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Modelling and simulating change in reforesting mountain landscapes using a social-ecological framework

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Keywords European mountains · Land use and cover change · Landscape multifunctionality · Agricultural land use · Integrated landscape assessment · Landscape scenario · Agent-based model · Transdisciplinarity · Rural development

Abstract Natural reforestation of European mountain landscapes raises major environmental and societal issues. With local stakeholders in the Pyrenees National Park area (France), we studied agricultural landscape colonisation by ash (*Fraxinus excelsior*) to enlighten its impacts on biodiversity and other landscape functions of importance for the valley socio-economics. The study comprised an integrated assessment of land-use and land-cover change (LUCC) since the 1950s, and a scenario analysis of alternative future policy. We combined knowledge and methods from landscape ecology, land change and agricultural sciences, and a set of coordinated field studies to capture interactions and feedback in the local landscape/land-use system. Our results elicited the hierarchically-nested relationships between social and ecological processes. Agricultural change played a preeminent role in the spatial and temporal patterns of LUCC. Landscape colonisation by ash at the parcel level of organisation was merely controlled by grassland management, and in fact depended on the farmer's land management at the whole-farm level. LUCC patterns at the landscape level depended to a great extent on interactions between farm household behaviours and the spatial arrangement of landholdings within the landscape mosaic. Our results stressed the need to represent the local SES function at a fine scale to adequately capture scenarios of change in landscape functions. These findings orientated our modelling choices the building an agent-based model for LUCC simulation (SMASH–Spatialized Multi-Agent System landscape colonization by ASH). We discuss our method and results with reference to topical issues interdisciplinary research into the sustainability multifunctional landscapes.

Introduction

Natural reforestation of mountain agricultural landscapes is of special concern for society and policy decision-makers in Europe from the local to the regional level (Soliva et al. 2008). Many studies have

stressed its detrimental impacts on the various environmental and socio-economical services provided by these landscapes of emblematic character and rich biodiversity (Rey Benayas et al. 2007). The role of agricultural abandonment as the major proximate driver of natural reforestation has been well established for several years. However recent works suggest that spatial patterns of agricultural abandonment do not in fact depend as much as previously believed on biophysical environmental conditions but also to a significant extent on social factors (Mottet et al. 2006; Gellrich et al. 2007). One can therefore assume that studies of land-use and land-cover change (LUCC) that include a spatially-explicit analysis of the relationships between social and ecological systems can provide further insights into changes in mountain landscapes and their drivers, and consequently improve our understanding of the conditions required for their sustainability.

Agent-based models (ABM) are considered to be of major interest for supporting progress in the modelling of interactions between human actors and their environment on a spatially-explicit basis (e.g. Parker et al. 2003; Bousquet and Le Page 2004; Grimm et al. 2005). But representing human decisions and biophysical processes in an integrated way in ABM for LUCC simulation (ABM/LUCC) is still a challenge (Janssen and Ostrom 2006; Matthews et al. 2007; Robinson et al. 2007). To facilitate this integration in a study of landscape reforestation processes and impacts in the Pyrenees National Park (PNP) area, we relied on the social-ecological system (SES) concept coined by Holling (2001) and we coupled an integrated assessment of past landscape change with the building of an ABM/LUCC. Here we present and discuss the method and current results of the study, which was conducted in close cooperation with landscape stakeholders.

Material and methodology

Research context and orientations

Participatory study on landscape multifunctionality at the initiative of stakeholders

In the early 2000s, the PNP scientific service, the agricultural services and rural planning agencies of the Hautes-Pyrenees district considered the continual reforestation of agricultural landscapes with ash (*Fraxinus Excelsior*) as a serious threat to the future of the natural environment and to valley socio-economics. They asked our research group to be involved in a study of landscape reforestation and its impacts on biodiversity, agricultural production and the landscape's cultural heritage and aesthetics. The resulting participatory research group (PRG) included scientists in landscape ecology, agricultural sciences, geographical information sciences and computer modelling. The PRG met in plenary workshops once a year, additional meetings being organized as required.

Sustainability sciences recommend making a clear distinction between sustainability of coupled human-natural systems, i.e. their capacity to persist despite uncertainty and change in their environment, and their sustainable development, i.e. the political vision of the desired function of the systems in the future (Kates et al. 2005). The relevance of this view for landscape ecology is acutely recognized (Wu 2006; Naveh 2007). It leads to consider landscape sustainability not as an endpoint but as an idea supporting the choice of development directions that will have a positive impact on landscape functions. Material and immaterial landscape functions can be regarded as the output of intended and non-intended impacts of concrete land use (Brandt and Vejre 2003; Helming and Wiggering 2003). The operative objectives of our study were thus (1) to gain an integrated understanding of the processes of change in the local landscape/land-use system regarded as a SES, i.e. a self-organised complex system, and (2) to build a ABM/LUCC to describe plausible behaviour of the system under a range of alternative scenarios, in order to assist management and policy decision making.

Overview of the study method

Landscape ecology supports an integrated understanding of spatial and temporal changes in ecological systems, their relation to human activities, and their role in the sustainability of landscape systems (e.g. Turner 2005; Otte et al. 2007). Land change science (LCS) addresses interactions among social systems and environmental factors regarding the behaviour of households or firms as the major proximate drivers of land change (Turner et al.

2007). Agricultural sciences consider change in agricultural land-use in relation to farming systems viewed as adaptive socio-technological systems driven by land condition, household behaviour, technology, socio-economic environment and public policy (Deffontaines et al. 1995; Dent et al. 1995; Gibon 1999; Bontkes and van Keulen 2003). We combined concepts and methods from these scientific domains to address landscape changes in the Pyrenees by means of a case study.

Study area

The study site consisted in four neighbouring villages (42°57′N, 0°3′W) located about 20 km south of Lourdes, selected as representative of local dynamics (Mottet et al. 2006). The local climate is typical of Atlantic mountains (average annual temperature of 12.5°C and precipitation of 900 mm). Village territories range from 450 to more than 2,000 m asl. Private agricultural land is located between 450 and 1,300–1,400 m asl., common pastures and forests occupying the remaining altitudes. Soils in the cultivated area are relatively deep brunisols (Julien et al. 2006). Local agriculture is specialised in raising beef cattle and/or sheep. Almost all the usable agricultural area (UAA) is dedicated to grassland, the rest being cultivated for fodder and cereal crops for animal feed. In 1955, there were 120 farms in the four villages; in 2000, only 42 farms remained.

As is the case in most European mountains (Rey Benayas et al. 2007; Soliva et al. 2008), Pyrenean agricultural landscapes were shaped by a very ancient agro-pastoral tradition, and experienced a slow evolution for a long period up to the first half of the twentieth century (Gibon and Balent 2005). The village was (and to a large extent still is) the basic institutional level of their organisation. Ancient communities organised agricultural systems according to a '*house-based*' social system (Augustins 1990), including farm holding ('*house*') transfer to a single heir, who was bound to care it for next generation. The house comprised private land and rights for use of the common land. Every household in the community was allocated a parcel of private land in each agricultural landscape unit (ALU) to enable it to benefit from the full range of village natural resources. Every parcel in a given ALU was subject to similar management decided by the community council. This resulted in close co-organisation between ecological and social systems at respectively three main levels of spatial organisation (Balent and Gibon 1999): (1) the ecological plot, the landscape unit, and the whole landscape for ecosystems; (2) the parcel, the individual farmholding, and all village private land for land use. Traditional landscapes in the study area comprised two broad types of units (Fig. 1). Bottom ALUs, located in valley bottoms and on the lowest slopes, included village settlements. Intermediary agricultural landscape units (IALUs) located higher up on valley slopes included scattered barns in which hay was stored and consumed by herds on the spot. The system remained mostly unchanged until the 1950s, when agricultural modernisation and decline in the number of farms led to diversification of farming strategies, and to land-use heterogeneity in the same ALU.

Research methodology

Integrated assessment of landscape and land-use change since the 1950s

Ecological dimension of reforestation processes: The ecological processes of landscape reforestation were studied in Villelongue agricultural landscape (360 ha), which was regarded as a good illustration of regional trends. To assess LUCC at the landscape scale, we built land-cover maps from aerial photographs taken at three dates (1948, 1971 and 2001; French National Geographic Institute) using the method of Muraz et al. (1999).

To assess the susceptibility of grasslands to colonisation within the landscape, we mapped all the old trees in the study landscape using aerial photographs taken in 1948 and applied a 100 m circular buffer around each tree according to the literature. Wardle (1961) observed ash seed dispersal over 125 m from the tree and Wagner (1997) showed that the density of the seed rain was high even at long distances (1.33 seeds/m^2 at a distance of 90 m).

The role of land management in ash colonisation was assessed at the parcel level using an empirical model of the relationships between botanical composition, and grassland biomass production and utilization (Balent 1991). The model is based on a Correspondence Analysis ordination (CA-Model) of

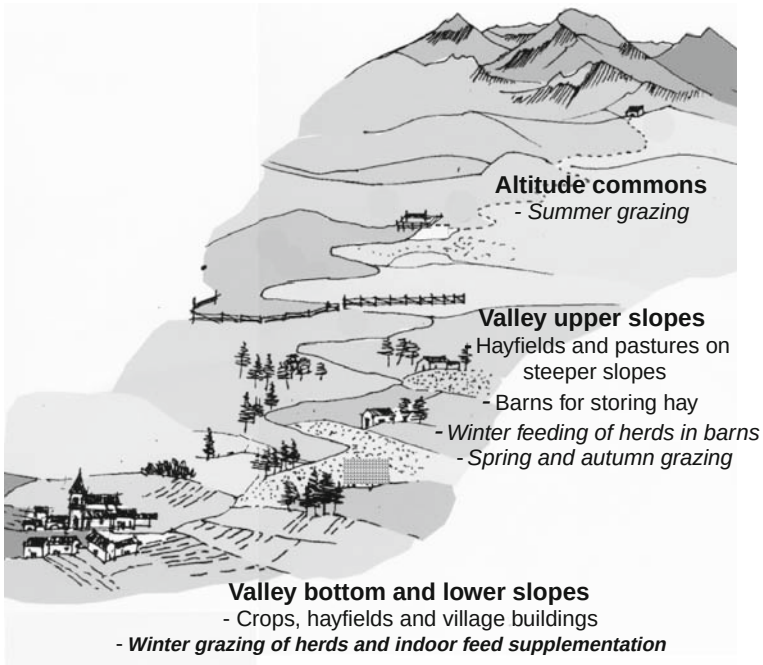


Fig. 1 Diagrammatic organisation of agricultural landscape units and land use practice in a traditional Pyrenean agro-pastoral system (adapted from a DDAF-65 drawing)

the botanical composition of a reference set of Pyrenean grasslands. The scores of the grasslands on the F1 and F2 axes of the CA model were calibrated with respect to soil fertility using the concentration of N, P and K in plants, which has been shown to be closely correlated to dry matter production (Duru et al. 1994), and to biomass utilization from direct measurement of grazing intake and surveys of hay crop yields (Balent 1991). The model enables the intensity of use of a parcel to be estimated as the ratio between biomass utilization and biomass production i.e. F2 score/F1 score in the model. We calculated the ordination scores of 96 grasslands randomly selected in the Villelongue territory in the CA-model by averaging the scores of the species they share with the CA-model (passive ordination *sensu* Økland 1990). Additionally, the presence of ash seedlings was visually observed along two walking transects covering the longest and shortest diagonals of each of the 96 parcels.

Human dimension of land-use change: In order to assess land use (LU) in 2003 and land use change (LUC) since 1950 at the parcel, farm and landscape levels, we combined proven methods based on LCC maps and census data (Tasser et al. 2009) with a field survey of every household that used some agricultural land in the study area, whatever their official profession and landholding area. We built a spatially-explicit survey method using a model of Pyrenean farms as complex SESs (Mottet et al. 2006; Fig. 2). The data collated concerned: (1) the characteristics of the farmholding and the household, the production and land-management systems, (2) land tenure, land cover (LC) and LU practice on each parcel in 2003, (3) change in land tenure and LU of each parcel dating back to 1950, and (4) the history of the farm since 1950. After assessing LUC and its drivers at the landscape level (Mottet et al. 2006), we analysed LU and LUC at the farm level in relation to land holding condition and household behaviour.

The diversity among farm households and holdings was analysed from a series of typologies built using selected sets of indicators and manual and multivariate statistical analyses according to Gibon (1999). Typologies concerned (Mottet 2005): (1) the farm structure, the household and its livelihood strategy, (2) the farmholding territory viewed both as a land estate and as a component of the agricultural landscape, (3) how the farming system operated with a focus on its management and on the land-use system. Changes in farm structure and management since 1950 were assessed using the concept of a 'farm trajectory' coined by Capillon (1993). The diversity encountered among farms was synthesized in the

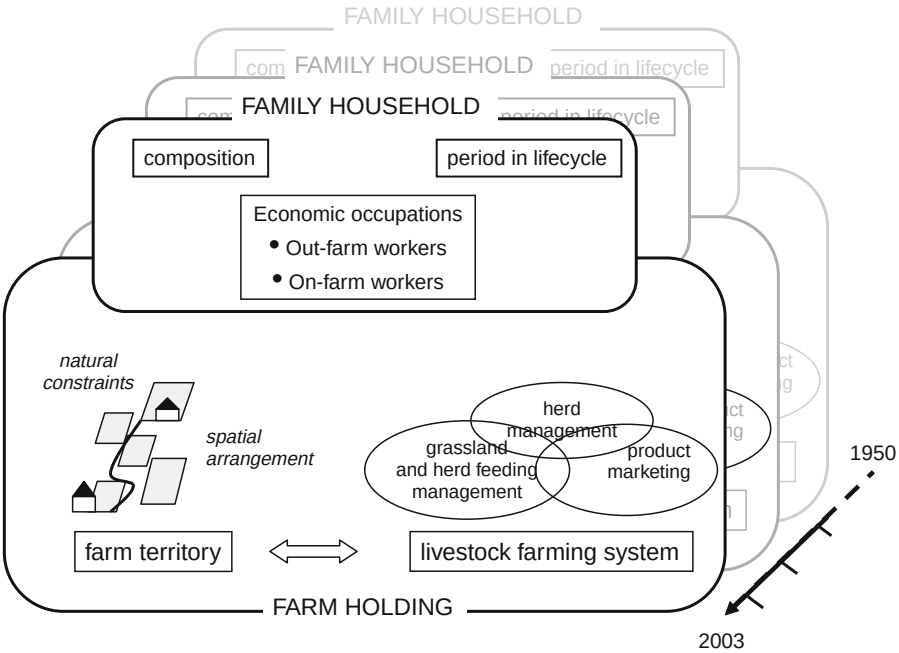


Fig. 2 Methodological framework used for the integrated study of family-farm dynamics (from Mottet 2005)

form of socio-technological archetypes concerning organisation and change in the farmholding structure and land condition, the land-use system and farm management, and the short- and long-term behaviour of the household.

Simulation of future LUCC scenarios and their impacts on landscape functions

General method for the development of the AMB/LUCC: The methods used in ABM/LUCC simulation to model individual behaviour and interactions between social actors, and their interactions with the natural environment in the determination of LCC, mainly depend on the orientation of the study (Janssen and Ostrom 2006; Robinson et al. 2007). In simulations for communication and social learning in common property natural resource management (e.g. the 'Companion Modelling' (ComMod) method; Barreteau et al. 2003), the social behaviour and interactions of individual land users are mostly modelled with their cooperation as heuristic rule-based models, under the real-world configuration of landholdings and households (e.g. Castella et al. 2005). At the other extreme, in simulations conducted for research or policy purposes, population demographics and change in landholdings are represented, and short and long-term decisions made by individual households are mostly modelled using an economic model from the literature and utility functions calibrated from census or/and survey data (e.g. An et al. 2005; Millington et al. 2008). Hybrid approaches are now being developed to enhance the account of the variety and mechanisms of household decision-making at the short and long term, in ABMs including modules that allow nesting utility functions, heuristic rule-based techniques, etc. (Manson and Evans 2007; Le et al. 2008; Fontaine and Rounsevell 2009; Valbuena et al. 2009). Because of our emphasis on the social dimension of behaviours, we chose the ComMod method to build an ABM/LUCC that would in the end combine the two approaches.

Framework approach for the development of the conceptual model of SMASH: Relying on hierarchy theory (Allen and Starr 1982; Wu and David 2002; Moreira et al. 2009), we assumed that the local land-use/landscape system could be represented as nested modules according to three levels of spatio-temporal organization:

- Module 1 deals with the long-term simulation of the farms' development until the scenario horizon

as trajectories of change (e.g. An et al. 2005; Le et al. 2008; Fontaine and Rounsevell 2009). It is run at a 5-year time step at which changes in individual farm structure and land allocation are simulated from a farm-development behaviour model according to household type and demographic stage, computerised change in the LU and LC condition of parcels (as an output Module 3) and results of interactions between landholders on the land market (as an output of Module 2);

- Module 2 deals with the simulation of interactions and transactions between actors on the land sale and rental market (e.g. Parker and Filatova 2008; Valbuena et al. 2009). It assumes they occur simultaneously at the same 5-year time steps. The interactions and transactions are simulated using policy-delineated areas for land-use allocation, landowner and landholder behaviour models, and contextual opportunities for land sale and rental (in relation with Module 1);
- Module 3 deals with the simulation of LCC at the parcel level as a result of the interactions between ecological dynamics and farmers' behaviour in land management. Yearly periods are used to simulate the agricultural production cycle. The conditions of individual farmholding and land management strategies are assumed to remain unchanged during the 5-year period, until their update as an output of Modules 1 and 2.

Five years was selected as the longest time step as an acceptable compromise between ABM simplicity and scenario realism. Module 3 addresses not only land allocation, but also the interactions and feedback between ecosystem dynamics and land-use behaviours. The PRG considered it to be the most critical factor in the future ABM capability to adequately simulate future spatio-temporal patterns of LCC. It was therefore given priority in the development of ABM. Up to now, it is the only module that is fully developed and implemented.

Scenario setting and assessment of landscape functions: The PRG selected the prospective (*'what-if')* scenario method and decided on the macro-drivers of LUCC to be considered as agricultural and environmental policy, and urbanisation pressure from tourism and populations relocating from towns. Policy stakeholders expressed a preference for extreme assumptions as regards hypothesized changes and their impact on landholder behaviours, but also wanted a realistic simulation at the fine scale of the resulting spatial and temporal patterns of change in the landscape. Landscape change was analysed using 2D maps, 3D virtual images and a set of metric indicators according to a method for multifunctional-landscape assessment that we elaborated with other teams in the European VisuLands project (Miller et al. 2009).

A GIS-based scenario study (Gibon and Fidalgo 2009) enabled the PRG to refine the view of the building and function of the ABM. Scenarios were worked out manually and mapped in GIS using policy-delineated areas, a basic model of landowner behaviour and a set of broad rule-based behaviour models of farm households built on the field-survey results. The Villelongue agricultural landscape and its condition in 2003 were selected as the scenario baseline, and their horizon was fixed at the year 2030.

ABM/LUCC building and implementation: We used the CORMAS platform (Bousquet et al. 1998) to develop and implement the ABM. The PRG combined (1) the use of the ARDI method (i.e. Actors, Resources, Dynamics and Interactions) developed by Etienne et al. (2008), (2) the knowledge and data provided by the historical assessment, and (3) results of previous transdisciplinary studies conducted on Pyrenean agropastoral systems.

Results of the historical assessment of LUCC

Ecological processes of landscape reforestation with ash

Forested land increased over 20% in the Villelongue landscape from 1948 to 2001, while agricultural land decreased by 24% and built up areas increased by around 9%. The impacts of reforestation were particularly visible in the IALUs (Fig. 3).

The mapping of ash seed rain showed that the density and spatial layout of old ash trees in the landscape (more than 3,000 for about 360 ha) made nearly all the grassland parcels susceptible to natural reforestation (see Supplementary material). This result was confirmed by in situ observation of the presence of ash seedlings in most of the 96 grasslands studied. Therefore, we considered landscape to be a neutral variable regarding the susceptibility of

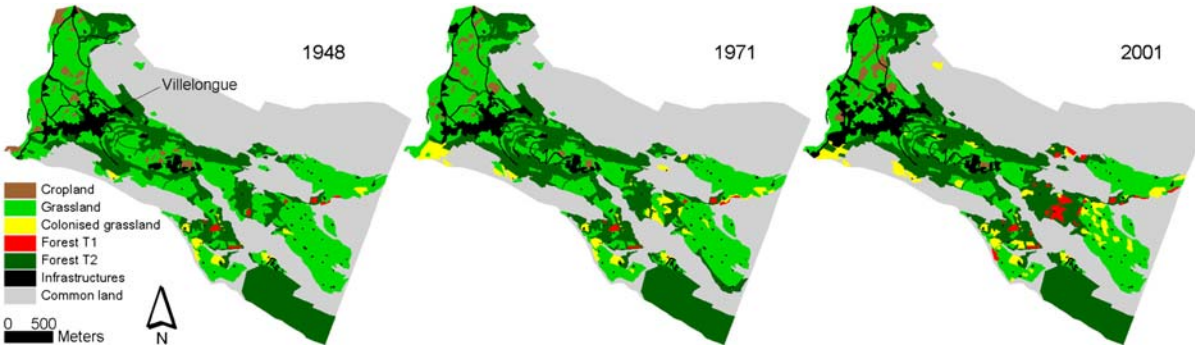


Fig. 3 Agricultural landscape change between 1948 and 2001 in Villelongue village (Hautes Pyrénées) (from Gibon and Fidalgo 2009). Valley commons are in grey. Colour codes for land-cover categories in the agricultural landscape: see legend in the map

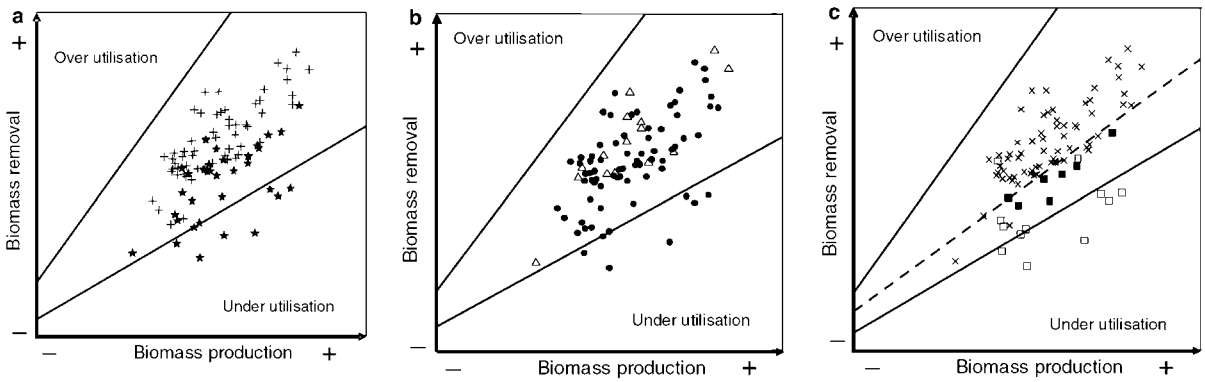


Fig. 4 Passive ordination of the grasslands of the Villelongue territory in the Correspondence Analysis Model (from Julien et al. 2006). **a** Plus signs are mixed grasslands, stars are grazed grasslands; **b** Triangles are grasslands without ash seedlings, dots are grasslands with ash seedlings; **c** Crosses are grasslands without established ash, filled squares are grasslands where vegetative reproduction of ash trees was observed. The area around the upper solid line corresponds to very intensively managed grasslands; the area around the lower solid line corresponds to low management intensity. Intensity is the ratio between biomass removal and biomass production. The area between the two lines corresponds to the most commonly observed range of management intensity. The dotted line represents a threshold of management intensity above which ash cannot establish itself

grasslands to colonization by ash. The passive ordination of the 96 grasslands in the CA Model (Fig. 4) showed that the presence of established ash trees was negatively linked to the biomass removal axis ($n = 96$, $t = 5.79$, $p < 0.001$) and independent of the biomass production level ($n = 96$, $t = 0.86$, NS). The colonization process was prevented by hay cutting (Julien et al. 2006). In grazed-only grasslands and for a given level of grassland production, established ash trees were preferentially found with a low utilization/production ratio. A threshold of intensity of use separating the parcels with and without established ash trees could be eye-adjusted. It corresponded to a 0.5 ratio line, i.e. when half the grass produced annually is used.

In fact, due to the spatial arrangement of ash trees in the landscape, which was inherited from the past, the way the farmers manage the land was found to be the major proximate driver -and current control- of grassland encroachment.

Agricultural LU and its change

The cumulated agricultural area occupied in 2003 by the 40 farms surveyed was about 1,000 ha, i.e. 75% of the traditional area. While farm households owned

almost all their farmland in 1950, in 2003, parcels rented under registered and oral agreements amounted respectively to 20 and 27% of their area (Mottet 2005). During the course of the study period, agricultural abandonment concerned less than 10% of their parcels, and a return to agricultural use occurred in 70% of their area. With the previous findings of Mottet et al. (2006), these results showed that agricultural abandonment in the study area since the 1950s mainly resulted from the fact that land belonging to collapsed farms had not been taken over when the farmer retired, rather than the intentional abandonment of parcels with high natural constraints in operational farms.

Contemporary farms were found to mostly result from the continuation of an ancient family-household farming tradition (31/40) or the taking over of a farmholding belonging to a retiring neighbour (5/40). After 1950, only four (small) farms were created by families of non-agricultural and/or non-local origin. In 2003, about 65% of the farmers were more than 50 years old, and only third of them had a certain successor. The most noticeable change in farm characteristics since the 1950s was a large but uneven increase in their size (Table 1). The LU strategies of the households appeared to vary among four archetypes (Table 2). The '*patrimonial strategy*' was the most widespread. This involves the patrimonial use of each parcel including scythe mowing on some steep slopes, maintenance of irrigation channels, etc. The '*Retreat strategy*' was found among ageing farmers who basically had a patrimonial strategy but who, due to the absence of a successor, were progressively restricting their farming activity until full retirement. The '*selective strategy*', which relies on farm technical and economic efficiency rationales, was encountered on part of the biggest farms. The '*niche strategy*' was found on very small landholdings kept for social and cultural reasons.

These results revealed the deep-rooted character of traditional cultural values of the farmer population who were attached to patrimonial land management in both the short and long term. The PRG concluded that it has been a positive factor in the preservation of local agroecosystems and landscapes up to now.

Simulation of future LUCC scenarios

Results of the GIS-based study

Three 'what-if' scenarios were built: a '***trend scenario***' (Scenario 1) assuming continuation of the current trend; a '***CAP reform***' scenario (Scenario 2), to address the impacts of the forthcoming application of the 2003 CAP reform, assuming that farmers will no longer be permitted to use parcels without an official rental agreement; and an '***urbanisation scenario***' (Scenario 3), assuming a municipal policy favouring new population settlement (enlargement of the area delineated for urbanisation). The behaviours of individual farm households were modelled according to archetypes as sets of decision rules to comply with hypothesized LU restrictions and to profit from opportunities on the land rental and sale market. The LU changes considered included sale of building land and agricultural abandonment, the 2003 LU being maintained in other cases. Reforestation of abandoned land was simulated from

Table 1 Categories of family farms in the study area in 2003 (adapted from Mottet 2005)

N°	Types of family farms	Average			
		Number	Farm size (ha)	Area (ha)	(% *total*)
1	Small farmholdings with alternative farming systems (sheep, dairy goats, dairy ewes/cows, horses)	6	4.0	24	*3.28*
2	Small sheep farms run by ageing farmers without a successor	11	6.9	76	*10.40*
3	Small cattle or mixed sheep-cattle farms run by ageing households without a successor	7	14.4	101	*13.82*
4	Medium to large cattle or cattle-sheep farms run by young farmers or by households with a successor	16	33.1	530	*72.50*
	Total	40	16.7	731	*100*

Table 2 Archetypes of farmers' behaviour in land management and farm development in the study area

Land use strategy Main drivers	Patrimonial strategy Cultural	Selective strategy Economic	Retreat strategy Social	Niche strategy Cultural
Family socio-economics	Local or other origin Part or full-time farming Long-term perspective	Local or other origin Part or full-time farming Long-term perspective	Local origin Late in lifecycle No successor	Local or other origin
Main objectives	Sustainability of agricultural land resource	Limitation of labour input to increase livestock production efficiency	Coping with a decrease in available labour	Maintenance of a small family-farm unit and/or "recreation" farming
Farm size and farmland spatial pattern	Medium to large Spread over valley slope–with barns	Medium to large Large land units and/or few access constraints	Small to medium Spread over valley slope–with barns	Small Land units around the farmstead
Animal production system	Cattle only or cattle & sheep	Cattle only or cattle & sheep	Cattle & sheep or sheep only	Alternative
Herd management	More or less close to tradition	'Modernised'	Close to tradition	
Land use practice	Maintenance agricultural use of each land unit	Abandonment of small or constrained land units	Progressive abandonment of remote land units	Maintenance agricultural use
Farmland change	Acquisition of entire farmland of retiring farmers	Acquisition of large parcels and/or parcels adjacent to existing ones	Renting or abandonment of excess land units	None
Occurrence	++++	++	+	+

LC transition rules (Cf. Fig. 7). Scenarios resulted in very distinct land-cover patterns in 2030 (Fig. 5) and values of landscape functions (Gibon and Fidalgo 2009). Under the assumptions of the simulation and the set of indicators used, the 'trend' scenario was revealed to be the most favourable of the three for the desired future landscape multifunctionality.

Conceptual model and implementation of the first SMASH version

The first ABM version (Module 3 of the whole SMASH) focuses on the simulation of LUCC in grasslands at the parcel level, under constant configuration of the farms. Other LU types (cropland, abandoned land, etc.) are assumed to be unchanged. In the whole SMASH model, the module will operate for a period of 5 years, at the end of which changes computed in the other ABM modules will initialise the configuration of farms and landscape for the following 5-year period.

The theory-driven view of interactions between grassland management and reforestation processes

The PRG had a common understanding of annual grazing pressure on a parcel being the result of interactions and feedback between (1) the condition of the grassland and LU at the parcel level, (2) the structure and operation of the grassland system at the farm level and (3) the climate conditions of the year concerned. In mountain conditions, fine scale heterogeneity in bio-physical conditions and grassland vegetation communities mean these interactions are very complex (Tasser et al. 2009). This makes them peculiarly difficult to model and simulate in agricultural sciences (Balent et al. 1998; Andrieu et al. 2007).

To address the relationships between grassland and farmer management from the parcel to the farm level, we used a conceptual model of the Pyrenean grassland system at the farm level built by Gibon et al. (1989). In this model, the grassland system is

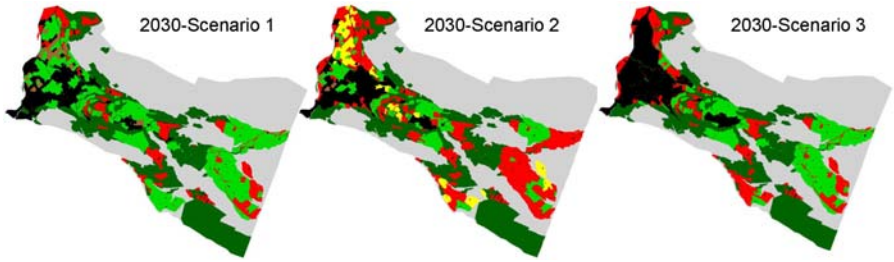


Fig. 5 Prospective LCC of the agricultural landscape in 2030 in Villelongue village according to the scenarios of the GIS-based study (from Gibon and Fidalgo 2009). *Scenario 1*: trend scenario; *scenario 2*: application of CAP reform; *scenario 3*: village urbanisation policy. Colour codes for land cover categories: see Fig. 3

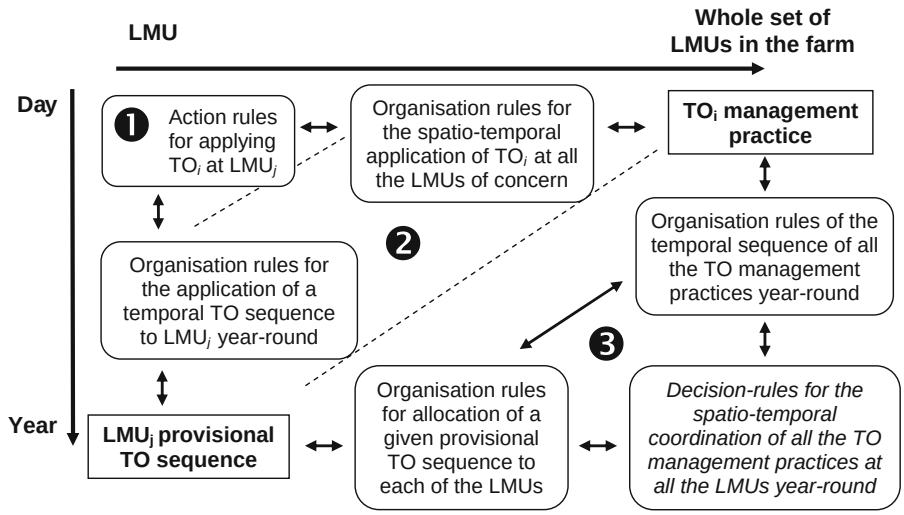


Fig. 6 Framework conceptual model of a farmer's management strategy of the grassland system at the farm level (adapted from Gibon et al. 1989). TO$_i$: technical operation of category i (e.g. early spring grazing, hay harvest). LMU$_j$: land management unit number j, ❶ , ❷ , ❸ : hierarchical levels in the organisation of a farmer's decision rules from the parcel/day (❶) up to the whole farm/year (❸)

regarded as an adaptive SES coupling a set of grasslands and a farmer's decision and action system aimed at meeting year-round and period-specific objectives at various time-steps at the farm and the parcel level. It is represented as a hierarchical system of decision rules for the application of the set of 'technical operations' (TO, e.g. herd grazing, hay cutting and harvesting), that shape the spatial and temporal patterns of production and use of the farm grasslands year round (Fig. 6).

Relationships between grassland production and management were modelled using an empirical model for Pyrenean grasslands built by Duru et al. (1998) in explicit relation to Balent's (1991) model. This model enables estimation of production from grass growth curves as a function of daily climate data and the time of the prior TO application, parameterized according to growth cycle and season. It includes rules to account for the impact of altitude on grassland production, and synthesizes the diversity of grass production patterns according to the condition of grassland in the form of calibrated growth curves for high, medium and low productivity grasslands (HP, MP and LP grasslands respectively).

ABM structure and operation

The baseline used to simulate the individual farm's grassland system consisted in (1) the set of grassland

parcels in real-world farm, (2) a virtual cattle herd whose size in 2003 was fitted by converting the number of sheep and cattle into Livestock Units and adding them up, and (3) an attributed rule-based model of management. Social entities (farmers viewed as computer agents) and spatial entities are described at different scales (see Supplementary material for details on the ABM structure). At the farm scale, the *farm territory* is represented by the set of its *farming parcels*, i.e. its land-management units, and the set of its *cadastral parcels,* i.e. the basic units for LU rights and land transactions. An additional category of parcels called *elementary parcels* was created to enable the model to mimic LU practice on heterogeneous parcels used both for hay cutting and grazing, in which the parts of the parcel that farmers consider to be too steep are usually not mown. Both the *cadastral parcels* and the *farming parcels* were modelled as aggregates of *elementary parcels*. The latter were initialised in CORMAS from a cell grid with a set of attributes imported from a rasterized vector layer built in GIS (Monteil et al. 2008; Table 3).

The basic time step used to represent the socio-ecological dynamics in the course of the year is 15 days. Its length results from a long-debated compromise in PRG workshops between an easy-to-run ABM simulation and a realistic representation of the interactions and feedback between agroecological processes and land management decisions.

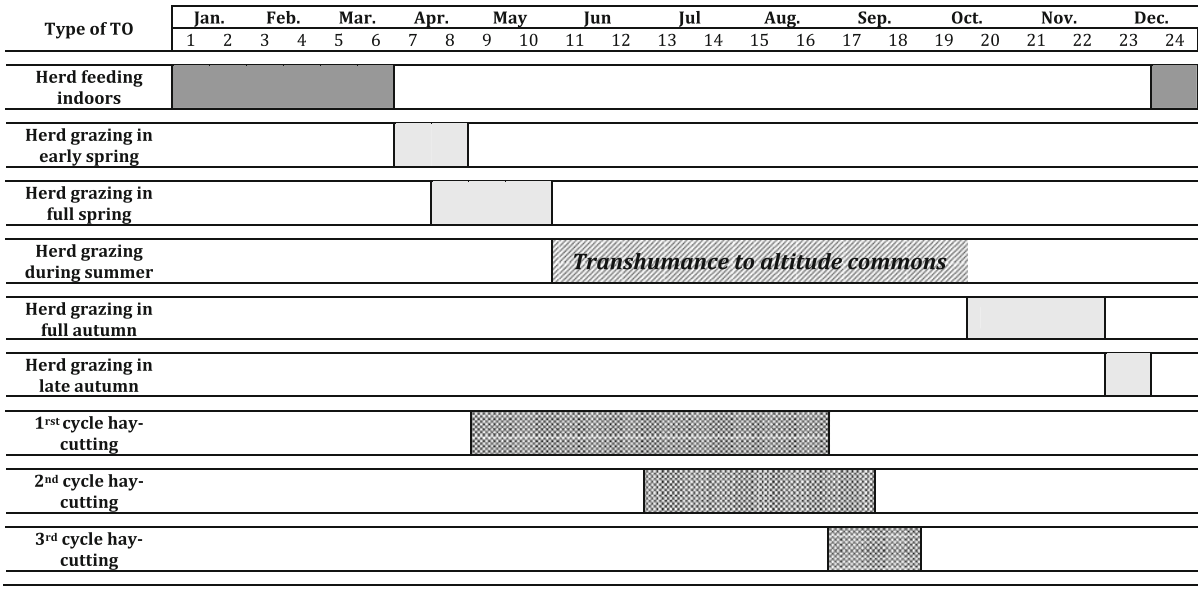
ABM representation of interactions between LUC and LCC from the farm level to the parcel level: The grassland management practices surveyed in 2003 were narrowed down to three behaviour types: (1) '*close-to-tradition*' grassland management attributed to households with a '*traditional*' or '*retreat*' strategy, (2) '*modernised*' grassland management attributed to households with a '*selective*' strategy, and (3) '*conservative*' grassland management attributed to households with a '*niche strategy*'. For the latter, the LU and LC baseline at each parcel were assumed to continue over time. Other management types were modelled as sets of parcel attributes and farmer management rules according to Gibon et al. (1989) model. Only '*close-to-tradition*' grassland management is currently implemented and simulated in the first version of SMASH. The management practice for each TO type is represented in the form of a fixed calendar (Table 4), for now neglecting most of the within-year adaptive rules. We represented the variety of the coupled grassland conditions-projected TO sequences as 'operational LU' categories which consider grassland productivity (HP, MP, LP), altitude and the TO sequence together

Table 3 Imported attributes of the ABM/LUCC cells from which the farming, cadastral and elementary parcels' attributes are derived

Attribute	Possible values
Farmer's number	1, 2, 3, 4, 6, 7, 501, 502
Farming parcel number	Number attributed with the farmer in the survey (Integer > 0)
Cadastral parcel number	Number in the official cadastral registrer (Integer > 0)
Classes of accessibility	0 (no information), 1 (road), 2 (track suitable for tractor), 3 (track not suitable for tractor), 4 (no direct access)
Classes of altitude	1 (450–600 m), 2 (600–800 m), 3 (800–1,000 m), 4 (1,000–1,350 m)
Classes of land use	1(cropland), 2 (meadow), 3 (pasture), 4 (abandoned land), 5 (woodland)
Classes of landcover	1(cropland), 2 (grassland), 3 (encroached grassland), 4 (young forest), 5 (mature forest), 6 (building), 7 (other)
Classes of slope	1 (0–10%), 2 (10–30%), 3 (30–50%), 4 (>50%)
Classes of operational land use*	**P1**: HP, Alt 1, MMM(G), **P2**: MP or LP, Alt 1, MG; **P3**: MP, Alt 1, MMG; **P4**: HP, Alt 2, gMMG(G); **P5**: HP, Alt 2, gM(M)G(G); **P6**: MP, Alt 2, gMG(G): **P7**: MP or LP,Alt 2, G(G)G; **P8**: MP or LP, Alt 3, MG(G); **P9**: MP or LP, Alt 3, GGG
Heterogeneity of parcel management	0 (no), 1 (yes)

* Operational land use combine the type of grassland productivity (HP, MP, LP), the altitude (Alt 1: < 600 m; Alt 2: 600–1,000 m; Alt 3: >1,000 m), and the projected TO sequence (as a succession of mowing (M), early spring grazing (g) and grazing (G) operations; operations in brackets are optional)

Table 4 Representation of the projected annual calendar of the grassland management practices for the 'close-to-tradition' management strategy in SMASH



(Table 3). Categories are initialised in the ABM by attributing to each parcel an operational LU category based on its condition and TO sequence as collated in the field survey.

Grass production at the parcel level is computed in the form of average daily grass growth for each 15 day-time step calibrated according to Duru et al. (1998) model from a local series of meteorological data (see Supplementary material). In the current ABM version, grass growth simulation does not account for grassland condition and altitude. It is simulated by applying the HP grassland model and a low altitude category. Annual grass consumption through grazing at the parcel level is calculated by cumulating simulated herd consumption during each grazing TO computerized in the course of the year, assuming a daily requirement of 13 Kg Dry Matter (DM) per Livestock Unit. The assessment of under-grazing for each grazed-only parcel is computed at the end of each year by calculating the simulated grass consumption/production ratio and comparing it with the empirical 0.5 threshold. The LUCC processes at the parcel level are modelled as a set of LC transition rules (Fig. 7). The PRG designed them from practical knowledge and the field data collated.

ABM simulation of the grassland system during a one-year cycle: The operation of the grassland system is simulated at a 15-day time step from the time the herd is turned out to graze in spring to when the herd is brought back into winter indoors. TOs are carried out at the 'farming parcel' level according to the farm calendar.

The organization of hay harvest (mowing) TOs is simulated as follows:(1) Selection of the parcels that have to be harvested during a given 15-day time step based on their projected TO sequences over the year; (2) A mowing objective for the time step is computed to deal with all the meadows concerned during the mowing period; (3) Mowing priority is given to meadows with the highest biomass and easiest access; (4) Mowing implies removing all available fodder from each elementary parcel that makes up the farming parcels concerned, except in heterogeneous parcels where the slope is greater than 30%.

The grazing operations are simulated as follows (see Supplementary material for details): (1) Parcels that can be grazed during a given time step are selected according to projected TO sequences; (2) Grazing priority is given to parcels with the smallest number of TOs already completed; (3) Grazing of additional

Table 5 Characteristics of grassland parcels and herd of Farms 1 and 3

FARM	Operational land-use categories of grassland parcels (area in ha)										Herd size (Livestock units*)		
	P1	P2	P3	P4	P5	P6	P7	P8	P9	Total	Cattle	Sheep	Total
1	6.65	0.86	–	10.94	2.05	0.57	6.35	31.78	12.96	72.16	75	23	98
3	4.34	1.27	3.63	–	–	2.04	0.46	8.91	–	20,65	34	0	34

* Livestock Unit = 1 adult cow = 7 adult ewes

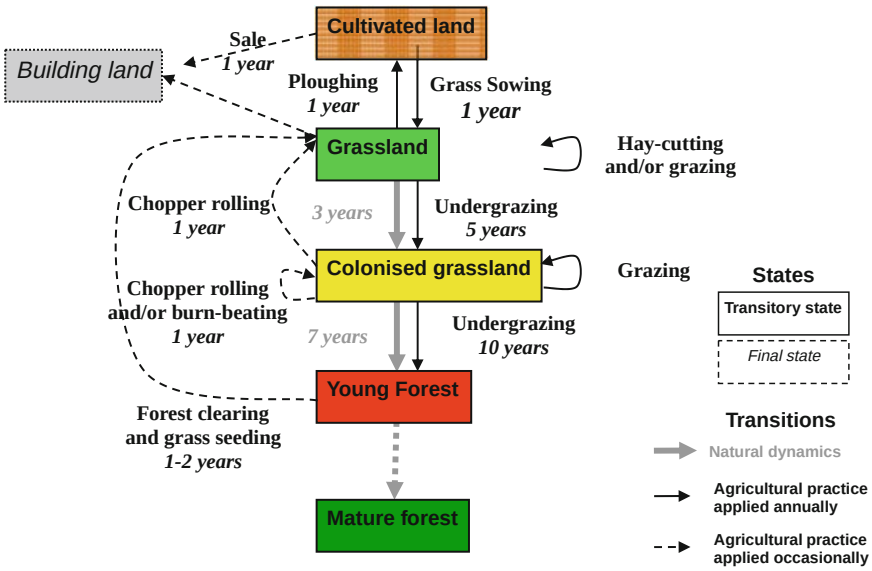


Fig. 7 Transition rules of natural resources with and without interaction with land-use practices (adapted from Monteil et al. 2008)

parcels is continued until the herd's needs for the 15-day period are satisfied, as long as there are still parcels to graze. At the end of the simulated year, the calculation of annual grazing pressure for each parcel and the updating of reforestation indicators are computed.

Results of the first simulation experiment

The simulation experiment aimed to test the ABM module, with reference to two main directions for ABM validation, i.e. the assessment of their computational and conceptual validity (Rykiel 1996). The ABM was therefore run for 30 years, regardless of the reconfiguration of the farms that will be computed every 5 years once the whole SMASH model is complete.

The results reported here concern two farms (Farms 1 and 3) whose attributes are listed in Table 5. The *'close-to-tradition'* model matches their real-world grassland management. The simulated impacts of reforestation at the end of the 30-year period on annual grass production at the farm level, i.e. hay harvested and grazing, are illustrated in Fig. 8a. For Farm 3, stable values for cumulated annual grass production and grass removal were obtained from the 13th year on. From this date, the computed grazing intensity of the grazed-only parcels became systematically higher than the threshold enabling encroachment, thus stopping their reforestation. For Farm 1, where computed annual grassland production largely exceeded herd needs, the process continued throughout the simulation period. Simulated LU and LC of the parcels resulted in 4.3 ha (i.e. 20.7% of the farm UAA) and 23.3 ha (i.e. 32.3% of the farm UAA) of encroached grasslands for Farm 3 and Farm 1 respectively. The general ABM behaviour revealed was consistent with the conceptual model of the reforestation process, but the large values obtained for the encroached areas underlined discrepancies in the simulation of the grassland system for both farms. These discrepancies appear to result mainly from the oversimplification applied in the simulation of grassland production at the parcel level, which will be corrected in the near future. But the higher value obtained for Farm 1 than for Farm 3 could also be due to

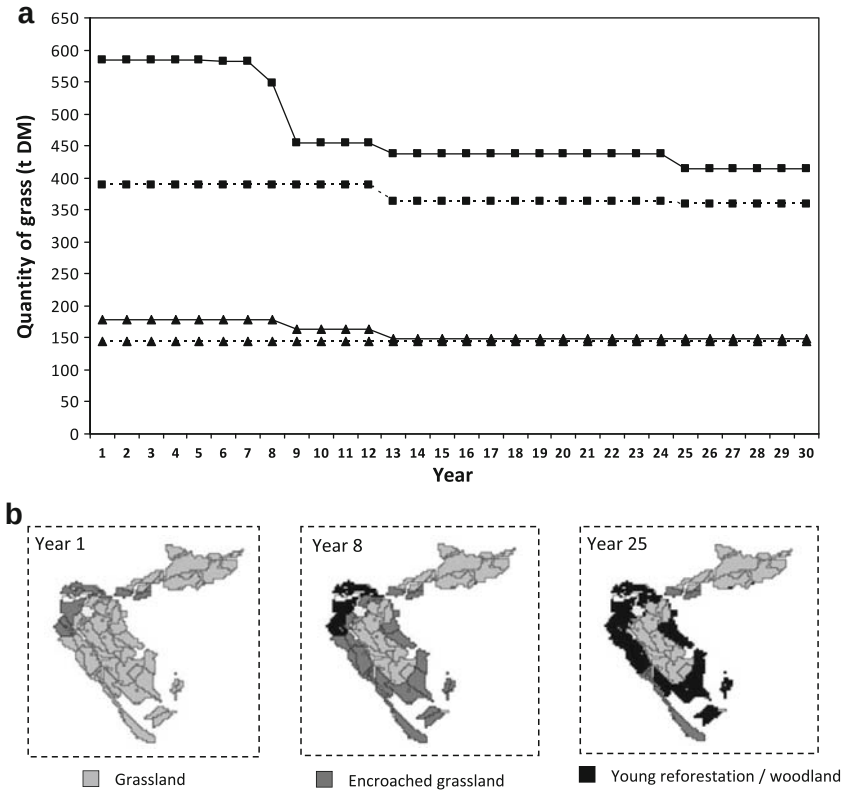


Fig. 8 Simulated results of the interactions between land use and land cover change over the 30-year simulation period for grasslands on Farm 1 and Farm 3. **a** Cumulated year-round grass production (*solid lines*) and grass removal by hay cutting and herd grazing (*dotted lines*) at the farm level for Farm 1 (*filled square*) and Farm 3 (*filled triangle*), in tonnes DM. **b** simulated land cover in years 1, 8 and 25 for the whole set of grassland parcels held by Farm 1 and Farm 3 in the upper IALUs. Natural process of forest growth after encroachment was accelerated in the simulation experiment, the last transition stages being reduced to 5 years to accentuate the impacts tested

the conversion of sheep into cattle in the ABM. The impacts of neglecting management differences between species therefore require further examination to determine whether there is a real need for separate representation of the two species.

In terms of spatial distribution, simulated reforestation mainly concerned the grazed parcels located at the highest altitudes and the steepest elementary mown parcels, as expected from the conceptual model (Fig. 8b). However the detailed results revealed some gaps in simulated TO sequences for parcels used both for grazing and hay cutting (see Supplementary material). This questions the interest of attempting to simulate LCC at a scale smaller than the cadastral parcel; i.e. the elementary parcel, in the next version of the SMASH model.

Discussion and conclusion

Changes in land-use systems and their impact on landscape functions

The character of agricultural landscapes in the PNP area can be understood as the output of the smooth co-evolution of social and natural systems in the traditional land-use system, and the changes they have undergone since the 1950s as the symbol of its collapse. Our results illustrate the major role played by social institutions in the sustainability of traditional coupled human-natural systems (Berkes and Seixas 2005). Until the second half of the twentieth century, the local organisation of landscape/land-use relationships relied on a set of properties, i.e.

hierarchical organisation, coordination, complementarity and integration between components, which are known to form the basis of adaptiveness and persistence in complex self-organised systems (Kolasa and Pickett 1989; Balent and Gibon 1999). The acceleration of global dependency and the decrease in local autonomy after the Second World War led to a visible break in the continuity with the past in European landscapes (Antrop 2005). It resulted in an increasingly wide array of uncoordinated social actors and bodies (up to the European level) who have direct or indirect authority over rural land use (Gibon 2005). From the point of view of a SES, the request of the Pyrenean stakeholders in charge of nature conservation and rural policy at the origin of our study can be viewed as an attempt to reintroduce some organization into local land-use systems with respect to the currently expected functions of landscape.

Culture as a pivotal driver of change in the mountain agricultural landscapes of Europe: Our results provide evidence for the interest of a fine-scale assessment of past organisation in land-use practice and the changes they have undergone since World War II to enhance the understanding of LUCC and its impacts on landscape functions. The spatially-explicit survey method we fined-tuned to assess the socio-ecological dimensions of LU change in the study landscape enabled us to overcome the basic difficulty linked to the limited availability of direct data on past land use (Tasser et al. 2009). Our method could be useful in other locations where the actors' recollection of LUC at the small scale is still alive. Insights gained into the social-ecological processes that shape LUCC in local landscapes confirm culture as a driver of landscape change (Burgi et al. 2004) in the Pyrenees. Farmers' behaviours strongly imprinted with traditional values have up to now restricted the magnitude of landscape reforestation. However, the results of our GIS-based scenarios indicate that the resilience of local agriculture is being increasingly eroded by economic liberalisation and rural urbanisation, as observed in other European mountains, where agriculture is already vanishing in some locations (Lundstrom et al. 2007; Streifeneder et al. 2007). Therefore, unless there is a shift in the direction of socio-economic change and policy, Pyrenean agricultural landscapes will likely undergo a much more drastic change in the near future than they have in recent decades. Drawing on Plieninger et al. (2006), we consider support for the continuation of remaining traditional land-use systems to be a major requirement for the future multifunctionality of European mountain landscapes.

Traps and tracks in the modelling of social-ecological processes for the ABM/LUCC simulation of landscape change

Our SES framework approach combining a range of methods helped us to smooth over recognised basic difficulties in the representation and parameterisation of a concrete landscape/land-use system (Berger et al. 2006; Verburg 2006; Robinson et al. 2007). The transdisciplinary assessment of landscape change produced essential conceptual and empirical knowledge and data to link the land and the people on spatially-explicit bases. The GIS-based scenarios supported a clear definition of the objectives of the ABM simulation and the functionalities expected from the ABM/LUCC. The concentration of ecological and socio-technical field studies in a small geographic area facilitated the parameterization and calibration of the model.

Modelling land-use behaviours and their interactions with the natural environment: The limitations of conceptual models and agent computational abilities to represent the behaviour of LU actors, and the interactions among them and with their environment have hampered the simulation of interactions and feedback in coupled human-natural systems and the capacity of ABM/LUCC simulation to answer real-world questions (Janssen and Ostrom 2006; Matthews et al. 2007). Our study is part of an effort to bridge this gap. Recently published ABM/LUCC works also focus on enhancing the conceptual and empirical modelling of land-users' decision-making processes at the local or regional scale, in the simulation of agricultural-land and/or forest change (Le et al. 2008; Manson and Evans 2007; Valbuena et al. 2009) or urban sprawl (Brown et al. 2008; Fontaine and Rounsevell 2009). The approaches applied are very similar to each other and to our approach. All rely on complexity science and combine typologies of individual land-user households and trajectories of change in the households/landholdings (in our case family farms) to represent the heterogeneity in social behaviours and the adaptive character of LU decision-making processes in the short and long term.

One main specificity of our work is addressing relationships and feedback between ecosystems dynamics and land management in ABM/LUCC simulation of landscape change.

Modelling cross-scale interactions and feedback between grassland ecosystems and their management at the landscape scale: a tricky challenge: The representation of interactions and feedback between ecosystems and their management in our ABM was not only supported by the view of the landscape/land-use system as a SES but also dictated by its contextual conditions and objectives. The account of the interrelationships between grasslands and their management in the grassland-dominated landscape studied was shown to be crucial for simulating reforestation processes and their impacts on landscape functions in a plausible way, which was the stakeholders main request.

To model the interactions and feedback between biophysical features, local grassland ecosystems and their management, from the parcel to the landscape level and from the short to the long term, we used the results of the integrated landscape assessment and also relied on conceptual and empirical models built in prior socio-ecological and technological research into sustainable development of Pyrenean agriculture. We spent a lot of time and effort in searching for the simplest representation and calibration of these interlinkages. But their complexity in mountain conditions led us to use a very fine basic time step (15 days) in the ABM/LUCC, which is—as far as we know—novel in ABM simulation of landscape change at a time scale of 2–3 decades. Indeed, simplifications are known to be a major stumbling block for the integrated simulation of human decision making and biophysical systems (Matthews 2006). Our simulation results show that oversimplification could render the ABM incapable of adequately describing the spatio-temporal patterns of reforestation in the local context, and consequently hamper the design of plausible scenarios of change in landscape functions. However, at the current stage of the development of the model, when one only of its three modules is available, it is still too early to fully assess the strengths and weaknesses of our modelling choices.

Conclusion

This study of landscape change was orientated by our strong commitment to the stakeholders of nature conservation and rural development in the Pyrenees National Park area, and our aim to help them '*navigate*' (cf. Berkes et al. 2003) the landscape/land-use system. As stressed by Fu et al. (2008), transdisciplinarity is an important stimulus for enhancing the bridging capability of research in support of the sustainability of multifunctional landscapes. This led us to invest a significant amount of work in integrated landscape assessment before building an ABM/LUCC to simulate of landscape change in our study area. European mountains are well-known to be 'complicated places' for landscape studies (Soliva et al. 2008). We developed a novel method combining knowledge from landscape ecology, land-change and agricultural sciences, and a coordinated set of field studies to elicit the cascade of short- to long-term interactions and feedback in the coupled human-natural system, from the parcel to the whole landscape, that locally shape landscape reforestation processes and patterns and modify landscape functions. Our results provide additional evidence of the special role of mountain agriculture in the creation and maintenance of rural landscapes of high ecological, social and economic values.

Like other recent studies in the literature, our study illustrates the advantages of approaches that rely on complexity sciences and hybrid mixes of methods to improve the representation of land-use decision-making processes and their interactions with the natural environment in ABM/LUCC simulation. Typologies of individual (household) behaviours and models of their trajectories of change appear as a general way of accounting for the social heterogeneity and adaptive character of human behaviours in the modelling of interactions and feedback in coupled human-natural systems.

Our study also provides evidence of the need to go beyond changes in LU and CC categories and to model interactions and feedback between the condition and management of ecosystems, the ABM/LUCC simulation being used to handle the multifunctionality of grassland-dominated landscapes. Results indicate that one way of meeting this special challenge is making available local typologies of grassland ecosystems and their short- and long-term management by farmers, from the parcel to the landscape scale, together with a conceptual model of their interrelationships. We therefore believe that agroecology and farming systems research can make

a crucial contribution to enhancing the capacity of landscape ecology to support the multifunctionality and sustainability of mountain and other grassland-dominated landscapes.

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