


Downscaling scenarios of future land use and land cover changes using a participatory approach: an application to mountain risk assessment in the Pyrenees (France)

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Abstract Better understanding the pathways through which future socioeconomic changes might influence land use and land cover changes (LULCCs) is a crucial step in accurately assessing the resilience of societies to mountain hazards. Participatory foresight involving local stakeholders may help building fine-scale LULCC scenarios that are consistent with the likely evolution of mountain communities. This paper develops a methodology that combines participatory approaches in downscaling socioeconomic scenarios with LULCC modelling to assess future changes in mountain hazards, applied to a case study located in the French Pyrenees. Four spatially explicit local scenarios are built each including a

narrative, two future land cover maps up to 2040 and 2100, and a set of quantified LULCC. Scenarios are then used to identify areas likely to encounter land cover changes (deforestation, reforestation, and encroachment) prone to affect gravitational hazards. In order to demonstrate their interest for decision-making, future land cover maps are used as input to a landslide hazard assessment model. Results highlight that reforestation will continue to be a major trend in all scenarios and confirm that the approach improves the accuracy of landslide hazard computations. This validates the interest of developing fine-scale LULCC models that account for the local knowledge of stakeholders.

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Keywords Land use and land cover changes · Modelling · Future · Narratives · Stakeholders

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Introduction

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European mountains have experienced substantial transformations in the last century and are expected to face major modifications over the next decades due to both climatic and socioeconomic changes. Climate change will affect snow cover, agricultural practices, and forest ecosystems (Olesen and Bindi 2002; Rousselot et al. 2012). These changes will lead to shifts in mountain vegetation that are likely to alter slope stability and to impact natural processes controlled by hydro-meteorological triggers (Katz and Brown 1992; Kohler et al. 2014; Borsdorf et al. 2015). Meanwhile, socioeconomic transformations will influence human activities, which will not only reshape mountain landscapes but also modify the exposure of societies to mountain hazards (e.g., floods, landslides, avalanches, mudflows, rock falls) (Fuchs et al. 2015b; Papathoma-Köhle et al. 2011). Thus, climatic and

socioeconomic changes will influence future land use and land cover changes (LULCCs), which in turn, will affect both the occurrence of natural hazards and the vulnerability of the built environment to hydro-meteorological risks.

Historically, the main land change trajectory in European mountains has been reforestation due to either de-intensification of agriculture or abandonment of agricultural (pastoral and arable) lands (Kozak et al. 2007; Fuchs et al. 2015a, 2015b; Houet et al. 2015). Most of European mountains and the Pyrenees in particular, where this study takes place, are subject to reforestation owing to the steady decline of population in the region (Galop et al. 2011). Most European spatially explicit scenario-based studies converge to the same result and expect reforestation to continue into the future (e.g., Verburg et al. 2010; Stürck et al. 2015a, 2015b; Vacquié et al. 2015; Price et al. 2015). Spontaneous reforestation has opposite effects on socioecological systems. On the one hand, reforestation may help to reduce gravitational risks by providing new natural protections (e.g., standing trees) and enhancing slope stability (Brang et al. 2001; Thomas and Pollen-Bankhead 2010; Genet et al. 2010; Forbes and Broadhead 2013; Kokutse et al. 2016; Moos et al. 2016). On the other hand, it may decrease the attractiveness of mountains to tourists as it modifies the emblematic character and esthetics of mountain areas (Gibon et al. 2010; Rey Benayas et al. 2007).

Better accounting for future LULCC is crucial to accurately assess the sustainability of mountain economies and the resilience of societies to mountain risks (Promper et al. 2014). Unfortunately, current practices fall short in this domain. In France, for instance, land management strategies accounting for risk exposure consider only known past hazards and current LULC. They fail to consider the potential feedbacks of future LULCC on the vulnerability of territories to natural hazards. However, considering multi-hazard assessments together with past, current, and future LULCC would contribute to identifying areas that are particularly likely to be threatened by future mountain hazards, and thereby, help design proactive adaptation strategies (IPCC 2012).

Any attempt to assess future LULCC requires characterizing future socioeconomic conditions since they are a significant driver of LULCC and serve as inputs to LULCC models. Because they represent a set of potential future states of the world, scenarios are particularly convenient to explore the uncertainties associated with future socioeconomic changes. Scenarios are coherent, internally consistent, and plausible descriptions of the pathways in which driving forces (e.g., technological change, energy costs, or climate policies) may influence future developments (Carter et al. 2001; van Vuuren et al. 2014). Depending on their design and development process, scenarios can be classified in many categories (e.g., deterministic versus probabilistic, forecasting versus backcasting, exploratory versus normative) (Carter et al.

2001; van Vuuren et al. 2014). Changes in driving forces may be simulated using numerical methods, such as Monte Carlo simulations (e.g., Graveline et al. 2012). However, such approaches tend to neglect extreme values that would result from breakdowns and structural changes in the economy (Graveline et al. 2014; Rinaudo et al. 2013). Participatory narrative methods involving local stakeholders allow avoiding this shortcoming while ensuring that scenarios are consistent with the local knowledge of stakeholders (Graveline et al. 2014; Malek and Boerboom 2015; Voinov and Bousquet 2010).

Many socioeconomic scenarios have been constructed at national and international scales (Bourgau et al. 2008; EEA 2007; Carter et al. 2001; Vert and Portet 2010; Vert et al. 2013; Pérez-Soba et al. 2015; Verkerk et al. 2016). Downscaling these scenarios so that they provide useful inputs to local LULCC models requires analyzing local economic drivers (e.g., employment) and social dynamics (e.g., attractiveness of mountain areas). Some studies have undertaken this exercise with the IPCC special report emission scenarios for Europe (e.g., Rounsevell et al. 2006; EEA 2007; Verburg et al. 2010; Verburg et al. 2013). Based on interpretations of the narratives, quantitative data are derived (from other sectorial models or projections) to define model parameters (e.g., land demand, suitability of areas for specific LULCC transitions—see Stürck et al. 2015b for instance) that simulate quantitative scenarios with a spatial resolution varying from 1 km² (e.g., Verburg et al. 2010) to few hundred meters (e.g., Price et al. 2015). Nevertheless, their resolution is not appropriate for gravitational hazards that require finer scales of analysis to account for hydro-meteorological triggers and the landscape configuration influencing biogeochemical fluxes. High-resolution LULCC simulations based on scenarios (e.g., 10 × 10 m pixels or vector-based objects—see for instance Houet et al. 2010, 2014, 2015) are particularly valuable in assessing possible local environmental impacts of future LULCC but show limitations when distant futures or normative visions are considered, for at least two reasons.

First, classical LULCC models struggle to translate narratives into quantitative input data (van Vliet et al. 2010). This is accentuated by the time horizon considered since, the longer it is, the more global drivers have to be accounted for in a telecoupled world (Liu et al. 2013). No conventional approach exists, and multiple methods can be used (Mallampalli et al. 2016). Some authors use statistical or probabilistic tools to assess the relative and/or respective weights of scenarios' variables (Kok 2009; van Vliet et al. 2010) and then use these weights to parameterize the models. Others use intermediate sectorial models (Stürck et al. 2015b) or expert knowledge to define future land demands (Vacquié et al. 2015).

Second, models using past land cover maps for initialization or calibration (Mas et al. 2014; Houet et al. 2016a) assume stationarity of the system (Kolb et al. 2013). No change

of the LULCC drivers may occur in the future, and the simulated outcomes inevitably rely on trend scenarios (Houet 2015). Thus, they are not appropriate to represent non-stationary LULCC affected by regime shifts (Müller et al. 2014). Better suited fine-scale LULCC models should meet three criteria.

1. They would have to be able to mimic observed LULCC in terms of dynamics (i.e., rates, locations, and processes) and to account for interactions between LULCC, which remains challenging (Verburg et al. 2016). For example, mountain land cover trends such as encroachment or reforestation may lead to land use changes (abandonment) of summer agropastoral lands. Inversely, land use changes such as the conversion of forests into new silvicultural lands may induce new land cover dynamics. In most LULCC models, land uses and land covers are grouped together and not modelled separately to integrate such interactions.
2. They would also have to be able to take trends and disruptions in scenario storylines into account (i.e., regime shifts and new types of LULCC). Therefore, they have to exhibit both path-dependent (Brown et al. 2005) and non-path-dependent properties (Houet et al. 2016a).
3. They should provide outcomes that are consistent (in terms of temporal and spatial resolutions) with the knowledge of stakeholders and the requirements of hazard assessment models (e.g., resolution or land cover classes).

Although these criteria place more constraints on the modelling, approaches coupling participation and models such as the storyline and simulation (SAS) framework, which consists of elaborating qualitative narratives that are then simulated using adapted LULCC models (Alcamo 2008), can help address this shortcoming.

This paper investigates the contribution of coupling participatory approaches in downscaling socioeconomic prospective scenarios with spatially explicit LULCC modelling to assess future changes in landslide hazards in the French Pyrenees. “**Material and methods**” section details the case study and the methodology developed. “**Results**” section presents the narratives produced and validated by stakeholders and compares the LULCC outcomes of the FOREcasting SCENARIOS for Mountains (FORESCEM) model. Future possible landscape changes (reforestation and deforestation) are assessed in a spatially explicit manner and used as inputs to the Assessment of Landslides Induced by Climatic Events (ALICE) model to evaluate their potential impacts on landslides. In the “**Discussion**” section, the method is discussed. The “**Conclusion**” section concludes on the interest of the participatory approach and the LULCC model to produce fine-scale spatially explicit scenarios useful to risk assessment.

Material and methods

Study site and observed trajectories

The study site is located in the French Pyrenees (centered on 0° 06' 50" W–42° 53' 27" N) and covers about 70 km² in the municipal area of Cauterets. The elevation ranges from 800 to 2700 m a.s.l. (Fig. 1a). Land use and land cover maps are derived from multisource GIS data (National Forest Inventory, landscape maps of the Pyrenees National Park) and historical maps based on photo-interpretations of aerial photographs.

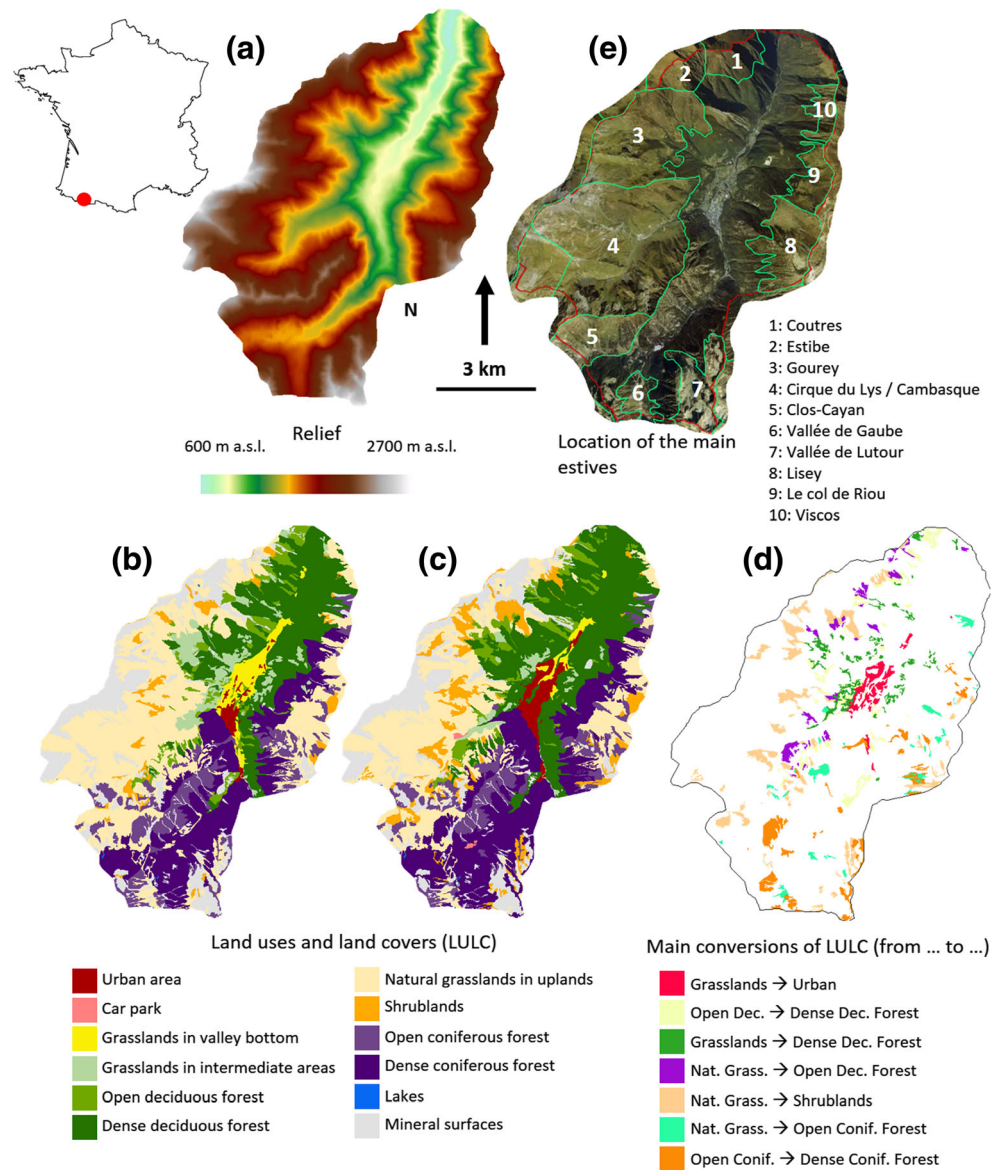
In 2010, the landscape is composed of grassland and shrubs in the uplands, urban, and cultivated areas in the valley bottom, forests, and mineral surfaces on the steepest slopes, and a few water bodies (Fig. 1c). It has experienced strong LULCC since the late 1950s (Fig. 1b). Urban areas have increased to the detriment of cultivation. The areas covered by deciduous and mixed coniferous and deciduous forests have largely increased while the extent of open forests has slightly declined. The analysis of gains and losses of land covers shows clear encroachment and reforestation trajectories. Natural grasslands of the uplands have significantly decreased and been converted into shrublands and open forests, while some shrublands have been converted into open forests and large areas of open forests turned into dense forests (Fig. 1d).

Over the last 60 years, socioeconomic development has been based on tourism activities with historic hydrothermal spas and a newly developed ski resort in the late 1970s. Moreover, the municipality has been part of the Pyrenees National Park since its creation in the late 1960s. These socioeconomic drivers favored urban development in the bottom part of the valley. Unlike most Pyrenean valleys, Cauterets has kept a stable population since the 1970s with about 1100 permanent inhabitants, although the population of farmers and loggers has significantly decreased (French Institute of Statistics). Pastoral activity is still important in summer, welcoming herds from the outer valleys to the administratively defined uplands called “estives” (Fig. 1e). The size of sheep herds has decreased slightly since the 1980s while cow and horse herds have remained stable (French General Agricultural Census). Land use practices (e.g., the presence of permanent shepherds) have changed, inducing a decrease in pastoral pressure. Some of the estives, such as the Viscos and Col de Riou areas (Fig. 1e), are nearly abandoned nowadays. Forests are underutilized because of the low profitability of forestry. Finally, Cauterets is of particular interest because it is subject to multiple natural hazards. A major rotational landslide occurred in 2006 as well as two centennial floods in October 2012 and June 2013.

Methodological approach

The overall methodological approach combines participatory narrative scenarios with LULCC models in order to (i)

Fig. 1 Presentation of the study site: **a** relief, land uses, and land covers in **b** 1959, **c** 2010, and **d** their changes, and **e** the main administrative estives



produce future land cover maps, (ii) identify areas likely to experience LULCC in the future, and (ii) assess the subsequent evolution of landslide hazard in Caunterets. It consists in co-constructing, with stakeholders, fine-scale socioeconomic scenarios, while developing a spatially explicit local LULCC model. Narrative scenarios are built to provide relevant inputs to the LULCC model while the model itself is developed to represent and quantify the likely LULCC identified in the narrative scenarios. This fine-scale spatially explicit approach (Houet et al. 2010; Houet et al. 2015; Houet et al. 2016b) allows identifying future LULCC likely to influence gravitational hazards.

Two foresight horizons (2040 and 2100) are considered. The former allows radical but realistic anthropogenic changes to be imagined while formulating relevant recommendations to decision-making timeframes. It is neither too close

(pursuing trends only) nor too distant (preventing stakeholders from projecting so far into the future) in time. The latter captures the impacts of climate changes, which are expected to increase more sharply after 2050 (IPCC 2014). In particular, peak oil, which is likely to have an impact on energy costs, and therefore, on the profitability of logging activities in forested areas, is assumed to occur in 2040 (Rozenberg et al. 2010).

Downscaling scenarios: combining literature, participatory workshops, and LULCC models

The methodology for downscaling scenarios comprises six sequential steps: (1) pre-constructing national context scenarios, (2) downscaling national context scenarios to local scale, (3) story-telling of the narrative scenarios at local scale, (4)

validating narratives and locating possible future land use changes, (5) simulating LULCC for each scenario, and (6) refining the narratives with quantitative and spatially explicit simulated outcomes.

- Step 1: Pre-constructing national context scenarios

The first step consisted of pre-constructing a set of national context scenarios describing the possible evolution of the social, economic, environmental, demographic, and political conditions driving land use changes in mountain regions up to 2040. They formed the overall context that drew the geographical and socioeconomic borders within which each of the local scale scenarios then had to fit.

A set of national and global driving forces and strong trends likely to influence future land uses in French mountain areas were first identified and characterized based on a literature review of existing prospective studies carried out at European and national levels (EEA 2007; Bourgau et al. 2008; Vert and Portet 2010; Vert et al. 2013) (Table 1). Driving forces are variables that are likely to vary across scenarios in the future, whether they stem from exogenous (e.g., volatility of agricultural prices, climate policies) or endogenous forces (e.g., urbanization, abandonment of farmland). Strong trends are variables whose evolution is considered as almost certain and that are occurring over all scenarios. They encompass global population growth, rising demand for agricultural products for food and feed uses and the impacts of climate change on mountain snow cover. Strong trends are used as contextual parameters to determine a set of pressures on the system. For instance, snow cover is expected to decrease by a factor of 2 to 5 from 2001 to 2030, compared to the reference period 1961–2000 (Rousselot et al. 2012; source: <http://www.cnrm.meteo.fr/scampe/>). As a result, the development of the ski resort is likely to be limited in absence of technological change.

As highlighted by Hérivaux (2015) and Petit and El Hadad-Gauthier (2014), most prospective studies reflect a broad consensus on the range of likely futures of European societies. A cross analysis of existing foresight exercises in Europe and France allowed identifying four broad families of scenarios conventionally considered: globalization, regionalization, environmental preservation, and sustainable food production. The national context scenarios were designed in line with these orientations and their underlying driving forces. For instance, the “lettuce surprise U” scenario from EEA (2007) was used to define the policy and governance drivers such as *decentralization of public policies* in national context scenario 2 (Table 1). The approach was complemented by a series of face-to-face interviews with five French experts in the fields of agriculture, forestry, and tourism in order to specify the likely evolution of some driving forces (e.g., the impact of technological change on ski resorts, the economic viability

of forestry in the Pyrenees), given the peculiarities of mountain areas. Each scenario was then built as a consistent combination of strong trends and a set of key assumptions regarding each driving force. Such an approach relying on existing prospective studies and expert interviews to characterize driving forces and strong trends at national level is in line with methodologies used in previous research (Rinaudo et al. 2013; Graveline et al. 2014). At the end of step 1, four national context scenarios were constructed up to 2040.

- Step 2: Downscaling national context scenarios to local scale

The second step consisted of organizing a first workshop in order to debate and downscale the pre-constructed national context scenarios with local stakeholders. A 1-day workshop took place in Cauterets in November 2014 and gathered ten participants, including local policy-makers, state representatives, land managers, and economic decision makers.

The workshop started with a retrospective analysis of the past evolution of the municipality based on historical LULCC maps from 1959 and 2010 (Fig. 1). Past trends and dynamics in Cauterets regarding land cover changes, demography, tourism, agro-pastoral activities, and forestry were presented and enriched with accurate explanations from local participants on both exogenous and endogenous drivers of change. This established a diagnosis of the situation of the municipality in 2010. The national context scenarios from 2010 to 2040 were then presented and debated. Participants were asked to react to the pre-constructed scenarios, complete the list of assumptions regarding the evolution of driving forces and re-construct local versions of the scenarios up to 2040 and 2100 as a combination of these new assumptions. For instance, the national context scenario 2 that depicts a quest for energy self-sufficiency was translated at local scale into the *intensification of forestry production* (Table 1).

The chain of events likely to occur from 2040 to 2100 was left open to participants, whose imagination was only constrained by two conditions common to all scenarios. First, the logical pathways between 2040 and 2100 had to match the trends described in each scenario from 2010 to 2040. This ensured that four local scale scenarios were built, each composed of two images (2040 and 2100), with two logical pathways (2010–2040 and 2040–2100). Second, the climate and energy contexts were predetermined, based respectively on the snow and temperature projections of Météo-France and the outputs of the IMACLIM-R model of CIRED describing possible changes in global energy prices through the twenty-first century (Rozenberg et al. 2010). At the end of step 2, we had the material to build four local translations of the national context scenarios that were consistent with global scenarios while accounting for local specificities.

Table 1 Main characteristics of the four national and local socioeconomic scenarios up to 2040

National context scenarios		Scenario 1	Scenario 2	Scenario 3	Scenario 4
Main driving forces	Economy	Globalization, strong reliance on fossil energies, high volatility of agricultural prices, increasing international competition	Continuous degradation of public finances, economic downturn, decreasing trade, development of renewable energies	Increasing international trade, high energy prices, high volatility of agricultural prices, development of renewable energies	Decreasing international trade, increasing price of fossil energies, development of renewable energies
	Policy and governance	Limited regulatory intervention of public authorities, lack of ambition in climate policies, gradual disappearance of European agricultural policies	Decentralization of public policies, development of regional agricultural policies, reinforcement of health policies	Economic development focused on pre-existing comparative advantages of territories	Greening of agricultural policies, ambitious climate policies (carbon tax), financial and organizational support to vulnerable areas
Lifestyles and behaviors	Demand trends	Decreasing solidarity, withdrawal of individuals from the management of public affairs, mass tourism	Growing health awareness, increasing demand for organic products, quest for food and energy self-sufficiency	Growing environmental awareness, increasing demand for country products and local food systems	Growing environmental awareness, increasing demand for organic products, decline of meat consumption, quest for social equity and well-being
	Environmental awareness				
Health requirements					
Sources of national context scenarios					
		Scenarios "Great Escape - Europe of Contrast" and "Clustered Networks - Europe of Structure"	Scenario "Lettuce Surprise U - Europe of Innovation"	Scenario "Big Crisis - Europe of Cohesion"	Scenario "Evolved Society - Europe of Harmony"
		Scenario "Health-Agriculture without Strong Energy Constraints"	Scenarios "Territorialization and Energy Conservancy in the face of Crisis"	Scenario "Ecological Agriculture and Energy Management"	Scenarios "Dual Agriculture and Energy Realism" and "Ecological Agriculture and Management"
		Scenarios "Liberalization and Focus on Production" and "Metropolization and consumerism"	Scenarios "A Mosaic of Areas and Stakeholders" and "Metropolization and consumerism"	Scenario "A Mosaic of Areas and Stakeholders"	Scenario "Energy and Environmental Transition"
		Scenario "All for Food" and "Forest Brownfields"	Scenarios "All for Energy" and "Competition between Food and Energy"	Scenario "All for Sustainable Development"	Scenario "All for Sustainable Development"
Local-scale scenarios	Resulting additional driving forces	Abandonment of the territory	Sheep and woods	A renowned tourism resort	Green town
	Territory	Decreasing interest in land-use planning policies, abandonment of natural areas	Contrasted landscapes, sanctuarization of natural areas, decreasing permanent population	Spatial planning fostering tourism, conservation of natural areas for their economic benefits, increasing population, urban densification	Conservation of natural areas, increasing rural population, urban densification
Tourism	Technological change	Declining tourism, loss of attractiveness of small landlocked ski resorts	Declining tourism, loss of attractiveness of mountain areas	High value-added tourism, increasing mountain attractiveness, use of snowmaking machines, diversification of summer activities	Decline of tourist frequentation, development of a sustainable tourism
	Mountain attractiveness				
Agriculture and forest	Agriculture	Continuing decline of mountain farming, abandonment of pastoral units, no development of the forest industry	Intensification of forestry production thanks to technological innovations, active agricultural development	Downward trend of agropastoralism, commodity chain structuring, maintenance of grazing areas for their bucolic landscape	Increasing use of mountain pastures, development of local supply chains, decrease in livestock production, development of the forest industry
	Forestry				

- Step 3: Story-telling of the narrative scenarios at local scale

The third step consisted in rewriting the scenarios that emerged during the workshop in a narrative way. Particular attention was paid to clarifying the logical pathways linking the different elements identified as relevant by stakeholders for the 2010–2040 and 2040–2100 periods. At the end of step 3, four fine-scale narratives were built and described. These scenarios were sent to stakeholders 2 weeks before the second workshop organized in step 4.

- Step 4: Validating narratives and locating possible future land use changes

Step 4 aimed to validate and provide a spatial characterization of the local scenarios in order to produce relevant data to be integrated in the LULCC model. A second 1-day workshop took place in January 2015 and involved the same stakeholders as those that attended the first workshop. Participants were asked to debate the narrative scenarios' internal consistency and estimate their spatial impacts in terms of land use changes. Land cover maps were used to help participants to pre-identify the likely zones of future land use changes and the time horizon for each. Such a participatory zoning technique based on both local stakeholders' verbal representations and scientists' comprehensive knowledge of the processes at play has been proved efficient as support to land management policies (Caron 1997; Caron and Cheylan 2005). Special attention was paid to future pastoral and forestry land uses as they have strong impacts on future land cover changes. Two types of maps were thus produced: (i) maps featuring the broad areas in which mountain estives might be abandoned, and (ii) maps featuring the broad areas in which forestry might occur. At the end of step 4, each scenario contained a revised narrative version of the local scale scenarios and two maps depicting the areas in which mountain land uses were likely to change from 2010 to 2040 and 2100 but without quantifying future LULCC.

- Step 5: Simulating LULCC for each scenario

Step 5 aimed to model the LULCC identified by stakeholders in order to ensure that they were consistent with the vegetation dynamics at play in Cauterets. The FORESCEM model used for mountain LULCC simulations was developed using the Dinamica-Ego platform (Soares-Filho and Coutinho Cerqueira 2002). It simulates LULCC at an annual time step and accounts for neighborhood interactions and feedbacks between some vegetation classes. To begin, it uses the two historical land use maps and land cover maps (10 × 10 m resolution) from which it computes transition probabilities between land covers and land uses. A weight-of-evidence

method is used to compute suitability maps to allocate future LULCC based on various spatially explicit drivers (geology, aspect, elevation, slope, and distance to infrastructures, land uses, and land covers). For each land use type (forestry, urbanization, agropastoral land use and abandonment considered as an absence of land use), land cover changes are defined either by transition probabilities or conversion rules aimed at reproducing vegetation dynamics (minimum duration, specific transitions from one land cover to another). Land use changes and conversion rules are driven by the narratives. Participatory zoning from step 4 is translated into GIS data to parameterize the land use changes in the model (details in supplementary material 1). For instance, pastoral land use changes (estive abandonment) define which estives are abandoned and when. When no abandonment is expected, land cover changes in the uplands are simulated according to trends estimated by the model. This may lead to land cover changes such as encroachment and reforestation which, in turn, may influence future land use changes (conversion from abandonment to forestry). Forestry land use changes are defined using an intermediate model (SYLVACCESS, Dupire et al. 2015, 2016) that delineates potential areas that can be logged according to logging practices. More precisely, it simulates all possible cableways used to remove cut trees, located within the zones pre-identified during step 4. When scenarios expect to limit or stop a specific land use change, the transition probability is set to 0 by the modeler. The land demand is not predefined but computed from all simulated land cover and land use changes based on historical changes. Finally, the biophysical impacts of global warming on reforestation are not taken into account because its influence on patterns and dynamics of mountain forests remains highly uncertain (Theurillat and Guisan 2001) and even more when considering land use changes and anthropogenic disturbances (Galop et al. 2011; Batllori et al. 2010).

- Step 6: Refining the narratives with quantitative and spatially explicit simulated outcomes

Step 6 used the results of steps 4 and 5 to fine-tune and improve each narrative with quantitative outcomes regarding the location and the amount of simulated LULCC. At the end of step 6, four spatially explicit narratives had been constructed. Each was made of a scenario narrative, two fine-scale maps of future land cover up to 2040 and 2100 and a set of quantitative assessments of the associated amounts of LULCC.

Assessing the future uncertainty of LULCC

Areas at risk regarding gravitational hazards are identified based on the future uncertainty of LULCC assessed through a comparison of LULCC across scenarios. As described in

Houet et al. (2015), the future uncertainty of land cover changes is defined as a multi-scenario ensemble assessment and computed using occurrences of specific land cover changes observed in all scenarios, similarly to Verburg et al. (2013). It delineates the largest spatial extent of future LULCC according to the envelope of possible futures. We assume that, in simulated scenarios, the more often a LULCC occurs at the same location, the more plausible and less uncertain it is (Wiek et al. 2013). In this paper, we focus on two vegetation dynamics that are most influential for gravitational hazards: reforestation and deforestation.

Reforestation is analyzed throughout the comparison of land cover maps for 2010 and 2100 to detect all transitions from any land cover to either dense forest or encroachment classes. Results from all scenarios are then combined into an occurrence map of reforestation and encroachment, transformed into relative probability (see Houet et al. 2015 for details). For deforestation, logging practices influence vegetation dynamics (growth–logging–regrowth over decades) and require a suitable procedure. Changes are extracted every decade from 2010 to 2100, and their occurrences are summed up in one map for each scenario, and then for all scenarios.

Assessing landslide hazard over time using LULCC

In order to demonstrate the interest of simulating future LULCC for decision makers and spatial planning policies, the simulated LULCC are used to assess changes in landslide activities in Causerets up to 2100. Only few studies assess the contribution of land use changes to changing risks (Promper et al. 2015), with a focus on the effect of land cover on slope stability (Reichenbach et al. 2014). These studies are based on statistical analyses that combine several parameters influencing landslide susceptibility. Here, landslide susceptibility is assessed using a spatially physical model.

LULCC are used as inputs to the Assessment of Landslides Induced by Climatic Events (ALICE) model (Baillis et al. 2012). ALICE is a slope stability assessment tool that combines (i) a mechanical stability model accounting for some geotechnical parameters of the soil layers, (ii) a hydrogeological model that simulates the main water cycle mechanisms, and (iii) a vegetation module that has recently been added in order to account for the effects of vegetation shifts on mechanical soil properties (i.e., cohesion and overload). This spatialized mechanical model produces landslide hazard maps at various scales from the single slope to hundreds of square kilometers. Together, the mechanical stability model and the hydrogeological model allow integrating climate change scenarios. They are complemented by the vegetation module that accounts for the effects of LULCC on slope failures. In the module, vegetation shifts change the mechanical properties of soils, that in turn, affect the probability of reaching failure (Thomas and Pollen-Bankhead 2010; Genet

et al. 2010; Kokutse et al. 2016). More precisely, the presence or absence of forest may have a counter-intuitive impact on slope stability as it can reinforce (i) the resistance to shear with an additional apparent cohesion of the soil due to roots or (ii) the instability due to the biomass additional weight.

Landslide hazards are assessed for the LULCC scenario that exhibits the least reforestation. The land cover maps for 2010 and 2100 are converted into additional cohesion and weights parameters and used as inputs to the ALICE model. In this application, rotational landslides with a length of 25 m, and a depth between 1 and 3 m are considered. The model simulates landslide hazards for 2010 and 2100 and assesses the evolution of slope stability between 2010 and 2100.

Results

Simulated land cover maps were produced annually for each scenario and are illustrated for the 2040 and 2100 states in supplementary material 2. However, since these maps do not highlight the dynamics of change between two states, the evolution of the surface covered by each main land cover (in ha) is presented at a 10-year temporal resolution in Fig. 2.

Spatially explicit narratives

Scenario 1: abandonment of the territory

Market liberalization intensifies competition throughout the world. In Europe, the Common Agricultural Policy (CAP) disappears progressively from 2020 onwards. Increasing imports of low-cost agricultural products fosters the decline of mountain farming. In Causerets, pastoral units that initially persisted thanks to transhumant herds coming from outer regions are eventually abandoned at a pace that depends on their accessibility, fodder potential and proximity to the valley. In 2040, farming is only maintained in a few highly productive grazing areas. In consequence, natural grasslands decrease in favor of dense forests that expand where both climate and soils are favorable to their expansion. By 2100, the effect of pastoral land abandonment is perceptible with an increase in the annual loss of natural grasslands in the uplands (5.6 ha/year) compared to the 2010–2040 period. The landscape has changed markedly with dense forests covering 33% of the territory in 1951, 41% in 2010, and 50% in 2100.

Scenario 2: sheep and woods

In Europe, greater power is transferred to the regions, whose autonomy and influence increase. This regional downturn leads to decreasing trade which allows preserving French agriculture from global competition. In the Pyrenees Mountains, the CAP is reoriented so as to support local agriculture and

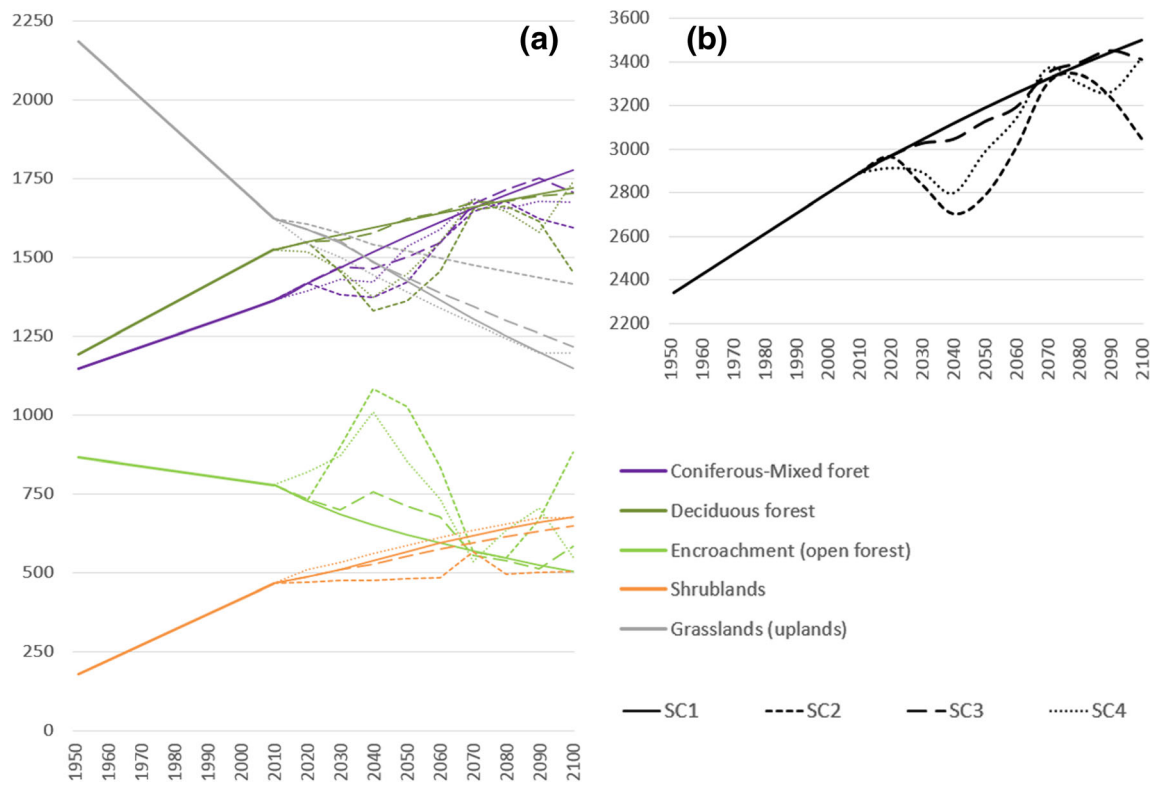


Fig. 2 Future land use and land cover changes (in ha) for **a** each main land cover and **b** the dense forests (coniferous + deciduous/mixed forests) for the four scenarios

renewable energy production. In Caunterets, uplands are grazed again and shrublands do not expand. Former agro-pastoral trails are remodeled for wood production and estives are reopened for agro-pastoralism on mountainsides. In parallel, the lack of investments in modernizing the equipment of the ski resort results in a decline in winter tourism. In 2040, Caunterets has lost its attractiveness for tourists. Compared to 2010, dense forests have lost 175 ha. By 2100, most of permanent inhabitants are gone. Logging activities induce significant landscape changes: mountainsides are regularly maintained and some previously abandoned pasture that evolved to shrublands and open forests are now reforested and exploited.

Scenario 3: a renowned tourism resort

With increasing globalization, the most vulnerable mountain areas are abandoned, while territories with higher economic potential are preserved for the purpose of their economic valorization. Due to its spectacular landscapes, Caunterets benefits from public support for the development of a high value-added tourism. The use of snowmaking machines allows winter frequentation to remain stable while summer frequentation increases with the diversification of outdoor activities. The municipality invests in logistical and financial support to maintain natural areas. However, forestry remains costly and

the downward trend of agro-pastoralism continues. Only grazing areas that are located close to tourist areas are artificially maintained in order to sustain a bucolic pastoral landscape (e.g., sheepfolds, flowery meadows). Some intermediate areas are reopened in order to prevent landscapes from closing. Elsewhere, landscape dynamics follow similar trends to scenario 1. In 2040, large areas of natural grassland have turned into shrublands or open/dense forests. Dense forest areas increase by 5.2 ha/year from 2040 to 2100. By 2100, 49% of the study area is covered by dense forests, which is perceived as an attractive factor since Caunterets has become a socially selective tourist destination.

Scenario 4: green town

Increasing environmental awareness modifies consumption habits and lifestyles. Prices of fossil fuels and imports increase while investments in renewable energy, local agriculture, and green technologies are boosted in Europe. In Caunterets, the wider use of telecommunications and teleworking reduces rural exodus of city dwellers. The use of grazing areas continues but the decrease in livestock in the valley reduces grazing pressure in the mountains. This results in shrub invasion and encroachment of the least productive estives. Meanwhile, wood production increases. By 2040, Caunterets is a multifunctional area providing a pleasant living environment and good-

quality services to its population. Compared to 2010, landscapes have significantly changed: they lost 11% of grasslands and 3.3% of dense forests. In the following decades, tourism decreases progressively with rising travel costs and the shrinking of the ski area. A small agro-pastoral activity remains but forest expands significantly across the whole area with reforestation trends comparable to what they were before 2010. In 2100, 49% of the study area is covered by dense forest, similarly to scenarios 1 and 3.

Comparison of land cover changes and identification of areas at stake

As a first result, a slower pace of reforestation and encroachment is observed in all scenarios compared to the 1951–2010 period. This difference in transitional rates may be explained by the productivity gains and subsequent massive rural exodus that French mountain agriculture experienced during the second half of the twentieth century which is out of proportion with any future change that might occur. Reforestation and encroachment occurring up to the present day have concerned mountainsides.

From 2010 to 2100, net changes in dense forests do not significantly differ from one scenario to another, except for scenario 2 (Fig. 2b). Although scenarios 1, 3, and 4 exhibit strong differences in terms of land uses and social values, they show similar trends in land cover changes. Scenario 2, which expects breakdowns regarding land use changes, limits the major trend of reforestation observed in the Pyrenees although it does not stop it totally. Shrublands in the uplands show similar results (Fig. 2a): scenarios 1, 3, and 4 exhibit identical trends even though pastoral land uses are maintained in some estives for scenarios 3 and 4.

Conversely, landscape changes exhibit subtle differences in terms of location (Fig. 3). The map of future uncertainty on deforestation provides an overview of the probability of areas becoming deforested in the future, according to future land management and land use changes described in the scenarios (Fig. 3a). As scenario 1 does not expect any deforestation, there is no pixel with a probability of 1. Forests having the highest probability of being deforested are located near builtup areas, which is of interest to gravitational hazards. As for reforestation and encroachment, the map of their future uncertainty (Fig. 3b) provides interesting insights into the areas at stake, since (i) most areas with a high probability of change are located in remote places and are encroached in 2010, and (ii) areas with a low probability (i.e., that may be forested in the distant future) are not necessarily currently shrublands. The estives of Cirques du Lys, Lisey, and Gourey appear to be highly susceptible to encroachment and reforestation although the first two are easily accessible (Fig. 3a). Finally, considering all scenarios, Fig. 3c identifies

the largest envelope and the relative probability of future forest cover changes, likely to influence gravitational hazards.

Landslide hazard assessment

Because it exhibits the most deforestation, scenario 2 was selected to assess the influence of the evolution of the vegetation cover on landslide activities up to 2100. Results that are presented in Fig. 4 focus on an area of Cauterets that has been particularly at risk in the past. They show an increase in the probability of landslide occurrence in the absence of forests and an increase in slope stability in the presence of forests (Fig. 4a). From 2010 to 2100, results indicate that reforestation will tend to increase the stability of the slopes, whereas the stability will be dropping in deforested areas (Fig. 4b). This demonstrates the significant influence of land covers in stability computations. Such results point out that for spatialized analysis of landslide hazard, considering spatially explicit LULCC undoubtedly improves the accuracy of the landslide hazard computations.

Discussion

The approach developed to construct the narratives at local scale relied on pre-constructed national scenarios that described the overall socioeconomic context with which each narrative had to be consistent. This guided stakeholders towards likely futures that were in line with the scenarios used to feed public policy developments at the national and European levels. Since workshop participants had never participated in a foresight exercise before, the national context scenarios also played a key role in helping them project into the future. In return, they limited the range of possible futures that could be considered during the workshops. However, the timeframe allotted to the construction of the scenarios within our research project (only 4 months) did not allow the past evolution of each of the driving forces to be thoroughly investigated and then contrasted hypotheses of their future evolution to be constructed, as recommended by Godet and Roubelat (1996). Given this constraint, our approach constitutes a time-efficient alternative for co-constructing useful prospective scenarios with local stakeholders.

Involving local stakeholders in the development of scenarios allowed exploring breakdowns and unexpected changes. It benefited to both scientists, who confronted their theoretical knowledge with ground realities, and local decision makers, whose participation in a formalized foresight exercise helped intellectualize and anticipate changes in a longer time horizon than the short-term constraints they are used to handling, as pinpointed by Rinaudo et al. (2013) and van Vliet et al. (2010). The approach also confirmed that participation enabled scientifically grounding the local knowledge of

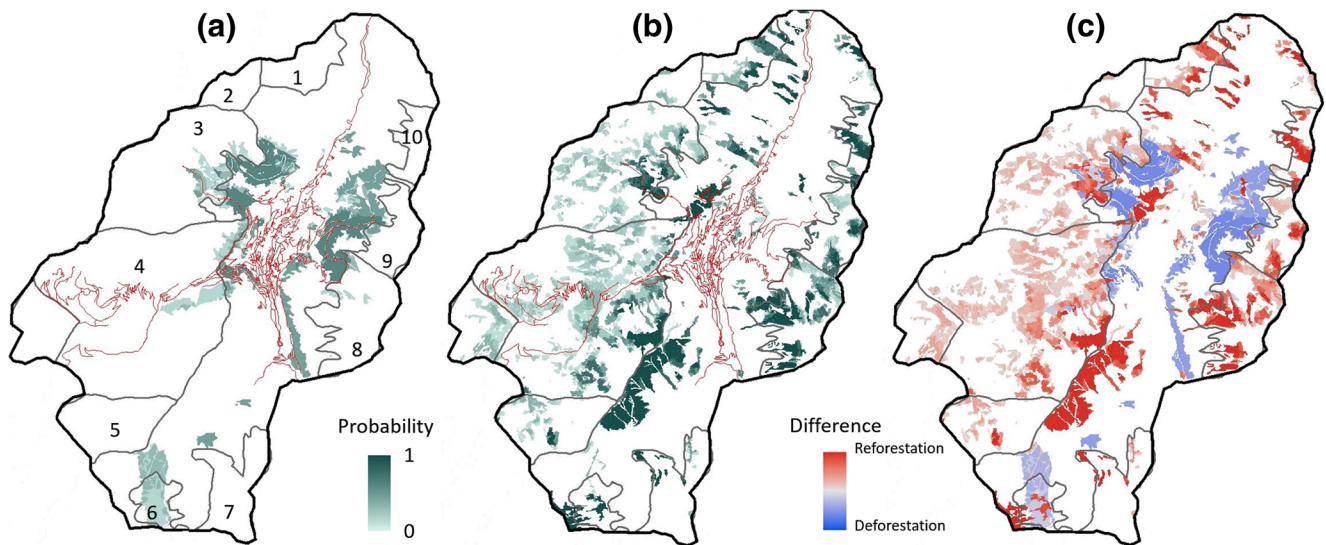


Fig. 3 Future uncertainty maps—probability ranges from 0 to 1—for a the deforestation and b the reforestation and encroachment. c Difference map between a and b underlying that few areas are concerned by both deforestation and reforestation dynamics in the future. Red lines illustrate

roads, and gray lines show boundaries of estives numbered in a (1 Coutres, 2 Estibe, 3 Gourey, 4 Cirque du Lys, 5 Clos-Cayan, 6 Vallée de Gaube, 7 Vallée de Lutour, 8 Lisey, 9 Le col de Riou, 10 Viscos) (color figure online)

participants while building a shared expertise among stakeholders. It brought together stakeholders with various opinions that now share a common vision of the future of their territory. In the future, this common understanding is likely to

facilitate the establishment of effective risk management strategies by providing sound foundations for the decision process.

The approach contributed to the design of the LULCC model architecture by decoupling land use changes driven

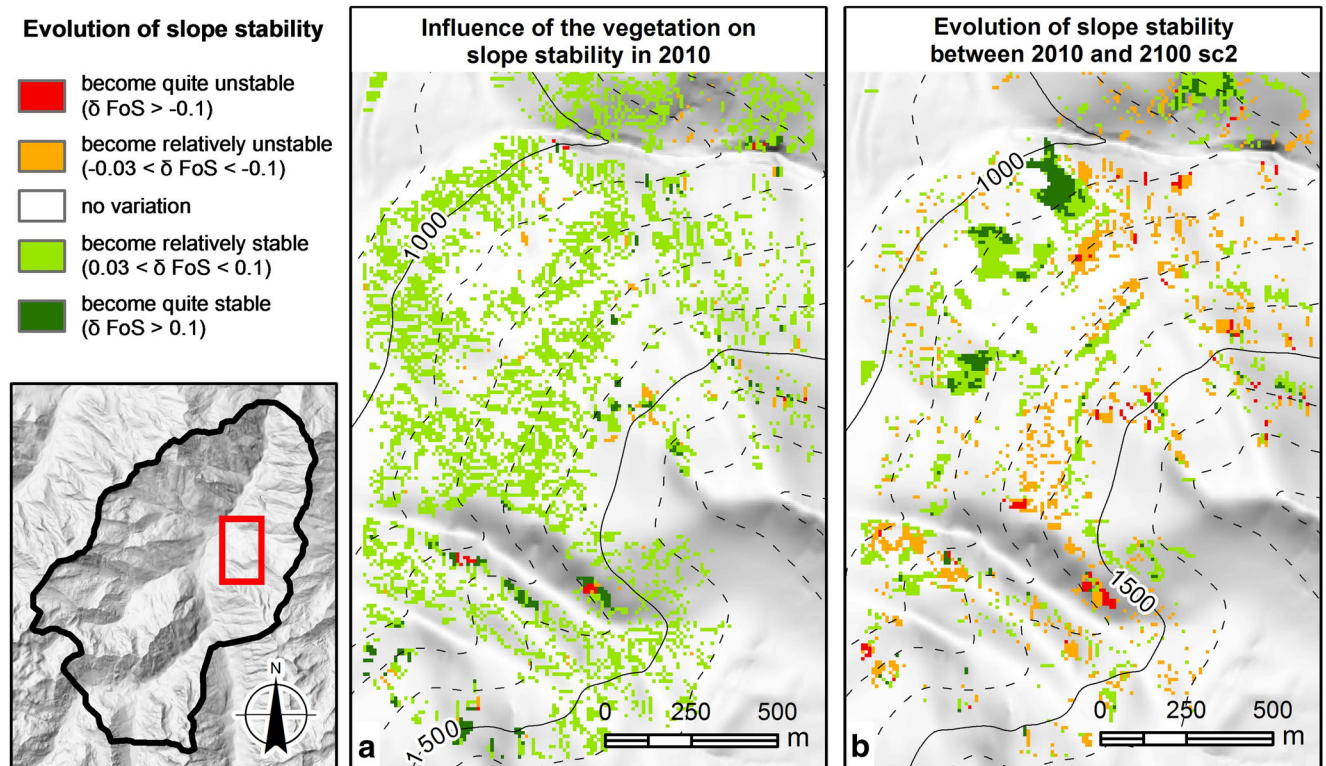


Fig. 4 Modelling the influence of vegetation on the factor of safety (FoS) of shallow rotational landslides susceptibility. a Differences between the FoS probabilities without and with the vegetation in 2010 illustrating the positive influence of the vegetation to limit landslides. b Differences

between the FoS probabilities using the land cover maps in 2010 and in 2100 according to Sc2, illustrating that land use and land cover changes may have subtle local impact on landslides

by the narratives, from land cover changes driven by vegetation dynamics observed between 1959 and 2010 and further simulated in the model. Thus, the parameters of the model were fine-tuned in light of up-to-date local information, thereby ensuring its calibration. In turn, the types of data required by the model fed the zoning technique used to spatialize land use changes associated with each scenario. Stakeholders were able to characterize the occurrence of the land use changes resulting from the scenarios in time and space, given local peculiarities. Conventional LULCC models would not have been able to define such changes by themselves when calibrated using historical changes. More generally, the consultation of stakeholders provided a solution to overcome the lack of accurate data at local scale, thus avoiding the “black-box” effect that explains the reluctance of some decision-makers to assimilate the results of models whose operation they do not fully understand. In regard to modelling issues, as highlighted by Verburg et al. (2016), the FORESCEM model tackles the challenge of accounting for iterative feedbacks between land cover changes and land use changes at a fine scale. Thus, a particular attention has been paid concomitantly to the impacts of pastoral (abandonment of summer pastures) and forestry (emergence of logging) land use changes on land cover changes and the impacts of some trends in land cover changes (natural reforestation) on land use changes. The ability of LULCC models to represent feedbacks is crucial for simulating co-constructed scenarios through a dynamic process.

Results of the LULCC model show a common trend across all scenarios. Natural grasslands exhibit a major declining trend in the uplands, in favor of encroachment and reforestation. Future LULCC, taken independently, may pursue the forest transition theory of Mather (1992) up to the beginning of the twenty-second century at least. Even if these trends are similar across all scenarios between 2010 and 2100, they exhibit subtle differences in terms of quantity and location over time. Results strongly depend on the date considered. For instance, the four scenarios show similar surfaces of forests in 2090 but trends diverge over the following decade, leading to different surfaces in 2100 (Fig. 2). Thus, it is of great importance to consider the landscape dynamics rather than only focusing on changes between two LULC maps. Moreover, while diverging global assumptions would be expected to have diverging impacts on future LULCC, they show similar outcomes in Cauterets over the next century (e.g., the economic downturn in scenario 2 and the boost of the green economy in scenario 4 lead to similar landscape configurations for some specific dates). In the same way, different local economic developments have similar effects on landscape changes (e.g., tourism development varies significantly in scenarios 1 and 4 while reforestation trends are rather similar). Although this analysis can be balanced by the spatial and temporal resolutions considered, these findings underline an important insight: global scenarios may not necessarily

result in similar effects locally over distinct valleys or mountains. Local specificities are likely to influence the translation of global/national contexts locally, leading either to diverging or converging landscape dynamics. This questions the relevance of large scale scenario-based studies to inform local decision-making processes.

From a more global point of view, assessing the future uncertainty of LULCC enabled identifying plausible areas for reforestation or deforestation across scenarios. In Cauterets, these areas differ greatly, with reforestation going mainly beyond the past tree line and deforestation occurring on mountainsides. Overall, some areas are particularly likely to encounter land cover changes (deforestation, reforestation and encroachment) no matter which scenarios are considered.

Conclusion

The present study investigates the contribution of coupling participatory approaches in downscaling socioeconomic prospective scenarios with LULCC modelling in order to assess gravitational risks in mountain areas, with an application to a case study located in the French Pyrenees. It develops a six-step methodology for co-designing with stakeholders fine-scale spatially explicit scenarios up to 2040 and 2100. The main interest of such a combination is to allow localizing and quantifying future LULCC in light of data stemming from local stakeholders and to account for the uncertainties associated with future socioeconomic changes.

Results show that national context scenarios are not strong drivers of land use changes at local scales, stressing the need to account for their local declination. Participatory approaches allow fulfilling this need by capturing local adaptations of communities to global contexts. As for the model, it enables to account for interactions and feedbacks between LULCC that may explain some specific local landscape changes. These findings highlight the importance of considering landscape dynamics (yearly or over decades) instead of one or two dates in the future to analyze and compare spatially explicit scenarios.

The information provided by the simulated LULCC also proved to be of particular interest for natural hazard assessments. Our approach allowed identifying changes in the vegetation cover that will significantly affect landslide hazards in upcoming decades. Such results confirm the added-value of accounting for future LULCC to improve the accuracy of gravitational risk assessments in mountain areas. They also highlight the relevance for policy-makers of scenario-based LULCC modelling that supports decision-making under uncertainty.

The next step of the methodology should be to further extend the consultation process so as to construct relevant multi-risk reduction strategies with local stakeholders in order

to reduce the vulnerability and foster the resilience of societies to climate-driven natural hazards.

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