover)[a]	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 (€)	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 (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 (L.S.U.[b])	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
	Gini coefficient between families	0.54 ± 0.13	0.52 ± 0.05	0.62 ± 0.04	0.70 ± 0.02	0.70 ± 0.02	I
Tensions	Anti-clan tension	/	300/X	1400 /X	3800/X	5600/X	
	Land tenure tension	/					

[a] Combined weed and shrub vegetation.
[b] Tropical Large Stock Unit equivalent.

and migration, the latter reaching about 72% of the average income, while gardening stays next to nothing.

However, a strong evolution at Zermou occurs towards small livestock. This goes together with a multiplication by 3.9 of the volume of this herd (939 ± 89 Tropical Livestock Units (TLU) vs. 240 ± 39 in "No-Evolution" over the last 25 years). The number of goats has been multiplied by 28 (254 vs. 9 in "No-Evolution"), the caprine herd thereby representing 33% of the total livestock vs. 5% for "No-Evolution", without a particularly strong decline of the vegetation cover (Table 3 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 "Evolution", 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 "No-Evolution". 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 transhumance.

The Fakara migration contribution in the income rises (66% of the average income over the last 25 years against 39% for "No-Evolution"), reducing the parts of gardening, agriculture and livestock keeping. The Fakara herd size stays stable (837 ± 98 TLU vs. 952 ± 87 for "No-Evolution"), but the composition evolves strongly as well with a multiplication by 7.2 of the goats, and by 3.7 of the sheep. Finally, the Gabi activities also change but through a focus on local activities: Agriculture and gardening are maintained,

Table 5
Selected indicator mean values for the last quarter *t*]= 75–100] for the three sites for the "Evolution" scenario (mean + standard deviation; *n* = 20).

	Zermou				
	UFCIS	NCFCIS	NCFMIS	UFMIS	
Income per capita (€)	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 (L.S.U.[b])	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 (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
Gini coefficients between families	0.75 ± 0.01	0.63 ± 0.03	0.61 ± 0.02	0.88 ± 0.01	H
Livestock keeping proportion in the income (%)	13.0 ± 3	5.0 ± 0.9	11.0 ± 2	6.0 ± 1.2	I
Migration proportion in the income (%)	52.0 ± 5	79.0 ± 8	67.0 ± 7	89.0 ± 9	J
Gardening proportion in the income (%)	2.0 ± 0.1	1.0 ± 0.1	4.0 ± 0.1	1.0 ± 0.1	K
Pearl millet agriculture proportion in the income (%)	33.0 ± 7	15.0 ± 2	17.0 ± 2	4.0 ± 1	L
	Fakara				
	UFCIS	NCFCIS	NCFMIS	UFMIS	
Income per capita (€)	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 (L.S.U.[b])	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 (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
Gini coefficients between families	0.73 ± 0.01	0.63 ± 0.02	0.62 ± 0.03	0.90 ± 0.04	H
Livestock keeping proportion in the income (%)	7.0 ± 1	10.0 ± 2	10.0 ± 1	9.0 ± 2	I
Migration proportion in the income (%)	36.0 ± 2	52.0 ± 4	58.0 ± 4	69.0 ± 6	J
Gardening proportion in the income (%)	12.0 ± 2	8.0 ± 0.4	11.0 ± 2	6.0 ± 0.6	K
Pearl millet agriculture proportion in the income (%)	45.0 ± 5	30.0 ± 3	21.0 ± 5	16.0 ± 2	L
	Gabi				
	UFCIS	NCFCIS	NCFMIS	UFMIS	
Income per capita (€)	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 (L.S.U.[b])	1.6 ± 0.4	1.5 ± 0.5	2.2 ± 0.9	2.4 ± 0.7	C
Livestock proportion (%)	21.3 ± 3.1	2.1 ± 0.3	53.1 ± 15.0	23.3 ± 4.8	D
Cropped surface per capita (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
Gini coefficients between families	0.73 ± 0.01	0.59 ± 0.02	0.60 ± 0.02	0.81 ± 0.04	H
Livestock keeping proportion in the income (%)	13.0 ± 1.1	22.0 ± 2	15.0 ± 1.4	28.0 ± 3	I
Migration proportion in the income (%)	3.0 ± 0.4	14.0 ± 1	5.0 ± 1	17.0 ± 2	J
Gardening proportion in the income (%)	34.0 ± 2	22.0 ± 1	49.0 ± 3	21.0 ± 1	K
Pearl millet agriculture proportion in the income (%)	50.0 ± 2	42.0 ± 2	31.0 ± 2	34.0 ± 2	L

[a] Combined weed and shrub vegetation.
[b] Tropical Large Stock Unit equivalent.

with a slight extension of the latter. Migration passes from 26% of the average income to less than 6%, whereas livestock keeping reaches 29% vs. 2% for "No-Evolution". 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: 611 sheep and 1910 goats vs. 11 sheep and 9 goats for "No-Evolution" on average over the last 25 years, increasing the proportion of small ruminants from 1% to 37% of the total.

3.2.4. *Production and sustainability at the family levels*

Analyzing the differences among family types provides information on their differentiated reactions throughout the 100 years of simulation. Table 2 presents the average values over the last 25 years of several indicators for each family type.

It is not the same social types that benefit from a better income per capita in the three sites (Table 5 line A): If the gaps between the types stays small in Zermou, with a slight advantage for NCFCIS in a globally poor context, the UFCIS of the two other sites remains the poorest, which can be explained by a higher ratio between children and adults. On the other hand, the NCFMIS income per capita reaches double that of other groups for these two sites. A high level of income does not imply an important availability in fields or in livestock (Table 5 lines C and E), but rather more efficient orientation of the available manpower.

4. Discussion

Concerning the results presented in this article, we first discuss the outputs from the simulations without the two evolution processes we implemented: the unitary organization that is implemented by default allows the distribution of activities to evolve along with the decline of the local resources, due to 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 even in this last site. This point is important: we simulate the history of a stereotypical village of these three study sites. The model has no cognitive rules and villager agents acts along a sequential process (they do things when they have to as observed during field inquiries). This method avoids hazardous rationality postulates but 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 their income.

This sole "adaptation" process allows the virtual population and their environment to stand as it happens in the reality, thereby enhancing the resilience capacity of a diversification approach in such an environment, in both virtual and real worlds, to compare with a pro-productivity development program as some development operators promote. The three sites "specialize" themselves in one activity apart from millet agriculture: migration in Fakara, gardening for Gabi and livestock keeping in Zermou. This specialization is not total due to many individual constraints and compulsory actions, still because of the sequential Programmation of the agents.

Once we introduced the two evolution processes, these two processes both reduce their corresponding tensions by sharing gains with more "equity" but also by creating new families (all implemented with the two tensions' values equal to zero). The repartition of these newly created family types varies according to the site. Because of the garden-female specificity of the Fakara site, the family organization process has a higher impact on the tension process. As many "advocacy" models do (Kieken, 2003), these results enhances the importance of intricate relations between social factors that in some conditions may have huge effects on one society' evolution. The evolution processes we implemented can be seen as tension-lowering adds-on. Such a model cannot prove that these observed processes do have such an effect but it helps to warn development workers and scholars about the danger of such tensions, for instance by enhancing the income-lowering and tension-rising effects of non-evolving social spots.

Considering both income and livestock altogether, the three simulated sites experience a better level of wealth per capita. The implemented populations of the three sites are more robust facing hazards of production activities. The most-favored site of Gabi gets this improvement through livestock keeping and savings and gardening, the less-favored site of Zermou through livestock keeping while the intermediate site, Fakara, get this improvement thanks to a lower increase of its population, because of a quicker orientation towards non-cooperative family modes, while migration becomes preponderant in terms of activity distribution for this site. This leads to point the gap with the "sites specialization" in "non-Evolution" but also the unpredictable aspect of such a simulation, even with no cognitive behaviours.

The expansion of livestock in "Evolution" is understandable because of several points in reality: 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 browsing areas (i.e. shrubby plateaus and hills) 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. These points, with the major effect of the expansion of transhumant cattle sent "abroad", explain why livestock keeping expand at the three sites. One may consider that livestock changes its status from of an "off-shore" saving account to that of a locally used "remunerating" account, particularly for the most favored site of Gabi.

Zermou and Fakara present social organization profiles that can be explained by the historical succession of the family types in the simulation (Figs. 3.1 and 3.5): even if the simulated family change rules allow the reappearance of families of ancient type, the original eldest group, the UFCIS, is the most involved in agriculture, whereas the most recent, the UFMIS, is the most involved in migration (Table 5 lines J and L). The Gabi population is different: thanks to a highest availability in fields and garden-suitable fields, a large part of the income of the UFMIS type comes from local productions (gardening and agriculture) and this group has a highest proportion compared to the two other sites. 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 from livestock is hard to interpret because it is not entirely linked to herd size but more likely to its turnover rate that is quicker for small ruminants. The part of these small ruminants is growing along a UFCIS-UFMIS-NCFCIS-NCFMIS gradient, which is compatible with the growing monetary constraints of these types of family (Figs. 3.1, 3.3 and 3.5).

The large development of the UFMIS family type in Gabi is due to the fact that most of the economic activities (gardening, migration, agriculture, cattle livestock: Table 2) remain in the hands of men, which allows the unitary organization to remain. It means that social rules may be strong enough in some places to counterbalance biophysical assets. Paradoxically, this group appears after the NCFMIS at the three sites rather than before these. They originate from formerly UFCIS families but also from formerly NCFMIS having evolved into UFMIS, in the case of young families having many young children and being unable to develop yet some activities other than the family head's ones. The UFMIS appearance in the best-endowed site in the simulation is corroborated in reality: urban and peri-urban areas of the Maradi region where Gabi is located have seen the development of a new middle-class of traders, called the "izalah", rather young families and very rigorous from a religious point of view, besides the old and big traders having established their fortune on clientele networks (Grégoire, 1986). 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. We thereby suppose that the main reason why we did not observe such families in the investigated villages is that they have shift in town, even if they still have and crop (and/or make crop) their fields in the village, or this group has not yet appeared in rural areas while they already exist in trading towns such as Maradi or Birni'n'Konni.

The SimSahel model is oriented towards the KIDS approach (Edmonds and Moss, 2005). We remind the reader that the model sensitivity analysis on the major parameters has already been done and results are presented in Saqalli et al. (2010), as well as a comparison of simulation outputs with results from other scholars. Its genuine complexity concerned the many relationships between simulated villagers and natural resources and not the behaviours of the villagers: As a matter of fact, the modeling does not introduce any cognitive process in the individual or family manpower allocation between 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.

Thus, the interpretation of the relationships between family types and economic productions 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 populations differentiate themselves into family groups following 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.

5. Conclusion

Introducing social change processes in a social model application generated 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" (lower increase of the population for Fakara, creation of a class of "permanent" migrants for Zermou or a class of "gardeners" for Gabi). These strategies are different for every site, depends on initial conditions and parameterization 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, these individuals are more autonomous in their choice of economic activities other than agriculture. As the gain from extra-agricultural activities is more important than from cropping, these 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.

5.1. Thematic issues

Thus, the introduction of social evolution factors (i.e. inheritance mode and 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 of development 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 of its population according to social origins between farming families and migrant families. The most favored site population is the only one to intensify its practices (better integration of livestock keeping and more gardening). The orientations of these evolutions were not predictable *a priori*, suggesting thereby a very cautious approach once analyzing "real" evolution patterns.

Questioning the impact of social drivers at the relevant unit is necessary because humans are the main factor of agro-ecosystem transformations. Following a radical metaphor, you cannot estimate future impacts of cyclones only through analyzing their present effects on landscape. You need to look after the main factors that determine their internal evolution before considering their impacts on the œkoumene and the landscape even if these lasts may have an impact on cyclones afterwards. In our case, the drivers of the main ecological transformation factor, humans, have to be analyzed at the relevant level, i.e. the decision unit. In the Sahelian case, the relevant decision unit is the individual included in his/her family network and these drivers are mainly social.

Moreover, beyond the quantitative differentiations, the integration of these factors informs on the discriminations between categories of gender and of family groups. Such informations that cannot be approached with other simulation tools 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 perceived main factors of social differentiation. In the future, additional factors that were observed in the field and may be important factors of emergence could be included. For instance, the transhumant Fulani herders, who had formerly an important role of fertility transfer and who represent between 10% and 25% of the locals, are not simulated, as well as the high proportion of divorces (two marriages on five according to our observations) that reinforce the autonomy of women through their herds and their gardening productions. Additional social changes could be considered as other driving forces of evolution of farming systems: the progressive settlements of transhumant and nomadic herders, 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 is also an important trail from a more operational decision-support point of view and has been assessed in a parallel work.

5.2. Modeling issues

The model correctly reproduces the behavior of individuals and families as observed in reality thanks to calibration. At the village level, the model outputs are consistent with the range of data coming from other scholars. The model sensitivity analysis provided information on its variability and its robustness regarding relevant parameters (Saqalli et al., 2010). A validation is always complex and difficult but the reconstitution of collective and differentiated behaviors based on simple, sequential and empirical behavior rules underlines the interest of such Agent-based modeling methodologies for analyzing the interactions between social and farming systems.

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.

Therefore, the common remark concerning agent-based modeling should be discussed: the common procedure regarding agent-based models is to settle a system with few parameters to explore all the space they determine and by then, quantify as much as possible the value of the model. Meanwhile, the selection of the parameters to keep is questionable: they are related to the question the scholar wants to explore, to the discipline he/she belongs, etc. They can therefore be affected by strong biases. If one wants to analyze the evolution of a rural population, a full methodology concerning the selection of the relevant parameters is yet to be settled. Meanwhile, we propose that a field-connected vast model such as Saqalli et al. (2010), when used to (i) first reconstitute the everyday situation of a Sahelian village such as the ones which were investigated, (ii) explore different social processes such as we have done, is a relevant tool for exploring the social environment of a local situation. We consider that it is only afterwards that more specific KISS models (Keep It Simple, Stupid) may be built to focus on specific questions. These questions may have been not opened unless this first exploration through the use we assessed of a holistic model such as the one of Saqalli et al. (2010). Building such a model, exploring it through thematic questions opened new insights and justifications for more investigations on the field on specific issues, and thereby more information on only then well-selected and well-designed parameters to include in a question-specific simplified KIDS model (Edmonds and Moss, 2005).

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