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

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17

18 **Abstract (199 words)**

19 Better understanding the pathways through which future socio-economic changes might influence land  
20 use and land cover changes (LULCC) is a crucial step in accurately assessing the resilience of  
21 societies to mountain hazards. Participatory foresight involving local stakeholders may help building  
22 fine-scale LULCC scenarios that are consistent with the likely evolution of mountain communities.  
23 This paper develops a methodology that combines participatory approaches in downscaling socio-  
24 economic scenarios with LULCC modelling to assess future changes in mountain hazards, applied to a  
25 case study located in the French Pyrenees. Four spatially-explicit local scenarios are built each  
26 including a narrative, two future land cover maps up to 2040 and 2100, and a set of quantified  
27 LULCC. Scenarios are then used to identify areas likely to encounter land cover changes  
28 (deforestation, reforestation and encroachment) prone to affect gravitational hazards. In order to  
29 demonstrate their interest for decision-making, future land cover maps are used as input to a landslide  
30 hazard assessment model. Results highlight that reforestation will continue to be a major trend in all  
31 scenarios and confirm that the approach improves the accuracy of landslide hazard computations. This  
32 validates the interest of developing fine-scale LULCC models that account for the local knowledge of  
33 stakeholders.

34 **Manuscript word count: 8507 words**

35 Manuscript: 7007 words

36 Figures (4): 1200 words

37 Table (1): 300 words

38 **Keywords:** Land use and land cover changes; Modelling; Future; Narratives; Stakeholders

## 39 **1. Introduction**

40 European mountains have experienced substantial transformations in the last century and are expected  
41 to face major modifications over the next decades due to both climatic and socio-economic changes.  
42 Climate change will affect snow cover, agricultural practices and forest ecosystems (Olesen et al.  
43 2002; Rousselot et al. 2012). These changes will lead to shifts in mountain vegetation that are likely to  
44 alter slope stability and to impact natural processes controlled by hydro-meteorological triggers (Katz  
45 et al. 1992; Kohler et al. 2014; Borsdorf et al. 2015). Meanwhile, socio-economic transformations will  
46 influence human activities, which will not only reshape mountain landscapes but also modify the  
47 exposure of societies to mountain hazards (e.g. floods, landslides, avalanches, mudflows, rock falls)  
48 (Fuchs et al. 2015b; Paphoma-Köhle et al. 2011). Thus, climatic and socio-economic changes will  
49 influence future land use and land cover changes (LULCC), which in turn, will affect both the  
50 occurrence of natural hazards and the vulnerability of the built environment to hydro-meteorological  
51 risks.

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

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

73 Any attempt to assess future LULCC requires characterizing future socio-economic conditions since  
74 they are a significant driver of LULCC and serve as inputs to LULCC models. Because they represent  
75 a set of potential future states of the world, scenarios are particularly convenient to explore the  
76 uncertainties associated with future socio-economic changes. Scenarios are coherent, internally  
77 consistent, and plausible descriptions of the pathways in which driving forces (e.g. technological  
78 change, energy costs or climate policies) may influence future developments (Carter et al. 2001; van  
79 Vuuren et al. 2014). Depending on their design and development process, scenarios can be classified  
80 in many categories (e.g. deterministic versus probabilistic, forecasting versus backcasting, exploratory  
81 versus normative) (Carter et al. 2001; van Vuuren et al. 2014). Changes in driving forces may be  
82 simulated using numerical methods, such as Monte Carlo simulations (e.g. Graveline et al. 2012).  
83 However, such approaches tend to neglect extreme values that would result from breakdowns and  
84 structural changes in the economy (Graveline et al. 2014; Rinaudo et al. 2013). Participatory narrative  
85 methods involving local stakeholders allow avoiding this shortcoming while ensuring that scenarios  
86 are consistent with the local knowledge of stakeholders (Graveline et al. 2014; Malek and Boerboom  
87 2015; Voinov and Bousquet 2010).

88 Many socio-economic scenarios have been constructed at national and international scales (Bourgau et  
89 al. 2008; EEA 2007; Carter et al. 2000; Vert and Portet 2010; Vert et al. 2013; Pérez-Soba et al. 2015;  
90 Verkerk et al. 2016). Downscaling these scenarios so that they provide useful inputs to local LULCC  
91 models requires analyzing local economic drivers (e.g. employment) and social dynamics (e.g.  
92 attractiveness of mountain areas). Some studies have undertaken this exercise with the IPCC special  
93 report emission scenarios for Europe (e.g. Rounsevell et al. 2006; EEA 2007; Verburg et al. 2010;  
94 Verburg et al. 2013). Based on interpretations of the narratives, quantitative data are derived (from  
95 other sectorial models or projections) to define model parameters (e.g. land demand, suitability of  
96 areas for specific LULCC transitions – see Stürck et al. 2015b for instance) that simulate quantitative  
97 scenarios with a spatial resolution varying from 1 km<sup>2</sup> (e.g. Verburg et al. 2010) to few hundred  
98 meters (e.g. Price et al. 2015). Nevertheless, their resolution is not appropriate for gravitational  
99 hazards that require finer scales of analysis to account for hydro-meteorological triggers and the  
100 landscape configuration influencing biogeochemical fluxes. High resolution LULCC simulations  
101 based on scenarios (e.g. 10 x 10 m pixels or vector-based objects – see for instance Houet et al. 2010,  
102 2014, 2015) are particularly valuable in assessing possible local environmental impacts of future  
103 LULCC but show limitations when distant futures or normative visions are considered, for at least two  
104 reasons.

105 First, classical LULCC models struggle to translate narratives into quantitative input data (van Vliet et  
106 al. 2010). This is accentuated by the time horizon considered since, the longer it is, the more global  
107 drivers have to be accounted for in a telecoupled world (Liu et al. 2013). No conventional approach  
108 exists and multiple methods can be used (Mallampalli et al. 2016). Some authors use statistical or

109 probabilistic tools to assess the relative and/or respective weights of scenarios' variables (Kok 2009;  
110 van Vliet et al. 2010) and then use these weights to parameterize the models. Others use intermediate  
111 sectorial models (Stürck et al. 2015b) or expert knowledge to define future land demands (Vacqu   et  
112 al. 2015).

113 Second, models using past land cover maps for initialization or calibration (Mas et al. 2014; Houet et  
114 al. 2016a) assume stationarity of the system (Kolb et al. 2013). No change of the LULCC drivers may  
115 occur in the future, and the simulated outcomes inevitably rely on trend scenarios (Houet 2015). Thus,  
116 they are not appropriate to represent non-stationary LULCC affected by regime shifts (M  ller et al.  
117 2014). Better suited fine-scale LULCC models should meet three criteria.

118 (i) They would have to be able to mimic observed LULCC in terms of dynamics (i.e. rates,  
119 locations and processes) and to account for interactions between LULCC, which remains  
120 challenging (Verburg et al. 2016). For example, mountain land cover trends such as  
121 encroachment or reforestation may lead to land use changes (abandonment) of summer  
122 agropastoral lands. Inversely, land use changes such as the conversion of forests into new  
123 silvicultural lands may induce new land cover dynamics. In most LULCC models, land  
124 uses and land covers are grouped together and not modelled separately to integrate such  
125 interactions.

126 (ii) They would also have to be able to take trends and disruptions in scenario storylines into  
127 account (i.e. regime shifts and new types of LULCC). Therefore, they have to exhibit both  
128 path-dependent (Brown et al. 2005) and non-path dependent properties (Houet et al.  
129 2016a).

130 (iii) They should provide outcomes that are consistent (in terms of temporal and spatial  
131 resolutions) with the knowledge of stakeholders and the requirements of hazard  
132 assessment models (e.g. resolution or land cover classes).

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

137 This paper investigates the contribution of coupling participatory approaches in downscaling socio-  
138 economic prospective scenarios with spatially-explicit LULCC modelling to assess future changes in  
139 landslide hazards in the French Pyrenees. Section 2 details the case study and the methodology  
140 developed. Section 3 presents the narratives produced and validated by stakeholders and compares the  
141 LULCC outcomes of the FORESCEM (FOREcasting SCEnarios for Mountains) model. Future  
142 possible landscape changes (reforestation and deforestation) are assessed in a spatially explicit manner  
143 and used as inputs to the ALICE (Assessment of Landslides Induced by Climatic Events) model to

144 evaluate their potential impacts on landslides. In section 4, the method is discussed. Section 5  
145 concludes on the interest of the participatory approach and the LULCC model to produce fine-scale  
146 spatially explicit scenarios useful to risk assessment.

## 147 **2. Material and methods**

### 148 **2.1. Study site and observed trajectories**

149 The study site is located in the French Pyrenees (centered on 0°06'50" W – 42°53'27" N) and covers  
150 about 70 km<sup>2</sup> in the municipal area of Cauterets. The elevation ranges from 800 m to 2700 m a.s.l.  
151 (Fig. 1a). Land use and land cover maps are derived from multisource GIS data (National Forest  
152 Inventory, landscape maps of the Pyrenees National Park) and historical maps based on photo-  
153 interpretations of aerial photographs.

154 In 2010, the landscape is composed of grassland and shrubs in the uplands, urban and cultivated areas  
155 in the valley bottom, forests and mineral surfaces on the steepest slopes, and a few water bodies (Fig.  
156 1c). It has experienced strong LULCC since the late 1950s (Fig. 1b). Urban areas have increased to the  
157 detriment of cultivation. The areas covered by deciduous and mixed coniferous and deciduous forests  
158 have largely increased while the extent of open forests has slightly declined. The analysis of gains and  
159 losses of land covers shows clear encroachment and reforestation trajectories. Natural grasslands of  
160 the uplands have significantly decreased and been converted into shrublands and open forests, while  
161 some shrublands have been converted into open forests and large areas of open forests turned into  
162 dense forests (Fig 1d).

163 *Figure 1 – Approximately here*

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

## 178 **2.2. Methodological approach**

179 The overall methodological approach combines participatory narrative scenarios with LULCC models  
180 in order to (i) produce future land cover maps, (ii) identify areas likely to experience LULCC in the  
181 future, and (ii) assess the subsequent evolution of landslide hazard in Causerets. It consists in co-  
182 constructing, with stakeholders, fine-scale socio-economic scenarios, while developing a spatially-  
183 explicit local LULCC model. Narrative scenarios are built to provide relevant inputs to the LULCC  
184 model while the model itself is developed to represent and quantify the likely LULCC identified in the  
185 narrative scenarios. This fine-scale spatially-explicit approach (Houet et al. 2010; Houet et al. 2015;  
186 Houet et al. 2016b) allows identifying future LULCC likely to influence gravitational hazards.

187 Two foresight horizons (2040 and 2100) are considered. The former allows radical but realistic  
188 anthropogenic changes to be imagined while formulating relevant recommendations to decision-  
189 making timeframes. It is neither too close (pursuing trends only) nor too distant (preventing  
190 stakeholders from projecting so far into the future) in time. The latter captures the impacts of climate  
191 changes, which are expected to increase more sharply after 2050 (IPCC, 2014). In particular, peak oil,  
192 which is likely to have an impact on energy costs, and therefore, on the profitability of logging  
193 activities in forested areas, is assumed to occur in 2040 (Rozenberg et al. 2010).

### 194 **2.2.1. Downscaling scenarios: combining literature, participatory workshops and LULCC** 195 **models**

196 The methodology for downscaling scenarios comprises six sequential steps: (1) pre-constructing  
197 national context scenarios, (2) downscaling national context scenarios to local scale, (3) story-telling  
198 of the narrative scenarios at local scale, (4) validating narratives and locating possible future land use  
199 changes, (5) simulating LULCC for each scenario, and (6) refining the narratives with quantitative and  
200 spatially explicit simulated outcomes.

#### 201 *Step 1: Pre-constructing national context scenarios.*

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

207 A set of national and global driving forces and strong trends likely to influence future land uses in  
208 French mountain areas were first identified and characterized based on a literature review of existing  
209 prospective studies carried out at European and national levels (EEA 2007; Bourgau et al. 2008; Vert  
210 et Portet 2010; Vert et al. 2013) (Table 1). Driving forces are variables that are likely to vary across  
211 scenarios in the future, whether they stem from exogenous (e.g. volatility of agricultural prices,

212 climate policies) or endogenous forces (e.g. urbanization, abandonment of farmland). Strong trends are  
213 variables whose evolution is considered as almost certain and that are occurring over all scenarios.  
214 They encompass global population growth, rising demand for agricultural products for food and feed  
215 uses and the impacts of climate change on mountain snow cover. Strong trends are used as contextual  
216 parameters to determine a set of pressures on the system. For instance, snow cover is expected to  
217 decrease by a factor of 2 to 5 from 2001 to 2030, compared to the reference period 1961-2000  
218 (Rousselot et al. 2012; source: <http://www.cnrm.meteo.fr/scampe/>). As a result, the development of  
219 the ski resort is likely to be limited in absence of technological change.

220 As highlighted by Hérivaux (2015) and Petit et al. (2014), most prospective studies reflect a broad  
221 consensus on the range of likely futures of European societies. A cross analysis of existing foresight  
222 exercises in Europe and France allowed identifying four broad families of scenarios conventionally  
223 considered: globalization, regionalization, environmental preservation and sustainable food  
224 production. The national context scenarios were designed in line with these orientations and their  
225 underlying driving forces. For instance, the ‘lettuce surprise U’ scenario from EEA (2007) was used to  
226 define the policy and governance drivers such as *decentralization of public policies* in national context  
227 scenario 2 (Table 1). The approach was complemented by a series of face-to-face interviews with five  
228 French experts in the fields of agriculture, forestry and tourism in order to specify the likely evolution  
229 of some driving forces (e.g. the impact of technological change on ski resorts, the economic viability  
230 of forestry in the Pyrenees), given the peculiarities of mountain areas. Each scenario was then built as  
231 a consistent combination of strong trends and a set of key assumptions regarding each driving force.  
232 Such an approach relying on existing prospective studies and expert interviews to characterize driving  
233 forces and strong trends at national level is in line with methodologies used in previous research  
234 (Rinaudo et al. 2013; Graveline et al. 2014). At the end of step 1, four national context scenarios were  
235 constructed up to 2040.

#### 236 *Step 2: Downscaling national context scenarios to local scale.*

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

241 The workshop started with a retrospective analysis of the past evolution of the municipality based on  
242 historical LULCC maps from 1959 and 2010 (Fig.1). Past trends and dynamics in Cauterets regarding  
243 land cover changes, demography, tourism, agro-pastoral activities and forestry were presented and  
244 enriched with accurate explanations from local participants on both exogenous and endogenous drivers  
245 of change. This established a diagnosis of the situation of the municipality in 2010. The national  
246 context scenarios from 2010 to 2040 were then presented and debated. Participants were asked to react



247 to the pre-constructed scenarios, complete the list of assumptions regarding the evolution of driving  
248 forces and re-construct local versions of the scenarios up to 2040 and 2100 as a combination of these  
249 new assumptions. For instance, the national context scenario 2 that depicts a quest for energy self-  
250 sufficiency was translated at local scale into the *intensification of forestry production* (Table 1).

251 The chain of events likely to occur from 2040 to 2100 was left open to participants, whose imagination  
252 was only constrained by two conditions common to all scenarios. First, the logical pathways between  
253 2040 and 2100 had to match the trends described in each scenario from 2010 to 2040. This ensured  
254 that four local scale scenarios were built, each composed of two images (2040 and 2100), with two  
255 logical pathways (2010-2040 and 2040-2100). Second, the climate and energy contexts were  
256 predetermined, based respectively on the snow and temperature projections of Météo-France and the  
257 outputs of the IMACLIM-R model of CIRED describing possible changes in global energy prices  
258 through the 21<sup>st</sup> century (Rozenberg et al. 2010). At the end of step 2, we had the material to build four  
259 local translations of the national context scenarios that were consistent with global scenarios while  
260 accounting for local specificities.

261 *Table 1 – approximately here –*

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

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

268 *Step 4: Validating narratives and locating possible future land use changes.*

269 Step 4 aimed to validate and provide a spatial characterization of the local scenarios in order to  
270 produce relevant data to be integrated in the LULCC model. A second one-day workshop took place in  
271 January 2015 and involved the same stakeholders as those that attended the first workshop.  
272 Participants were asked to debate the narrative scenarios' internal consistency and estimate their  
273 spatial impacts in terms of land use changes. Land cover maps were used to help participants to pre-  
274 identify the likely zones of future land use changes and the time horizon for each. Such a participatory  
275 zoning technique based on both local stakeholders' verbal representations and scientists'  
276 comprehensive knowledge of the processes at play has been proved efficient as support to land  
277 management policies (Caron 1997; Caron and Cheylan 2005). Special attention was paid to future  
278 pastoral and forestry land uses as they have strong impacts on future land cover changes. Two types of  
279 maps were thus produced: (i) maps featuring the broad areas in which mountain estives might be  
280 abandoned, and (ii) maps featuring the broad areas in which forestry might occur. At the end of step 4,

281 each scenario contained a revised narrative version of the local scale scenarios and two maps depicting  
282 the areas in which mountain land uses were likely to change from 2010 to 2040 and 2100 but without  
283 quantifying future LULCC.

284 *Step 5: Simulating LULCC for each scenario.*

285 Step 5 aimed to model the LULCC identified by stakeholders in order to ensure that they were  
286 consistent with the vegetation dynamics at play in Cauterets. The FORESCEM model used for  
287 mountain LULCC simulations was developed using the Dinamica-Ego platform (Soares-Filho and  
288 Coutinho Cerqueira 2002). It simulates LULCC at an annual time step and accounts for neighborhood  
289 interactions and feedbacks between some vegetation classes. To begin, it uses the two historical land  
290 use maps and land cover maps (10 x 10m resolution) from which it computes transition probabilities  
291 between land covers and land uses. A weight-of-evidence method is used to compute suitability maps  
292 to allocate future LULCC based on various spatially-explicit drivers (geology, aspect, elevation, slope,  
293 and distance to infrastructures, land uses and land covers). For each land use type (forestry,  
294 urbanization, agropastoral land use and abandonment considered as an absence of land use), land  
295 cover changes are defined either by transition probabilities or conversion rules aimed at reproducing  
296 vegetation dynamics (minimum duration, specific transitions from one land cover to another). Land  
297 use changes and conversion rules are driven by the narratives. Participatory zoning from step 4 is  
298 translated into GIS data to parameterize the land use changes in the model (details in supplementary  
299 material 1). For instance, pastoral land use changes (estive abandonment) define which estives are  
300 abandoned and when. When no abandonment is expected, land cover changes in the uplands are  
301 simulated according to trends estimated by the model. This may lead to land cover changes such as  
302 encroachment and reforestation which, in turn, may influence future land use changes (conversion  
303 from abandonment to forestry). Forestry land use changes are defined using an intermediate model  
304 (SYLVACCESS, Dupire et al. 2015, 2016) that delineates potential areas that can be logged according  
305 to logging practices. More precisely, it simulates all possible cableways used to remove cut trees,  
306 located within the zones pre-identified during step 4. When scenarios expect to limit or stop a specific  
307 land use change, the transition probability is set to 0 by the modeler. The land demand is not  
308 predefined but computed from all simulated land cover and land use changes based on historical  
309 changes. Finally, the bio-physical impacts of global warming on reforestation are not taken into  
310 account because its influence on patterns and dynamics of mountain forests remains highly uncertain  
311 (Theurillat and Guisan, 2001) and even more when considering land use changes and anthropogenic  
312 disturbances (Galop et al. 2011; Batllori et al. 2010).

313 *Step 6: Refining the narratives with quantitative and spatially explicit simulated outcomes.*

314 Step 6 used the results of steps 4 and 5 to fine-tune and improve each narrative with quantitative  
315 outcomes regarding the location and the amount of simulated LULCC. At the end of step 6, four

316 spatially explicit narratives had been constructed. Each was made of a scenario narrative, two fine-  
317 scale maps of future land cover up to 2040 and 2100 and a set of quantitative assessments of the  
318 associated amounts of LULCC.

### 319 **2.2.2. Assessing the future uncertainty of LULCC**

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

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

### 336 **2.2.3. Assessing landslide hazard over time using LULCC**

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

343 LULCC are used as inputs to the ALICE (Assessment of Landslides Induced by Climatic Events)  
344 model (Baills et al. 2012). ALICE is a slope stability assessment tool that combines (i) a mechanical  
345 stability model accounting for some geotechnical parameters of the soil layers, (ii) an hydrogeological  
346 model that simulates the main water cycle mechanisms, and (iii) a vegetation module that has recently  
347 been added in order to account for the effects of vegetation shifts on mechanical soil properties (i.e.  
348 cohesion and overload). This spatialized mechanical model produces landslide hazard maps at various  
349 scales from the single slope to hundreds of square kilometers. Together, the mechanical stability  
350 model and the hydrogeological model allow integrating climate change scenarios. They are

351 complemented by the vegetation module that accounts for the effects of LULCC on slope failures. In  
352 the module, vegetation shifts change the mechanical properties of soils, that in turn, affect the  
353 probability of reaching failure (Thomas and Pollen-Bankhead 2010; Genet et al. 2010; Kokutse et al.  
354 2016). More precisely, the presence or absence of forest may have a counter-intuitive impact on slope  
355 stability as it can reinforce (i) the resistance to shear with an additional apparent cohesion of the soil  
356 due to roots or (ii) the instability due to the biomass additional weight.

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

### 362 **3. Results**

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

#### 367 **3.1. Spatially-explicit narratives**

##### 368 **3.1.1. Scenario 1: Abandonment of the territory**

369 Market liberalization intensifies competition throughout the world. In Europe, the Common  
370 Agricultural Policy (CAP) disappears progressively from 2020 onwards. Increasing imports of low-  
371 cost agricultural products fosters the decline of mountain farming. In Cauterets, pastoral units that  
372 initially persisted thanks to transhumant herds coming from outer regions are eventually abandoned at  
373 a pace that depends on their accessibility, fodder potential and proximity to the valley. In 2040,  
374 farming is only maintained in a few highly productive grazing areas. In consequence, natural  
375 grasslands decrease in favor of dense forests that expand where both climate and soils are favorable to  
376 their expansion. By 2100, the effect of pastoral land abandonment is perceptible with an increase in  
377 the annual loss of natural grasslands in the uplands (5.6 ha/year) compared to the 2010-2040 period.  
378 The landscape has changed markedly with dense forests covering 33% of the territory in 1951, 41% in  
379 2010, and 50% in 2100.

##### 380 **3.1.2. Scenario 2: Sheep and Woods**

381 In Europe, greater power is transferred to the regions, whose autonomy and influence increase. This  
382 regional downturn leads to decreasing trade which allows preserving French agriculture from global  
383 competition. In the Pyrenees Mountains, the CAP is reoriented so as to support local agriculture and  
384 renewable energy production. In Cauterets, uplands are grazed again and shrublands do not expand.

385 Former agro-pastoral trails are remodeled for wood production and estives are reopened for agro-  
386 pastoralism on mountainsides. In parallel, the lack of investments in modernizing the equipment of the  
387 ski resort results in a decline in winter tourism. In 2040, Cauterets has lost its attractiveness for  
388 tourists. Compared to 2010, dense forests have lost 175 ha. By 2100, most of permanent inhabitants  
389 are gone. Logging activities induce significant landscape changes: mountainsides are regularly  
390 maintained and some previously abandoned pasture that evolved to shrublands and open forests are  
391 now reforested and exploited.

### 392 **3.1.3. Scenario 3: A renowned tourism resort**

393 With increasing globalization, the most vulnerable mountain areas are abandoned, while territories  
394 with higher economic potential are preserved for the purpose of their economic valorization. Due to its  
395 spectacular landscapes, Cauterets benefits from public support for the development of a high value-  
396 added tourism. The use of snowmaking machines allows winter frequentation to remain stable while  
397 summer frequentation increases with the diversification of outdoor activities. The municipality invests  
398 in logistical and financial support to maintain natural areas. However, forestry remains costly and the  
399 downward trend of agro-pastoralism continues. Only grazing areas that are located close to tourist  
400 areas are artificially maintained in order to sustain a bucolic pastoral landscape (e.g. sheepfolds,  
401 flowery meadows). Some intermediate areas are reopened in order to prevent landscapes from closing.  
402 Elsewhere, landscape dynamics follow similar trends to scenario 1. In 2040, large areas of natural  
403 grassland have turned into shrublands or open/dense forests. Dense forest areas increase by 5.2 ha/year  
404 from 2040 to 2100. By 2100, 49% of the study area is covered by dense forests, which is perceived as  
405 an attractive factor since Cauterets has become a socially selective tourist destination.

### 406 **3.1.4. Scenario 4: Green Town**

407 Increasing environmental awareness modifies consumption habits and lifestyles. Prices of fossil fuels  
408 and imports increase while investments in renewable energy, local agriculture and green technologies  
409 are boosted in Europe. In Cauterets, the wider use of telecommunications and teleworking reduces  
410 rural exodus of city dwellers. The use of grazing areas continues but the decrease in livestock in the  
411 valley reduces grazing pressure in the mountains. This results in shrub invasion and encroachment of  
412 the least productive estives. Meanwhile, wood production increases. By 2040, Cauterets is a  
413 multifunctional area providing a pleasant living environment and good-quality services to its  
414 population. Compared to 2010, landscapes have significantly changed: they lost 11% of grasslands  
415 and 3.3% of dense forests. In the following decades, tourism decreases progressively with rising travel  
416 costs and the shrinking of the ski area. A small agro-pastoral activity remains but forest expands  
417 significantly across the whole area with reforestation trends comparable to what they were before  
418 2010. In 2100, 49% of the study area is covered by dense forest, similarly to scenarios 1 and 3.

### 419 **3.2. Comparison of land cover changes and identification of areas at stake**

420 As a first result, a slower pace of reforestation and encroachment is observed in all scenarios  
421 compared to the 1951-2010 period. This difference in transitional rates may be explained by the  
422 productivity gains and subsequent massive rural exodus that French mountain agriculture experienced  
423 during the second half of the 20th century which is out of proportion with any future change that might  
424 occur. Reforestation and encroachment occurring up to the present day have concerned mountainsides.

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

432 *Figure 2 – Approximately here*

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

446 *Figure 3 – Approximately here*

### 447 **3.3. Landslide hazard assessment**

448 Because it exhibits the most deforestation, scenario 2 was selected to assess the influence of the  
449 evolution of the vegetation cover on landslide activities up to 2100. Results that are presented in Fig. 4  
450 focus on an area of Cauterets that has been particularly at risk in the past. They show an increase in the  
451 probability of landslide occurrence in the absence of forests and an increase in slope stability in the  
452 presence of forests (Fig 4a). From 2010 to 2100, results indicate that reforestation will tend to increase

453 the stability of the slopes, whereas the stability will be dropping in deforested areas (Fig 4b). This  
454 demonstrates the significant influence of land covers in stability computations. Such results points out  
455 that for spatialized analysis of landslide hazard, considering spatially-explicit LULCC undoubtedly  
456 improves the accuracy of the landslide hazard computations.

457 *Figure 4 – Approximately here*

#### 458 **4. Discussion**

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

471 Involving local stakeholders in the development of scenarios allowed exploring breakdowns and  
472 unexpected changes. It benefited to both scientists, who confronted their theoretical knowledge with  
473 ground realities, and local decision makers, whose participation in a formalized foresight exercise  
474 helped intellectualize and anticipate changes in a longer time horizon than the short term constraints  
475 they are used to handling, as pinpointed by Rinaudo et al. (2013) and van Vliet et al. (2010). The  
476 approach also confirmed that participation enabled scientifically grounding the local knowledge of  
477 participants while building a shared expertise among stakeholders. It brought together stakeholders  
478 with various opinions that now share a common vision of the future of their territory. In the future, this  
479 common understanding is likely to facilitate the establishment of effective risk management strategies  
480 by providing sound foundations for the decision process.

481 The approach contributed to the design of the LULCC model architecture by decoupling land use  
482 changes driven by the narratives, from land cover changes driven by vegetation dynamics observed  
483 between 1959 and 2010 and further simulated in the model. Thus, the parameters of the model were  
484 fine-tuned in light of up-to-date local information, thereby ensuring its calibration. In turn, the types of  
485 data required by the model fed the zoning technique used to spatialize land use changes associated  
486 with each scenario. Stakeholders were able to characterize the occurrence of the land use changes

487 resulting from the scenarios in time and space, given local peculiarities. Conventional LULCC models  
488 would not have been able to define such changes by themselves when calibrated using historical  
489 changes. More generally, the consultation of stakeholders provided a solution to overcome the lack of  
490 accurate data at local scale, thus avoiding the ‘black-box’ effect that explains the reluctance of some  
491 decision-makers to assimilate the results of models whose operation they do not fully understand. In  
492 regard to modelling issues, as highlighted by Verburg et al. (2016), the FORESCEM model tackles the  
493 challenge of accounting for iterative feedbacks between land cover changes and land use changes at a  
494 fine scale. Thus, a particular attention has been paid concomitantly to the impacts of pastoral  
495 (abandonment of summer pastures) and forestry (emergence of logging) land use changes on land  
496 cover changes and the impacts of some trends in land cover changes (natural reforestation) on land use  
497 changes. The ability of LULCC models to represent feedbacks is crucial for simulating co-constructed  
498 scenarios through a dynamic process.

499 Results of the LULCC model show a common trend across all scenarios. Natural grasslands exhibit a  
500 major declining trend in the uplands, in favor of encroachment and reforestation. Future LULCC,  
501 taken independently, may pursue the forest transition theory of Mather (1992) up to the beginning of  
502 the 22<sup>nd</sup> century at least. Even if these trends are similar across all scenarios between 2010 and 2100,  
503 they exhibit subtle differences in terms of quantity and location over time. Results strongly depend on  
504 the date considered. For instance, the four scenarios show similar surfaces of forests in 2090 but trends  
505 diverge over the following decade, leading to different surfaces in 2100 (Fig 2). Thus, it is of great  
506 importance to consider the landscape dynamics rather than only focusing on changes between two  
507 LULC maps. Moreover, while diverging global assumptions would be expected to have diverging  
508 impacts on future LULCC, they show similar outcomes in Cauterets over the next century (e.g. the  
509 economic downturn in scenario 2 and the boost of the green economy in scenario 4 lead to similar  
510 landscape configurations for some specific dates). In the same way, different local economic  
511 developments have similar effects on landscape changes (e.g. tourism development varies significantly  
512 in scenarios 1 and 4 while reforestation trends are rather similar). Although this analysis can be  
513 balanced by the spatial and temporal resolutions considered, these findings underline an important  
514 insight: global scenarios may not necessarily result in similar effects locally over distinct valleys or  
515 mountains. Local specificities are likely to influence the translation of global / national contexts  
516 locally, leading either to diverging or converging landscape dynamics. This questions the relevance of  
517 large scale scenario-based studies to inform local decision-making processes.

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



## 523 **5. Conclusion**

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

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

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

544 The next step of the methodology should be to further extend the consultation process so as to  
545 construct relevant multi-risk reduction strategies with local stakeholders in order to reduce the  
546 vulnerability and foster the resilience of societies to climate-driven natural hazards.

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## 779 **Figure captions**

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

782 Fig. 2: Future land use and land cover changes (in hectares) for (a) each main land cover and (b) the dense  
783 forests (coniferous + Deciduous/Mixed forests) for the four scenarios.

784 Fig. 3 Future uncertainty maps – probability ranges from 0 to 1 - for (a) the deforestation, (b) the reforestation  
785 and encroachment. (c) illustrates the difference map between (a) and (b) underlying that few areas are  
786 concerned by both deforestation and reforestation dynamics in the future. Red lines illustrate roads and grey  
787 lines show boundaries of estives numbered in (a) (1 Coutres, 2 Estibe, 3 Gourey, 4 Cirque du Lys, 5 Clos-  
788 Cayan, 6 Vallée de Gaube, 7 Vallée de Lutour, 8 Lisey, 9 Le col de Riou, 10 Viscos)

789 Fig. 4: Modelling the influence of vegetation on the Factor of Safety (FoS) of shallow rotational landslides  
790 susceptibility. (a) Differences between the FoS probabilities without and with the vegetation in 2010  
791 illustrating the positive influence of the vegetation to limit landslides. (b) Differences between the Fos  
792 probabilities using the land cover maps in 2010 and in 2100 according to Sc2 illustrating that land use and  
793 land cover changes may have subtle local impact on landslides.

794 Table 1: Main characteristics of the four national and local socio-economic scenarios up to 2040