



HAL
open science

Maintaining biodiversity promotes the multifunctionality of social-ecological systems: holistic modelling of a mountain system

Zhun Mao, Julia Centanni, Franck Pommereau, Alexia Stokes, Cédric Gaucherel

► To cite this version:

Zhun Mao, Julia Centanni, Franck Pommereau, Alexia Stokes, Cédric Gaucherel. Maintaining biodiversity promotes the multifunctionality of social-ecological systems: holistic modelling of a mountain system. *Ecosystem Services*, 2021, 47, pp.101220. 10.1016/j.ecoser.2020.101220 . hal-03043249

HAL Id: hal-03043249

<https://hal.inrae.fr/hal-03043249>

Submitted on 15 Nov 2022

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Maintaining biodiversity promotes the multifunctionality of social-ecological systems: holistic modelling of a mountain system

Zhun Mao^{1*}, Julia Centanni^{1,2,#}, Franck Pommereau³, Alexia Stokes¹, Cédric Gaucherel^{1*}

Affiliations:

1 Univ Montpellier, AMAP, INRAE, CIRAD, CNRS, IRD, 34000 Montpellier, France

2 Université Pierre et Marie Curie – UPMC, 75005 Paris 5e cedex 05, France

3 IBISC, Université d'Evry-val d'Essonne, Université Paris-Saclay, Evry, France

* Corresponding authors: maozhun04@126.com; cedric.gaucherel@cirad.fr

Current address: CEFÉ, Univ Paul Valéry Montpellier 3, Univ Montpellier, CNRS, EPHE, IRD, Montpellier, France

1 Maintaining biodiversity promotes the multifunctionality of
2 social-ecological systems: holistic modelling of a mountain
3 system

4
5 Zhun Mao^{1*}, Julia Centanni^{1,2,#}, Franck Pommereau³, Alexia Stokes¹, Cédric Gaucherel^{1*}

6 **Affiliations:**

7 1 Univ Montpellier, AMAP, INRAE, CIRAD, CNRS, IRD, 34000 Montpellier, France

8 2 Université Pierre et Marie Curie – UPMC, 75005 Paris 5e cedex 05, France

9 3 IBISC, Université d'Evry-val d'Essonne, Université Paris-Saclay, Evry, France

10 * Corresponding authors: maozhun04@126.com; cedric.gaucherel@cirad.fr

11 # Current address: CEFÉ, Univ Paul Valéry Montpellier 3, Univ Montpellier, CNRS, EPHE,
12 IRD, Montpellier, France

13

14 **Abstract**

15

16 Monitoring the provision of multiple ecosystem services (ES) in social-ecological systems is a
17 major challenge. Most tools usually tackle the problem by modelling individual ES, but do
18 not perform a holistic analysis of a dynamic and integrated system. We developed a discrete-
19 event model (*DORIAN*) and explored its potential for assessing biodiversity and
20 multifunctionality of a mountain ski resort subjected to a changing climate. We represented
21 this social-ecological system as a network comprising 16 binary components and 51 processes
22 that define component interactions. We identified 22 economy- and ecology-related ES,
23 depending on the presence/absence of components. We simulated six scenarios representing
24 different economic, environmental and climatic situations and calculated a score (the sum of
25 proxies for ES or biodiversity), corresponding to the level of biodiversity and
26 multifunctionality. Results showed that climate change reduced the system's
27 multifunctionality and increased the number of degraded states, as well as the trajectories
28 from healthy to degraded states. With increasing levels of biodiversity, only ecology-related
29 ES were boosted at low biodiversity levels, while both high levels of ecology and economy-
30 related ES were maintained at high biodiversity levels. This result demonstrates the
31 importance of conserving high biodiversity in a social ecological system, for an optimal
32 “biodiversity – multifunctionality” win-win strategy.

33

34 **Keywords:** biodiversity, ecosystem service, social-ecological system, discrete-event model,
35 qualitative modelling, mountain, economy.

36

37 **1 INTRODUCTION**

38 The concept of ecosystem services (ES), that bridge both biophysical and economic processes
39 in a social-ecological system, has been increasingly incorporated into management scenarios
40 related to ecosystem governance and landscape planning (Costanza et al., 1997; de Groot et
41 al., 2010; MEA, 2005; Lescourret et al., 2015). Within the current context of a changing
42 climate, researchers and decision-makers have struggled to find ideal models for predicting
43 and optimizing highly complex bundles of ES in social-ecological systems, hindering the
44 adoption of ES into national policies (Bernués et al., 2019; de Groot et al., 2010; Washbourne
45 et al., 2020). Although understanding social-ecological systems is critical for climate change-
46 adapted ES management and biodiversity conservation initiatives, the inclusion of
47 biodiversity as an ecological factor affecting these systems is deficient in most studies
48 (Rissman and Gillan, 2016). As biodiversity loss is a modern day grand challenge (Future
49 Earth, 2014), the success of addressing this challenge lies in suitably quantifying the
50 contribution of biodiversity to multifunctional social-ecological systems.

51 Models are useful tools to assess ES values and the multifunctionality of a system under study
52 (Nelson et al., 2009; Neugarten et al., 2018; Shoyama et al., 2017). Most ES models aim to
53 quantify individual indicators within a bundle of ES. Usually, these models are either process-
54 based or empirical and are tightly ES or ES-indicator dependent (e.g., see Merritt et al. (2003)
55 for a review of models of sediment transport and erosion control and Manzoni and Porporato
56 (2009) for a review of models of soil carbon sequestration and climate regulation). By
57 coupling several specialized ES models, multiple SE can be independently quantified and then
58 articulated to trace their spatiotemporal dynamics and trade-off patterns (Elkin et al., 2013;
59 Lafond et al., 2017). While such an approach has greatly enhanced our understanding of the
60 multifunctionality of socio-ecological systems, it can be criticised due to its lack of a holistic

61 treatment of a system that is multi-scale and contains tightly interdependent components.
62 Another drawback of such an approach is the poor consideration of the dynamic nature of a
63 system, that evolves over time and often shifts to another system subjected to anthropogenic
64 pressure, e.g., management and disturbance (Fraterrigo and Rusak, 2008). Therefore, the
65 suitability of existing ES models, that are often developed or calibrated for certain situations
66 but are used in other situations, is questionable. Additionally, this modelling approach can
67 sometimes be time-consuming and technically difficult due to the high interdisciplinary level,
68 unbalanced multisource data, model availability and a high dependence on multi-sectorial
69 cooperation. As a consequence, most results on system multifunctionality from different
70 studies are rarely comparable, due not only to the use of contrasting models and ES proxies,
71 but also because of the diverse ranges of ES categories. If we are to determine and compare
72 management scenarios for different complex social-ecological systems, we need a robust
73 model that allows the exploration of a large number of ES using a generic methodology.

74

75 Novel modelling approaches based on the concept of networks have emerged recently, that
76 could provide an alternative solution for the modelling of complex ecological process and ES
77 bundles. These models aid decision-making through e.g., the development of decision trees
78 (Crossman et al., 2010; Delphin et al., 2013; Zerbe et al., 2013), Bayesian belief networks
79 (Aguilera et al., 2011; Landuyt et al., 2013; McDonald-Madden et al., 2016), artificial neural
80 networks (Larsen et al., 2012), social networks (Puga-Gonzalez and Sueur, 2017),
81 optimisation networks (Xiao et al., 2018), Boolean qualitative networks (Kristensen et al.,
82 2019) and Petri nets (Di Giusto et al., 2019; Gaucherel et al., 2017; Gaucherel and
83 Pommereau, 2019). These modelling approaches share a similar concept in that individual
84 components' simple behaviours are governed by basic laws that can lead to a sophisticated
85 behaviour of the whole network. These models, that are sometimes semi-quantitative or even

86 qualitative, differ in terms of network configuration and parametrization. For example,
87 Bayesian belief networks simulate whether one or multiple events will occur, based on a
88 probabilistic network composed of variables and conditional dependencies (Aguilera et al.,
89 2011; Landuyt et al., 2013; McDonald-Madden et al., 2016). Decision trees, sometimes
90 considered as non-flexible and as simplified Bayesian belief networks, are usually devoted to
91 the diagnosis of an event, into which probabilistic conditions and stochastic processes could
92 be incorporated if desired (Crossman et al., 2010). Several types of network-based model,
93 such as Bayesian belief networks and decision trees, are promising with regard to the coupling
94 of quantitative ES models (Delphin et al., 2013; Fontana et al., 2013; Pérez-Miñana, 2016).
95 But these models are classified as quantitative ES models based on the theory of Bayesian
96 statistics, even though sometimes their diagnostic outputs are qualitative.

97

98 Qualitative models, such as Boolean qualitative networks (Kristensen et al., 2019) and
99 discrete-event models (Di Giusto et al., 2019; Gaucherel et al., 2017, 2019), have recently
100 been developed to describe complex ecosystems. The conceptual approach behind such
101 qualitative models is that they avoid making any subjective assumptions concerning
102 parameters' prior distributions and/or ranges, the choices of which are a potential source of
103 bias. Instead, by setting Boolean rules or discrete rules accounting for the interactions among
104 components and by rigorously handling them, they aim at grasping the holistic nature of a
105 system's behaviour. Unlike e.g., Boolean qualitative networks that involve one-to-one
106 interactions between components for a rule (Kristensen et al., 2019; Thomas and Kaufman,
107 2001), discrete-event models are able to model non-dyadic (i.e., not only pair relationships but
108 multi-node) interactions in a single rule, a property mandatory in realistic socio-ecosystem
109 functioning. Discrete-event models are built on the theory of Petri nets, i.e., a classic
110 mathematical tool in computer science that allows the description and analysis of concurrent

111 processes that arise in systems with many components (Petri, 1966). By setting deterministic
112 rules, yet with several outcomes, discrete-event models enable the exploring all the possible
113 states reached by the system from a given initial state (Gaucherel et al., 2017; Gaucherel and
114 Pommereau, 2019). Discrete-event models have been successfully used to describe pathways
115 of status changes of a complex system in terms of component composition and the underlying
116 processes driving such changes (Gaucherel et al., 2017), suggesting their potential for also
117 tackling questions related ecosystem evolution and simulating ES dynamics.

118 We developed a discrete-event and qualitative model (named *DORIAN*) for assessing the
119 long-term maintenance of biodiversity and ES in a social-ecological system. We examined
120 multiple ES and biodiversity at a mountain ski resort in the French Alps, popular for both
121 winter and summer sports, and where forestry and hunting also provide income for the local
122 community. This small mountain town is susceptible to anthropogenic pressure linked to
123 climate change and tourism, which is damaging the local environment, and so is a suitable
124 case study on which to test our model. Using the discrete-event modelling approach, we ask:

- 125 (i) how changes due to anthropogenic pressure (i.e., climate change) modify a
126 system's provision of multiple ES?
- 127 (ii) what is the role of biodiversity in the maintenance of a highly complex ES bundle
128 and the system's multifunctionality?

129 Answering the first question will enable us to better understand a system's vulnerability with
130 regard to ES provision and allow us to seek adaptive management strategies for a more
131 sustainable social-ecological system (McCarthy et al. 2001). We hypothesize that a changing
132 climate will adversely affect multiple ES provision, but that it is possible to mitigate the
133 adverse effects via management policies. Answering the second question will provide novel
134 data for the global initiatives that focus on including values for biodiversity and ES into

135 decision-making. Here, we hypothesize that increased biodiversity has a positive impact on
136 multiple ES provision and so promotes multifunctionality.

137

138 2 MATERIALS AND METHODS

139 2.1 *The study site*

140 Chamrousse (45°06'33"N, 5°52'28"E) is a ski resort located 30 km from the city of Grenoble
141 (France) and within the Belledonne mountain range, which forms a part of the French Alps.
142 The Chamrousse municipality extends along an altitudinal range from 1400 to 2250 m a.s.l..
143 Chamrousse has 422 inhabitants (data in 2017), but this population can increase to 15 000
144 during the winter ski season (<http://chamrousse.com>). The most important economic resource
145 is alpine skiing (the total revenue from the cable cars was 8.17 M€ in the winter of
146 2015/2016), comprising >90% of the town's income. To attract tourists, Chamrousse also
147 develops various activities in winter, including cross-country skiing and ice diving. However,
148 natural snow has become more scarce in the French Alps since the 1960s (Durand et al.,
149 2009). From 2005 onwards, the snow pack at Chamrousse was under the critical threshold
150 (i.e., 0.3 m for a minimum period of 100 days), necessary for downhill skiing (Durand et al.,
151 2009). Therefore, Chamrousse was equipped with artificial snow cannons in 2009 to keep ski-
152 slopes open (Spandre et al., 2015), although there are concerns about the negative ecological
153 impact of artificial snow on mountain vegetation and soil quality (Rixen et al., 2004, 2003;
154 Roux-Fouillet et al., 2011). Also, the rise in mean annual temperature and increase in long,
155 dry periods has led to an increase of tree mortality, with diverse implications for forest
156 functioning (Moser et al., 2011; Csilléry et al., 2017).

157 In the summer, there is a decrease in tourist activities and income from cable cars is only 0.16
158 M€ (2015 – 2016). Mountain biking and hill-walking are much promoted by the town hall and
159 tourist office, making summer tourism increasingly popular and a high potential. For the rest
160 of the year (spring and autumn), the village is little frequented by tourists. The hunting season
161 starts in the late summer and usually concerns the local community rather than tourists.

162 Around Chamrousse, there is a wide diversity of landscapes, including small subalpine lakes,
163 low altitudinal peat bogs and mixed montane forest that continuously extends from low
164 altitudes (<1000 m) up to the treeline (at 2000 m). Each type of landscape has natural habitats
165 hosting a rich variety of species that may need protecting now or in the future. IUCN red-
166 listed species include *Aquila chrysaetos* L. (Golden eagle) and *Parnassius apollo* L. (Apollo
167 butterfly). At high elevations, alpine ibexes (*Capra ibex* L.), chamois (*Rupicapra rupicapra*
168 L.), tetra lyre (*Tetrao tetrix* L.) and Arolla pines (*Pinus cembra* L.) are commonly found
169 (<https://inpn.mnhn.fr/>). While these species attract tourists and help the economic growth of
170 Chamrousse, tourism can cause disturbances to species' habitats, including pollution due to
171 waste, soil quality degradation due to the use of artificial snow and ecosystem fragmentation
172 due to ski paths and mountain bike trails. Forest harvesting for timber can also drastically
173 change the microhabitat and cause soil loss through erosion and shallow landslides.

174 Overall, the whole Chamrousse zone provides many ES, beneficial for tourists but also for
175 residents, such as cultural services (mountain beauty, mountain sports and hunting),
176 regulating services (such as the effect of forests on carbon sequestration and erosion control
177 and maintenance of soil fertility), provisioning services (timber, wild food product, fresh
178 water and hunting products). Considering the close link between cultural services and tourism
179 at Chamrousse, here we consider cultural and provisioning services as economy-related ES
180 and regulating and supporting services as ecology-related ES. Such a context makes
181 Chamrousse an ideal mountain town for studying the dynamics of multiple ES and the
182 compromise between economy and ecology under different management scenarios and to
183 examine the role of biodiversity for multiple ES provision.

184

185 ***2.2 DORIAN, a discrete-event model***

186 The discrete-event model that we developed, named *DORIAN* (Discrete-event model for
187 ecOsystem seRvIce AssessmeNt), models a system in a network composed of two sorts of
188 elements:

- 189 (i) discrete objects (termed “nodes”) representing tangible and non-abstract components
190 constituting a realistic social-ecological system (Table 1 and S1).
- 191 (ii) discrete rules connecting the nodes (termed “edges”), referring to the processes that
192 can occur under the condition of the presence or absence of one or a certain number
193 of nodes that make the functionality of one or certain nodes appear or disappear
194 (Table 2 and S1).

195 In this qualitative model, each node has binary status: either functionally present in the system
196 (called “ON” and noted as “+”), or functionally absent from the system (called “OFF” and
197 noted as “-”) (Tables 1 and S1). The status of a node depends on the status of the nodes to
198 which it is connected by an edge or edges which are triggered by specific semantics (Tables 2
199 and S1). The semantics that make the nodes pass from one status to another (Gaucherel et al.,
200 2017; Gaucherel and Pommereau, 2019) can be either rules (R) or constraints (C). A rule is
201 facultative and optional, defined as a process that can (or cannot) be applicable when its
202 condition or conditions of application are met, while a constraint is a mandatory order and
203 always applied in priority (before all rules), as soon as their conditions of application are met
204 (Tables 2 and S1). Semantics can either be simple (i.e., with one-to-one node interaction) or
205 multiple (i.e., several nodes jointly trigger an event affecting other nodes). Each rule or
206 constraint has a unique name composed by the abbreviation of category (R or C) and an
207 identification number (Table 2).

208 A state refers to ensemble of the nodes’ status (ON or OFF) in a simulation step. The initial
209 condition (Table S1), defined as the first state from which a simulation starts, should be set
210 prior to a simulation by model user (Table 1). During a simulation, each new step consists of

211 triggering one of the possible semantics based on the existing state, then forming a new state.
212 From the initial condition, the model explores all the possibilities of rules and constraints to
213 form new states. This approach allows either forming new states of the system or going back
214 to a state that already appeared. Such a full exploration provides a state space representing
215 assembly of all the possible states, and thus, the exhaustive system trajectories (Fig. 1a). Each
216 simulated state has its unique assembly of nodes at ON status and mirrors a possible state that
217 the real system may reach. Once it comes to a state that contains no node at ON status or a
218 state when none of the semantics are available to be executed, the state is called a deadlock
219 state (Gaucherel and Pommereau, 2019), and is stable. During the simulation, the model
220 allows the distinguishing of some related states, i.e., strongly connected components (SCC,
221 Fig 1b-d). A SCC reflects an assembly of states in structural stability in which all states have
222 possible two-way circulations from one to the other (Fig. 1d). The whole simulation
223 terminates when all states are either in SCC or deadlocks, or are causally connecting these
224 SCC or deadlocks. The model then records all trajectories reached, and displays them as a
225 state space graph (Fig. 1a).

226 The networks in *DORIAN* should not be confused with those in Bayesian network models, in
227 which probabilities, weighting and uncertainties are usually present. Bayesian network
228 models simulate the likelihood that a system may fall into a specific state given the scenario,
229 while *DORIAN* is non-probabilistic and does not give any likelihood. *DORIAN* is possibilistic,
230 as it simulates all the possible fates of a dynamic system with a given scenario. *DORIAN*'s
231 simulation result is mathematically deterministic and finite and, therefore, unique and
232 reproducible.

233

234 ***2.3 Modeling a mountain social-ecological system***

235 **2.3.1 Components and processes**

236 To synthesize knowledge about the mountain town of Chamrousse and to reduce the
237 computational cost, we defined the complex social-ecological system into a network
238 composed of 16 nodes corresponding to observed components and 51 edges (42 optional rules
239 and 9 constraints) corresponding to observed processes defining the main interactions among
240 the elements (Tables 1 and 2; Fig. S1). Choosing such a configuration is not random, but a
241 compromise between the model's simulation cost and degree of resemblance to a real social-
242 ecological system. Each node, either natural- or human-related, and each edge that is related
243 to either biophysical or socio-economic aspects, have a unique ID number and name (Tables 1
244 and 2; Fig. S1). These edges or processes are determined by common sense (e.g., in the
245 winter, natural snow can fall, i.e., R4), academic knowledge (e.g. artificial snow can adversely
246 affect the environment, i.e., R28 and R38) or information from local stakeholders after a
247 series of interviews were held (e.g., summer activities can attract tourists, i.e., R15 and R16;
248 Table 2). For the interviews, a list of 70 questions was conceived (Table S2) and each
249 question was asked to representatives of the following organisms: Chamrousse Town Hall,
250 Chamrousse Ski Club, Chamrousse Ski freestyle, Ski lifts Chamrousse, French National
251 Federation of Hunters, National Office of Hunting and Wild Animals and a resident
252 professional journalist for a mountain biking magazine. Not all questions could be answered
253 by each representative, but enough data were obtained to construct the list of edges (Table 2).
254 These stakeholders therefore provided information about activities of Chamrousse that are not
255 included in the academic literature, including ski station management, artificial snow
256 cannons, tourism, hunting and timber production. According to Fig. S1, *Win* (winter, 16
257 times), *Wat* (water, 13 times), *Res* (residents, 9 times) and *For* (forests, 9 times) were the most
258 frequent nodes involved in rules or constraints as a condition, indicating their fundamental
259 roles in triggering social and ecological processes. Those nodes, that represented flora and
260 fauna [*Ffau* (10 times), *Oflo* (9 times), *Fflo* (8 times) and *Ofau* (5 times)], tourism [*Tou*

261 (tourists; 7 times) and *Ski* (ski station; 5 times)], were the most frequent involved in rules or
262 constraints as a consequence (Fig. S1), indicating their high susceptibility to environmental
263 changes.

264 To define the initial state of the system, *DORIAN* requires an initialization process, in which
265 each node's state (ON (+) versus OFF (-)) should be defined. At the same time, one can
266 manually comment some semantics, i.e., deciding if one or some of the rules/constraints
267 should be considered or not, to mimic different management possibilities. We elaborated six
268 simulation scenarios (S) that differed in initial states or rules conditioning to mimic different
269 disturbance and/or management policies. The six scenarios could be divided into two groups
270 depending on if climate change occurred (in S2, S4 and S6) or not (in S1, S3 and S5, as
271 control scenarios). In a semantic form, this disparity was caused if both the rule R5 “*Win+*
272 (winter) >> *Nsn-* (natural snow)” and R6 “*Win-* >> *Wat-* (water)” were considered (in S2, S4
273 and S6) or not (in S1, S3 and S5). Activating R5 and R6 mimicked the phenomena of winter
274 snow decline and summer water stress, respectively, as a potential consequence of climate
275 change (Dayon et al., 2018). Alternatively, the six scenarios could be divided into three pairs
276 (S1–S2, S3–S4 and S5–S6), differing in initial states and management policies. S1 and S2 had
277 the same initial states to mimic the natural and non-human situations, while the other four
278 scenarios (S3–S6), had the same initial states to mimic situations under human impact (Table
279 1). In a semantic form, S3–S6 contained the node *Res* (residents), while S1 and S2 did not.
280 With the presence of *Res* in the initial state, all the other human nodes, such as *Tim* (timber),
281 *Tou* (tourists), *Ski* (ski activities) and *Asn* (artificial snow), could appear later and had possible
282 interactions with natural nodes in S3 and S4, that were the closest to the actual reality of
283 Chamrousse. These components, including *Tim*, *Tou* and *Asn*, could not appear in S1 and S2
284 due to the absence of *Res*. Differing from S3 and S4, scenarios S5 and S6 mimicked an
285 extreme management policy in which the ski station was closed and ski activities did not take

286 place. To reach this point, a reduced number of rules was used, among which the rules related
287 to the ski station and activities were deactivated (R11, R12, R13, R17, R18, R28 and R38)
288 (Table 2).

289

290 2.3.2 Ecosystem services

291 The presence/absence of certain nodes and occurrence of certain interactions among nodes
292 can represent the biophysical or socio-economic processes or interactions, where ES can be
293 produced or removed. Based on the MEA (2005)'s ES list table (Table S3), we rigorously
294 defined all the possible conditions that make each of the ES appear in the context of the
295 Chamrousse case study (Table 3). Accordingly, missing a condition will make the related ES
296 disappear. One ES could be triggered by several possible conditions (Table 3). The list of ES
297 in Table S3 is slightly different from that in the MEA (2005)'s report, as we adapted ES to the
298 Chamrousse situation. For example, we detailed subcategories of the recreational SE to better
299 reflect Chamrousse's kernel touristic economy (Table S3). Only ES with the number of
300 conditions > 0 were in our case study (Table 3), and not when ES number of conditions = 0
301 (i.e., several ES in the MEA (2005) list, Table S3).

302 In all, there were 22 ES identified for Chamrousse, including 6 provisioning, 5 cultural, 7
303 regulating and 4 supporting ES (Table 3). We classified provisioning and cultural services as
304 economy-related ES (11 in all) and regulating and supporting ES as ecology-related (11 in
305 all). Ecology-related ES refer to the naturally biophysical process-dominated ES that are less
306 directly used for economy, while economy-related ES refer to the human process-dominated
307 ES that can directly supply either lucrative or potentially lucrative goods. For each simulated
308 state, we judged the presence/absence of each ES according to the conditions in Table 3. As
309 each single ES proxy is binary (0 = absence, or 1 = presence), the scores could be considered

310 as metrics of multifunctionality. Here, multifunctionality reflects the system's capacity of
311 hosting the number of items of ES to supply, but does not reflect the abundance of ES.

312 We also created proxies for specific biodiversity indicators by referring to the components in
313 the natural habitat type (Tables 3 and S3). Biodiversity per se can be considered as a
314 supporting ES, but in most cases biodiversity is usually examined separately to investigate its
315 relationship with a single ES or an ES bundle (de Groot et al., 2010; Mace et al., 2012).
316 Accordingly, the proxies for biodiversity were not counted into the ES scores in this study.
317 There were four biodiversity proxies in all, forming a gradient of biodiversity level in five
318 modalities: 0, 1, 2, 3 and 4 (Table 3).

319

320 ***2.4 Simulation and post-treatments***

321 The modelling and simulation work was carried out in Python 3.7 and the TINA tool
322 (Berthomieu 2017). For each scenario, the output datasets of *DORIAN* contained a list of
323 states. For each state, the presence/absence of each node, related SCC, father/son states in
324 evolution, as well the rules that drove such evolution, were all recorded. Then, post-treatments
325 on the model's outputs, including information extraction, indicator calculation, statistical
326 analysis and plotting, were carried out in R 3.6.3 (R Core Team, 2015).

327 To characterize the developmental stage of the study system, we illustrated evolution
328 trajectories among SCC that were determined by their sequence order (i.e. the order in which
329 they appear from the initial state in a graph). To quantitatively determine the sequence order
330 of SCC in a scenario, we calculated a confluent index (*CI*, dimensionless) for each SCC in
331 a network using a derived protocol inspired from the Strahler number for defining river
332 branching (Strahler, 1952) and centripetal protocol used for defining plant root system
333 architecture (Berntson, 1997) (Fig. 1c):

$$334 \quad CI_k = - \sum_{i=1}^{Q-1} (CI_i + 1) \Delta_{i \rightarrow k} \quad (\text{Eq. 1})$$

335 where, CI_k is the confluent index of SCC k ($k \in [1, Q]$, where Q is the total number of
 336 SCC), $CI_i \leq 0$; i is the iterator counting from 1 to $Q-1$; $\Delta_{i \rightarrow k}$ is a binary variable determining if
 337 there is a direct arrow link from i to k (1: presence; 0: absence). Each simulation has only
 338 one initial SCC, and we defined $CI_1 = 0$ for the first SCC. Then, CI_k for all the SCC from 1 to
 339 Q could be computed one by one. As there are no double direction arrows between two SCC
 340 (otherwise they would have formed a bigger SCC), the solution vector is unique for a given
 341 SCC network. Then, all the CI_k are ranged in a descending order and the subscript k of each
 342 SCC is considered as the sequence order (SO) of the SCC. The descending sequence order
 343 (Q^{th} , $Q-1^{th}$, ..., 2^{nd} , 1^{st}) corresponds to the descending order of CI (Fig. 1c). All the states in
 344 the same SCC have the same CI and sequence order as those for their SCC.

345 To explore the effect of biodiversity on the system's multifunctionality, we used boxplots and
 346 principal component analysis (PCA) to show the relationship among biodiversity and ES
 347 scores. To assess the extent to which ecology-related ES are favored relative to economy-
 348 related ES, we calculated the proportion of ecology-related ES score in the total ES score (p_e ,
 349 in %), at either the state or SCC level:

$$350 \quad p_e = \frac{\text{score of ecology-related ES}}{\text{score of ecology-related ES} + \text{score of economy-related ES}} \quad \text{Eq. (2)}$$

351 Following the IPCC's standard definition (McCarthy et al., 2001; Fussler and Klein, 2006),
 352 here, a system's vulnerability of ES provision is defined as the degree to which the system
 353 under external pressure (e.g., climate change), is susceptible or unable to provide ES. Here,
 354 we examined the vulnerability of Chamrousse to climate change (no snowpack and very dry
 355 summers) by comparing the ES proxies between treatment and control scenarios. For a given
 356 indicator (i), its change rate (V_i , in %) of the value in the treatment scenario ($M_{i,T}$, referring to
 357 climate change), relative to the value in the control scenario SC ($M_{i,C}$, referring to no climate
 358 change) can be calculated as:

359
$$V_i = \frac{M_{i,T} - M_{i,C}}{M_{i,C}} \quad \text{Eq. (3)}$$

360 The examined indicators (i) included total ES score, ecology-related ES score, economy-
361 related ES score and p_e , whose change rate of mean value was calculated for healthy,
362 degraded and all states, respectively. Differentiating healthy and degraded states allowed us to
363 know if a system's vulnerability under a treatment scenario was dependent on ES scores. To
364 split healthy and degraded states, we used the quantile 50th of the total ES score in all the
365 states that appeared as the threshold.

366 Besides V_i for the four ES indicators, we additionally examined the change rates (W_j , in %) of
367 the number of healthy states, number of degraded states and number of degraded trajectories
368 (i.e., a degraded trajectory refers to a path crossing from a healthy state to a degraded state)
369 from the control scenario to the treatment scenario:

370
$$W_j = \frac{N_{j,T} - N_{j,C}}{N_{j,C}} \quad \text{Eq. (4)}$$

371 Where, $N_{j,T}$ and $N_{j,C}$ are numbers of the object j (which could be healthy states, degraded
372 states or degraded trajectories) in treatment (climate change) and control (no climate change)
373 scenarios, respectively.

374 V_i and W_j could be both considered as metrics of vulnerability at the system scale, but differed
375 in interpretations. A lower V_i signified a lower ability of the system in treatment for ES supply
376 or for favouring ecology ES. A system is considered less desirable under a treatment scenario
377 when W_j for healthy states is low and/or W_j for degraded states or degraded trajectories is
378 high.

379 **3. RESULTS**

380 ***3.1 State and strongly connected component (SCC) patterns among scenarios***

381 The six scenarios generated unequal numbers of states and SCC (Fig. 2). The natural scenario
382 S1 contained the lowest number of states (88) and SCC (2) (Fig. 2a). The highest numbers of
383 states and SCC were found in different scenarios: 1614 states in realistic S4 and seven SCC in
384 the scenario S6 where skiing was stopped. Scenarios considering the effect of climate change
385 (S2, S4 and S6) always contained more states and SCC than those without climate change
386 (S1, S3 and S5).

387 All six scenarios generated 4210 states and 28 SCC in total. As identical states and SCC in
388 terms of node composition could appear in different scenarios, we identified 1804 different
389 states and 27 SCCs appeared in all the simulations. The number of states also greatly differed
390 among SCC, ranging from two (SCC T) to 484 (SCC K, L and M) (Fig. 2g). SCC were highly
391 specialized with regard to scenarios, there was only one common SCC (P) that appeared in
392 two scenarios (S4 and S6). Different from SCC, states could be either specialists or
393 generalists: among the 1804 states, 258 were found in only a single scenario, 1118 in two
394 scenarios, 36 in three scenarios and 402 in four scenarios. None of the states was present in all
395 the six scenarios.

396 Total ES were positively correlated with the confluent index, *CI* (Fig. S2), upon which was
397 based the sequence order of each SCC (i.e., their trajectory) being determined. The disparities
398 in state and SCC sizes among scenarios resulted in contrasted levels of complexity in terms of
399 trajectories (Fig. 2). The natural scenarios (S1 and S2) had the simplest trajectory with either a
400 simple one-to-one connection (Fig. 2a) or a triangle connection (Fig. 2b), while the human-
401 related scenarios (S3–S6) had more sophisticated trajectories (Figs. 2c-2f). Except for the two
402 natural scenarios (S1 and S2), the number of nodes and ES scores always showed decreasing
403 tendencies from healthy SCC (e.g., Q, R and S in S5) to degraded SCC, especially with regard

404 to those having lost all ecology-related ES (e.g., T and U in S5; Fig. 2e). Climate change
405 scenarios (S2, S4 and S6) exhibited more sophisticated SCC trajectories than their control
406 scenarios. Except for S1, in all the other scenarios with climate change and/or human impact
407 (S2 – S6), all states could directly reach the degraded SCC (i.e., E, J, O, T and Z; Fig. 2),
408 where ES scores were extremely low after the loss of *For* (forest) or *Soh* (topsoil) (Table 3).

409

410 ***3.2 Composition of states and ecosystem services***

411 We presented the spectrum of all the non-repetitive 1804 states that appeared in all the
412 simulations and ranked them in a descending order of total ES score for each of the six
413 scenarios (Fig. S3). Compared to climate change, situation played a more critical role in
414 determining the spectrum structure (including both positioning of a state in the spectrum and
415 number of states) and the number of degraded trajectories (Fig. S3).

416 By juxtaposing the presence and absence of the components (nodes), biodiversity and ES
417 proxies, we could obtain a full picture of the Chamrousse social-ecological system and
418 dynamics for either a given scenario (Fig. 3) or all scenarios together (Fig. S4). In the
419 example of the realistic scenario with climate change (S4), the presence of biodiversity and
420 ES proxies were strikingly different depending on seasons and ES categories (Fig. 3, part I).
421 Among the top 12 most frequently present indicators whose presence was higher than 50%
422 (i.e., from fuel to erosion), two thirds were ecology-related ES, including four supporting and
423 four regulating ES (Fig. 3, part I). Among the ten least frequently present indicators whose
424 presence was less than 30% (i.e., from wild to hunting), most were provisioning (four) or
425 cultural SE (three) (Fig. 3, part I). Similar results could be found when all scenarios were
426 plotted with all 27 SCC, composed of 4202 states (Fig. S4, part I).

427 Regarding the state spectrum with components, ecosystem components differed greatly in
428 their ability to affect biodiversity and ES bundle delivery (Fig. 3, part III and Fig. S4, part

429 IV). Residents (*Res*), topsoil (*Soh*), and forests (*For*) were the most essential components of
430 the system, as they were present in more than 90% of the states and served as the basis of the
431 biodiversity and ES scores (Fig. 3, part III and Fig. S4, part IV). The nodes of forest flora
432 (*Fflo*) and water (*Wat*) were also very important elements of the system, the presence of
433 which resulted in the highest number of ES proxies corresponding to a high ES score (Fig. 3,
434 part III). Timber (*Tim*) was occasionally present, playing a marginal role in enriching ES (Fig.
435 3, part III). The highest ES scores (>15) were found in summer states (*Win-*): the seasonality
436 (oscillation between *Win+* and *Win-*) had a limited role in determining ES scores, despite its
437 importance in influencing the status of several nodes, such as artificial snow (*Asn*), water
438 (*Wat*) and ski activities (*Ski*) (Fig. 3). Natural components were more frequently present than
439 human components, that were more sensitive to the setting of situation (Figs. 3, S3 and S4).

440

441 **3.3 The social-ecological system's vulnerability to climate change**

442 At the state level, the V_i index showed different tendencies for the four ES scores (Table 4). V_i
443 of ecology-related ES and V_i of p_e were usually negative, signifying that ecology-related ES
444 were in decline due to climate change. In contrast, V_i of economy-related ES were usually
445 positive in the two human scenario pairs (S3 – S4 and S5 – S6), signifying that economy-
446 related ES were increasing when climate change was occurring. Contrasted tendencies
447 between ecology- and economy-related ES rendered a generally negative sign of V_i for total
448 ES when pooling all the situations, but diverse signs of V_i for total ES at the situation-level.
449 Among the three scenario pairs corresponding to three situations (natural for S1 – S2, realistic
450 for S3 – S4, no-ski for S5 – S6), V_i of total ES in the S3 – S4 pair increased by over 30%, but
451 decreased by 20% to almost 40% for S5 – S6 and for S1 – S2, respectively. ES proxies in
452 degraded state subsets showed more sensitivity to a changing climate than those in healthy
453 state subsets, if their absolute values of V_i in the significant cases were compared. Regarding

454 the total ES, the absolute values of V_i of total ES in the healthy state subsets were small
455 (<11%), even close to 0, as a result of the offset effect of ecology- and economy-related ES.
456 Yet, in the degraded state subsets, total ES reached very high magnitudes and complex signs
457 of V_i : climate change increased total ES by more than 40% for the S3 – S4 pair, but decreased
458 it by 16% for S5 – S6 and by 55% for S1 – S2.

459 When a changing climate was considered, W_j of healthy states, degraded states and degraded
460 trajectories either increased or remained unchanged (Table S4). Among the three indicators in
461 Table S4, W_j of degraded states and W_j of healthy states increased the most and least,
462 respectively. Among the three situations, the realistic situation (S3 – S4 pair) achieved a
463 better compromise than that when skiing was stopped (S5 – S6 pair), as it had a much smaller
464 W_j of degraded states and trajectories. In climate change scenarios, a number of states with
465 water stress (Wat^-) in both summer (Win^-) and winter (Win^+) were observed, especially in
466 degraded states (Table S5), although Wat^- was only triggered in the summer (via R6, Table
467 2).

468

469 ***3.4 Biodiversity and ecosystem service patterns among scenarios***

470 Compared to the control scenarios (S1, S3 and S5), climate change scenarios (S2, S4 and S6)
471 had comparable economy-related ES scores (Fig. 4b), but only half of the biodiversity (Fig.
472 4d) and ecology-related ES scores (Fig. 4c), resulting in much lower total ES scores (Fig. 4a).
473 Not surprisingly, the natural scenarios (S1 and S2) had the highest biodiversity (mean: 2.5 for
474 S1 and 1.2 for S2, Fig. 4d), the highest ecology-related ES score (9.4 for S1 and 5.4 for S2,
475 Fig. 4c) and the lowest economy-related ES scores (mean: 2.0 for S1 and 1.8 for S2, Fig. 4b),
476 leading to a low total ES score (11.4 for S1 and 7.1 for S2, Fig. 4a). Compared to the natural
477 scenarios, the human-related scenarios (S3–S6) resulted in a lower biodiversity score, but
478 higher ES scores (Fig. 4). The highest total ES score was found in S5 (13.8) for control

479 scenarios, but in S4 (9.6) for climate change scenarios (Fig. 4a). In S4, ecology-related ES
480 declined less due to climate change than that in S6 (Fig. 4c) and the economy-related ES even
481 slightly rose compared to its control scenario (S3) (Fig. 4b). When the ES were presented
482 according to the four categories defined in MEA (2005), regulating and supporting ES (Fig.
483 S5e and S5f) were both more susceptible to climate change than provisioning and cultural ES
484 (Fig. S5c and S5d), thus supporting our classification of economy/ecology-related ES.

485 When pooling all the scenarios together, there were positive synergetic patterns between the
486 biodiversity score and the scores of ES, including ecology-related ES, economy-related ES
487 and total ES (Fig. 5). Similar results were achieved when all the scenarios were not pooled
488 together (i.e., only in climate change scenarios or only in no climate change scenarios),
489 indicating a limited effect of climate change on such synergetic patterns (Fig. S6). The highest
490 increase in total and ecology-related ES scores occurred when the biodiversity score shifted
491 from 0 to 1 (Fig. 5a and 5c). When the biodiversity score continued to increase from 1 to 4,
492 the increment of total and ecology-related ES scores decreased and reached a stable level
493 (Figs. 5a and 5c). The positive effect of biodiversity on economy-related ES score was
494 present, but to a lower extent compared to that for ecology-related ES (Fig. 5b). When the
495 biodiversity score changed from 0 to 1, no increase in economy-related ES score was found
496 (Fig. 5b). A more pronounced increase in the economy-related ES score was only found with
497 higher biodiversity scores (from 1 to 4; Fig. 5b). An increasing biodiversity score tended to
498 decrease the variance of ecology-related ES scores (Fig. 5c), but had a small effect on
499 economy-related ES (Fig. 5b).

500 The generally synergetic relationships among the investigated biodiversity and SE indicators
501 were also represented in the principal component analysis with all scenarios included (Fig.
502 S7). All indicators were linked together along the 1st principal component (*x*-axis) explaining
503 66.2 % of the total variance. This axis could therefore be interpreted as both gradients of

504 biodiversity and ES, here in synergy. The 2nd principal component (y-axis) explained 28.1 %
505 of the variance and differentiated economy- and ecology-related ES, corresponding to the
506 phenomenon that certain scenarios (e.g., S1 and S2) and SCC (e.g., A and B) favored ecology
507 over economy.

508 4. DISCUSSION

509 4.1 Changes in the provision of ecosystem services in a changing climate (Hypothesis 1)

510 Our study is one of the first to show how a model can be used to disentangle the trajectories of
511 numerous ES in a complex bundle. In particular, we demonstrated the negative effect of
512 climate change on ecology-related ES in a mountain social-ecological system undergoing
513 anthropogenic pressure. We show that climate change would reduce the system's
514 multifunctionality through several mechanisms. For example, because of drier summers and a
515 reduced natural snowpack in the winter, water reserves dropped by 40% – 50%, leading to a
516 succession of transitions affecting other processes in which water was an indispensable
517 component (Figs. 3 and S3). Our results are consistent with the literature in that water stress
518 has a negative long-term effect on both mountain prairies and forests, with detrimental effects
519 on ES provision (Deléglise et al., 2015; Hartl-Meier et al., 2014). Our model also showed that
520 in the climate change scenarios (S2, S4 and S6), summer water stress could extend into the
521 winter periods, where a number of states with water deficits (*Wat-*) were present in the zone
522 of degraded states (Figs. 3 and S3; Table S5). Data on this legacy of summer water stress on
523 winter ecosystem functioning and ES provision are scanty in literature, probably due to the
524 difficulty in establishing causal effects between summer and winter processes via an
525 experimental approach. Therefore, compared to other ES models, our discrete-event model
526 allows us to investigate and anticipate transitional events across periods (e.g. seasons).

527 The frequency of the natural snowpack (*Nsw+*) was not very sensitive to climate change,
528 because it could only be triggered in the winter (*Win+*, Table 3; Fig. 3) and was variable
529 regardless of climate. In contrast, an increase in water reserves (*Wat+*) could be due to either
530 abiotic (natural snow presence, R8; Table 2) or biotic (difference in water conditions between
531 forests and bogs, R7; Table 2) factors, and so was more sensitive to changes in climatic
532 conditions.

533 Although a changing climate change had a limited effect on the number and positioning of
534 healthy states in the spectra, it significantly increased the number of degraded states, and so
535 produced more pathways through which a healthy state could shift to a degraded state (Table
536 4; Fig. S3). The important lesson to learn from this result is that even though a system can be
537 healthy in terms of multifunctionality, it could be more prone to degradation in the context of
538 climate change. This result highlights the necessity to consider a system as highly dynamic
539 where its functions and ES have many possible trajectories: a simple diachronic approach
540 cannot be used to assess the impact of climate change on a system.

541 In spite of the generally negative effect of climate change, economy-related ES scores could
542 be maintained and even show a positive response to climate change (e.g. touristic activities in
543 degraded states) (Table 4). Therefore, *DORIAN* is useful for examining individually the
544 trajectories of ecology- and economy-related ES scores along the state and SCC evolutions.
545 Additionally, the holistic approach that *DORIAN* also offers allows the user to determine
546 tradeoffs between ES facing perturbations.

547

548 ***4.2 The regulating role of management in vulnerability mitigation (Hypothesis 1)***

549 To date, the impacts of climate change and management on multiple ES are still inadequately
550 explored in mountain regions (Schirpke et al., 2013). Compared to studies that usually focus
551 on one single landscape (e.g., mountain forests), one single leverage (e.g., forestry
552 management) or one single category of ES (e.g., regulating ES) in a study (Elkin et al., 2015;
553 Lafond et al., 2017; Seidl et al., 2019), a more multidisciplinary approach embracing a
554 multitude of disturbance sources (e.g., management policy and climate change) and a wider
555 range of ES is much needed (Schirpke et al., 2013; Brunner et al., 2017). To tackle such a
556 challenge, our case study that was simulated by *DORIAN* enriches our knowledge on how
557 management policies could mitigate the effect of climate change on a system's

558 multifunctionality. We found that the three modelled situations responded very differently to
559 climate change, validating our first hypothesis (Tables 4 and S4). In the ‘natural’ situation
560 (absence of human beings), healthy states had a low vulnerability to climate change, but this
561 situation is not realistic and so provides limited management indicators for stakeholders.
562 Between the two situations where humans were present, the most realistic situation (with
563 human-related winter activities) was less vulnerable to climate change. Although the ecology
564 -related ES score did not significantly drop when climate change occurred, the economy-
565 related ES score was boosted (Table 4). This phenomenon occurs because human-related
566 skiing activities (*Ski*) and artificial snow (*Asn*) were both active in the realistic scenarios.
567 Accordingly, the number of healthy states that were increased was effective against the drop
568 of ecology-related ES scores. In terms of economy, the artificial snow production (*Asn+*)
569 ensures that tourists (*Tou+*) come to the town, which in turn activates the skiing (*Ski*) and
570 cultural ES, even in the absence of the natural snowpack. In the third situation that we
571 modelled (where humans were present but skiing activities did not take place), winter
572 activities were much lower than in the more realistic situation (with human-related winter
573 activities, Fig. 3), and thus could greatly reduce the town’s economic gain.
574 Our results show that although certain economic activities can mitigate negative effects of
575 climate change on ES provision, regardless of situation, even a healthy and stable state with
576 high multifunctionality could directly jump to a degraded state with low multifunctionality
577 without passing through any intermediary states (e.g., SCC F → J in S3 or Q → T in S5; Fig.
578 2). Such a phenomenon could occur if certain key components (e.g. forest and topsoil)
579 become absent or dysfunctional (Figs. 3 and Fig. S3). In addition, this trajectory was not
580 sensitive to climate change (Fig. S3), meaning that irrational practices (e.g., clear-cutting of
581 forest or agriculture on steep slopes causing erosion and topsoil loss), that were harmful to
582 fundamental components, could immediately make the system collapse.

583

584 **4.3 Effect of biodiversity on multifunctionality (Hypothesis 2)**

585 Results from our model scenarios showed that a system with no biodiversity at all could only
586 provide small amounts of ES of any category (Fig. 5). This result is well in agreement with
587 many studies showing that significant biodiversity loss due to e.g., pollution and habitat
588 degradation, can lead to serious ecological dysfunction and social-economic problems
589 (Cardinale et al., 2012; Díaz et al., 2006; Hooper et al., 2012). However, while a positive
590 effect of increased biodiversity on the overall ES level of a system is clear, the relationship
591 between biodiversity and each ES category is questionable (de Groot et al., 2010). Studies
592 testing the effect of high biodiversity on different social-ecological systems found it can be
593 positively, neutrally, or negatively associated with different functions or ES (Chan et al.,
594 2007; Loreau, 2001; van der Plas et al., 2016). But most of these studies examined
595 biophysical process-based ES, not economy-related ES. Here, our results provide new
596 evidence, showing that increased biodiversity improved the total ES score, but it had a
597 minimal effect on economy-related ES (Figs. 5 and S6). At the same time, biodiversity was
598 found to favour the system's stability with regard to the supply of ecology-related ES, as the
599 variance of ecology-related ES scores at higher biodiversity levels was lower (Fig. 5c). Yet,
600 such a phenomenon was absent for economy-related ES (Fig. 5b). These results are due to the
601 ecology-related ES corresponding to biophysical processes that depend on the presence of
602 natural elements (i.e., soil, water, forest and bogs). The absence of these elements suppressed
603 not only most of the supporting and regulating services, but also other elements that depend
604 on them (e.g. flora and fauna). Economy-related SE were more related to anthropological
605 components (e.g., tourists, logging and ski activities) despite some dependency on natural
606 elements. We found that, with increasing biodiversity, only ecology-related ES were boosted
607 at low biodiversity levels, while high-level ecology- and economy-related ES were both

608 maintained at high biodiversity levels. This result highlights the primary importance of
609 conserving high biodiversity in a social ecological system, for an optimal “biodiversity –
610 multifunctionality” win-win strategy.

611 For fulfilling the Sustainable Development Goals of United Nations, associating biodiversity
612 conservation with socio-economic improvements for communities has been launched in the
613 Man and the Biosphere (MAB) Programme of UNESCO (Persha et al., 2011). Although the
614 importance of integrating a “biodiversity – multifunctionality” win-win strategy against both
615 ecological and/or economical risks is major (Chan et al., 2007; Xiao et al., 2018), the current
616 theoretical framework of biological conservation still inadequately juxtaposes multiple ES,
617 especially economy-related ES, to the equally high level of importance given to biodiversity
618 (Xiao et al., 2018, 2019). One of the major reasons is due to the lack of information on the
619 provisional and feedback links between biodiversity and their interactions, and ecosystem
620 functions and services (Xiao et al., 2019). Our model shows that the interwoven biophysical
621 and social-economic aspects share several components (e.g. habitat, tourists and ski
622 activities), and that a holistic approach is necessary when studying a social-ecological system.
623 Therefore, we propose that the theoretical concept or practical roadmap of biological
624 conservation is revised by either expanding the paradigm to include social-economic aspects
625 or to create a new, parallel but complementary paradigm. This paradigm would concern
626 social-economic conservation, that tackles the vulnerability of social-economic aspects of a
627 system.

628

629 ***4.4 Advantages and limitations of DORIAN for ecosystem service modelling***

630 To investigate the vulnerability of ES provision to climate change, previous studies have
631 mostly quantified ES values and occasionally their magnitudes and spatiotemporal patterns.
632 ES provision is then compared in treatment and control scenarios of climate change (e.g.,

633 Schröter et al., 2005; Elkin et al., 2015). However, finding robust and data-supported case
634 studies and well-calibrated quantitative ES models is usually difficult, thus hindering our
635 understanding of the effects of climate change and biodiversity on multiple ES relationships
636 in social-ecological systems. Here, with the discrete-event model *DORIAN*, we propose an
637 alternative, but complementary approach to assess multiple ES without the necessity to
638 quantify any ES value.

639 Although stakeholders and policy-makers need quantitative ES values for diagnosis and
640 decision-making, knowing the trajectory and fate of ES is even more important than their
641 value in the global change context (e.g. knowing if a system is a carbon sink or source, rather
642 than how much carbon is stored, Mao et al., 2019). Therefore, a qualitative and discrete-event
643 model has a specific niche when examining complex bundles of ES. As *DORIAN* simulates
644 fully all the states of a system, as well as the pathways or trajectories among states, important
645 ecological concepts, such as multifunctionality and disturbance (e.g. climate change in our
646 case study), can be rigorously defined and quantified. Therefore, by using *DORIAN*, we
647 avoided characterizing ES in one or several snapshot-like states of a system as is usually
648 performed by many quantitative ES models e.g., Schroter (2005). *DORIAN* can also
649 investigate the legacy effect of a process as it occurs, as well as the potential consequences
650 over time. These legacy effects (e.g. the influence of summer water stress on winter ES in our
651 case study), are usually ignored in quantitative ES models due to limited data. *DORIAN*
652 therefore provides a feasible and efficient way to include ES when tackling the question of
653 multifunctionality of a system.

654

655 A common criticism of discrete-event models is that assumptions are over-simplified because
656 of the binary status of components and qualitative processes. In a discrete-event model, while
657 model configuration is qualitative at the component and process levels, simulations and post-

658 analyses are quantitative at the network system level. Both quantitative ES models and
659 discrete-event models mimic a simplified reality, as in any model, but they differ in their
660 focus of description of a system. A quantitative ES model, which can be either probabilistic
661 (i.e., frequentist or Bayesian) or deterministic, focuses on the description of the inherent
662 biophysical and social driven processes in one or several components, triggering the ES of a
663 system under one or several states. A discrete-event model however, makes the inherent
664 processes as simple as possible (e.g., by using binary values to represent presence and
665 absence), but gives more focus on the extensive interactions between components within or
666 across states. Therefore, discrete-event models can be used to model highly complex social-
667 ecological systems (e.g., large interaction networks with hundreds of components and
668 rules/constraints intervening at multiple scales) and to focus on changes over the long term. In
669 our case study, 22 services from all four ES categories (MA, 2005) were included in *DORIAN*,
670 but all the listed ES in either MEA (2005) or in TEEB (Kumar, 2010) criteria could be
671 included if desired (Tables 3 and S3). This methodology for ES modelling (Table 3) is generic
672 and can be standardized and transposed to other case studies, enabling valuable comparisons
673 to be made across different types of ecosystems and social-ecological systems. It is to be
674 noted that *DORIAN* has the potential to be coupled with quantitative ES models, provide that
675 the latter could be calibrated and validated in all or several specific states. In the current
676 definition of multifunctionality, relative importance among ES is not yet represented, but can
677 be taken into account in the optimisation of desired systems and management scenarios,
678 provided that multisectorial decision-makers could provide such information on the priority of
679 ES.

680 The paired component interactions in a discrete-event model require users to identify and
681 define relevant components and processes. We were able to represent the complex
682 Chamrousse social-ecological system using only 16 components (e.g. type of landscape, taxa

683 and anthropogenic activities), that interacted via 51 processes. This simplification enabled us
684 to reach a compromise between our research question and the available computational
685 capacity. Processes may have different confidence levels according to the reliability of
686 sources of knowledge. We did not include the estimation of confidence levels when applying
687 the model to the Chamrousse case study, as we considered that the knowledge used to
688 parametrize the processes was robust and testing the effect of confidence level of rules was
689 not the objective of this study. Such an issue could be tackled by conducting uncertainty
690 analyses, which consist in creating extra scenario pairs with activated or deactivated
691 semantics mimicking the uncertainty process.

692 An advantage of discrete-event models is that any spatial or time scale can be investigated, as
693 any ecosystem component can be included. However, ecological and anthropogenic processes
694 can be short- or long-term, or even both, e.g., destruction of a forest. In our case study, we did
695 not differentiate between time scales, therefore, direct comparisons between stable states are
696 difficult. However, our objective was to identify the potential degradation of states and system
697 vulnerability in diverse situations. To better integrate the temporal scale into *DORIAN*, we
698 suggest characterizing connectivity among states or SCC, which can partially reflect the
699 concept of time by indicating the orders of occurrence for processes.

700 Validating results from *DORIAN*'s simulations on the dynamics of a system is another
701 challenge, as independent ground-truth data on socio-ecological systems are still scanty.
702 Moreover, these data may never exist, as some states that occurred in the model's results may
703 never occur in reality. However, conducting such exploratory model simulations would still
704 be highly useful, as it can provide valuable information on a system's fate and anticipate
705 catastrophic events due to certain management practices.

706

707 **5. CONCLUSION**

708 Using a discrete-event model, *DORIAN*, we examined modifications in the provision and
709 trajectories of ES in three diverse situations in a mountain social-ecological system subjected
710 to climate change (dry summers and warm winters with reduced snowpack). The degree of
711 human impact differed in each situation, and scores (total number of biodiversity and ES
712 proxies) were calculated for each scenario simulated. Climate change reduced the system's
713 multifunctionality (ES scores decreased), and increased the number of degraded states, as well
714 as the trajectories from healthy to degraded states. Certain economic activities, e.g., skiing,
715 could mitigate the negative effect of climate change on overall ES provision. However,
716 *DORIAN* showed that even a healthy and stable state with high multifunctionality could
717 directly jump to a degraded state with low multifunctionality without passing through any
718 intermediary states. Such a phenomenon could occur if certain key components become
719 absent within the system. With increasing levels of biodiversity, only ecology-related ES were
720 boosted at low biodiversity levels, while both ecology- and economy-related ES were
721 maintained at high biodiversity levels. This result highlights the primary importance of
722 conserving high biodiversity in a social-ecological system, for an optimal “biodiversity –
723 multifunctionality” win-win strategy. The holistic modelling approach with *DORIAN* is
724 methodologically generic and provides a novel and alternative solution to assess the
725 multifunctionality of social-ecological systems without the necessity to quantify any ES.

726

727 **ACKNOWLEDGMENTS**

728 We thank the Mairie de Chamrousse, D. Leyssieux, E. Lauer, N. de Klerc, C. Arlot and F.
729 Mounier for interviews and document sharing related to Chamrousse. We thank H. Rey
730 (CIRAD) and C. Carpentier (University of Namur) for their technical support in terms of
731 interviews and model simulation. Funding was provided by the French and Mexican

732 governments (ECOPICS project, ANR-16-CE03-0009 and CONACYT-2 73659). Finally,

733 we thank the anonymous reviewers for their valuable comments on our manuscript.

734

735 **REFERENCES**

- 736 Aber, J.D., Melillo, J.M., McLaugherty, C.A., 1990. Predicting long-term patterns of mass
737 loss, nitrogen dynamics, and soil organic matter formation from initial fine litter
738 chemistry in temperate forest ecosystems. *Can. J. Bot.* 68, 2201–2208.
739 <https://doi.org/10.1139/b90-287>
- 740 Aguilera, P.A., Fernández, A., Fernández, R., Rumí, R., Salmerón, A., 2011. Bayesian
741 networks in environmental modelling. *Environmental Modelling & Software* 26, 1376–
742 1388. <https://doi.org/10.1016/j.envsoft.2011.06.004>
- 743 Andereck, K.L., 1995. Environmental consequences of tourism. In *Linking tourism, the*
744 *environment, and sustainability: topical volume of compiled papers from a special*
745 *session of the annual meeting of the National Recreation and Park Association, 1994:*
746 *Minneapolis, MN, October 12-14, 1994 (Vol. 323, p. 77).* Intermountain Research
747 Station
- 748 Berntson, G.M., 1997. Topological scaling and plant root system architecture: developmental
749 and functional hierarchies. *New Phytol* 135, 621–634. <https://doi.org/10.1046/j.1469-8137.1997.00687.x>
- 751 Bernués, A., Alfnes, F., Clemetsen, M., Eik, L.O., Faccioni, G., Ramanzin, M., Ripoll-Bosch,
752 R., Rodríguez-Ortega, T., Sturaro, E., 2019. Exploring social preferences for ecosystem
753 services of multifunctional agriculture across policy scenarios. *Ecosystem Services* 39,
754 101002. <https://doi.org/10.1016/j.ecoser.2019.101002>
- 755 Bragazza, L., 2008. A climatic threshold triggers the die-off of peat mosses during an extreme
756 heat wave. *Global Change Biology* 14, 2688–2695. <https://doi.org/10.1111/j.1365-2486.2008.01699.x>
- 758 Bragg, O.M., 2015. Mountain peatlands. *Mires and Peat*, 15, 1-3. <http://www.mires-and-peat.net/pages/volumes/map15/map1500.php>
- 760 Breeuwer, A., Robroek, B.J.M., Limpens, J., Heijmans, M.M.P.D., Schouten, M.G.C.,
761 Berendse, F., 2009. Decreased summer water table depth affects peatland vegetation.
762 *Basic and Applied Ecology* 10, 330–339. <https://doi.org/10.1016/j.baae.2008.05.005>
- 763 Brunner, S.H., Huber, R., Grêt-Regamey, A., 2017. Mapping uncertainties in the future
764 provision of ecosystem services in a mountain region in Switzerland. *Reg. Environ.*
765 *Chang.* <https://doi.org/10.1007/s10113-017-1118-4>
- 766 Bugmann, H., 2001. A review of forest gap models. *Climatic Change* 51, 259–305.
767 <https://doi.org/10.1023/A:1012525626267>
- 768 Cardinale, B.J., Duffy, J.E., Gonzalez, A., Hooper, D.U., Perrings, C., Venail, P., Narwani,
769 A., Mace, G.M., Tilman, D., Wardle, D.A., Kinzig, A.P., Daily, G.C., Loreau, M.,
770 Grace, J.B., Larigauderie, A., Srivastava, D.S., Naeem, S., 2012. Biodiversity loss and
771 its impact on humanity. *Nature* 486, 59–67. <https://doi.org/10.1038/nature11148>
- 772 Chan, K.M.A., Pringle, R.M., Ranganathan, J., Boggs, C.L., Chan, Y.L., Ehrlich, P.R., Haff,
773 P.K., Heller, N.E., Al-Khafaji, K., Macmynowski, D.P., 2007. When Agendas Collide:
774 Human Welfare and Biological Conservation. *Conservation Biology* 21, 59–68.
775 <https://doi.org/10.1111/j.1523-1739.2006.00570.x>
- 776 Costanza, R., Limburg, K., Naeem, S., O'Neill, R.V., Paruelo, J., Raskin, R.G., Sutton, P.,
777 1997. The value of the world's ecosystem services and natural capital 387, 8.
- 778 Crossman, N.D., Connor, J.D., Bryan, B.A., Summers, D.M., Ginnivan, J., 2010.
779 Reconfiguring an irrigation landscape to improve provision of ecosystem services.
780 *Ecological Economics* 69, 1031–1042. <https://doi.org/10.1016/j.ecolecon.2009.11.020>
- 781 Csilléry, K., Kunstler, G., Courbaud, B., Allard, D., Lassègues, P., Haslinger, K., Gardiner,
782 B., 2017. Coupled effects of wind-storms and drought on tree mortality across 115

783 forest stands from the Western Alps and the Jura mountains. *Global Change Biology* 23,
784 5092–5107. <https://doi.org/10.1111/gcb.13773>

785 Dayon, G., Boé, J., Martin, É., Gailhard, J., 2018. Impacts of climate change on the hydrological cycle
786 over France and associated uncertainties. *Comptes Rendus Geoscience* 350, 141–153.
787 <https://doi.org/10.1016/j.crte.2018.03.001>

788 de Groot, R.S., Alkemade, R., Braat, L., Hein, L., Willemsen, L., 2010. Challenges in
789 integrating the concept of ecosystem services and values in landscape planning,
790 management and decision making. *Ecological Complexity* 7, 260–272.
791 <https://doi.org/10.1016/j.ecocom.2009.10.006>

792 Deléglise, C., Meisser, M., Mosimann, E., Spiegelberger, T., Signarbieux, C., Jeangros, B.,
793 Buttler, A., 2015. Drought-induced shifts in plants traits, yields and nutritive value
794 under realistic grazing and mowing managements in a mountain grassland. *Agriculture,*
795 *Ecosystems & Environment* 213, 94–104. <https://doi.org/10.1016/j.agee.2015.07.020>

796 Delphin, S., Escobedo, F.J., Abd-Elrahman, A., Cropper, W., 2013. Mapping potential carbon
797 and timber losses from hurricanes using a decision tree and ecosystem services driver
798 model. *Journal of Environmental Management* 129, 599–607.
799 <https://doi.org/10.1016/j.jenvman.2013.08.029>

800 Di Giusto, C., Gaucherel, C., Kludel, H., Pommereau, F., 2019. Pattern Matching in Discrete
801 Models for Ecosystem Ecology:, in: *Proceedings of the 12th International Joint*
802 *Conference on Biomedical Engineering Systems and Technologies*. Presented at the
803 10th International Conference on Bioinformatics Models, Methods and Algorithms,
804 SCITEPRESS - Science and Technology Publications, Prague, Czech Republic, pp.
805 101–111. <https://doi.org/10.5220/0007485801010111>

806 Díaz, S., Fargione, J., Iii, F.S.C., Tilman, D., 2006. Biodiversity loss threatens human well-
807 being. *PLOS Biology* 4, e277. <https://doi.org/10.1371/journal.pbio.0040277>

808 Diwold, K., Dullinger, S., Dirnböck, T., 2010. Effect of nitrogen availability on forest
809 understorey cover and its consequences for tree regeneration in the Austrian limestone
810 Alps. *Plant Ecol* 209, 11–22. <https://doi.org/10.1007/s11258-009-9715-z>

811 Drescher, M., Thomas, S.C., 2013. Snow cover manipulations alter survival of early life
812 stages of cold-temperate tree species. *Oikos* 122, 541–554.
813 <https://doi.org/10.1111/j.1600-0706.2012.20642.x>

814 Durand, Y., Giraud, G., Laternser, M., Etchevers, P., Mérindol, L., Lesaffre, B., 2009.
815 Reanalysis of 47 years of climate in the French Alps (1958–2005): Climatology and
816 trends for snow cover. *J. Appl. Meteor. Climatol.* 48, 2487–2512.
817 <https://doi.org/10.1175/2009JAMC1810.1>

818 Elkin, C., Gutiérrez, A.G., Leuzinger, S., Manusch, C., Temperli, C., Rasche, L., Bugmann,
819 H., 2013. A 2 °C warmer world is not safe for ecosystem services in the European Alps.
820 *Glob Change Biol* 19, 1827–1840. <https://doi.org/10.1111/gcb.12156>

821 Fontana, V., Radtke, A., Bossi Fedrigotti, V., Tappeiner, U., Tasser, E., Zerbe, S., Buchholz,
822 T., 2013. Comparing land-use alternatives: Using the ecosystem services concept to
823 define a multi-criteria decision analysis. *Ecological Economics* 93, 128–136.
824 <https://doi.org/10.1016/j.ecolecon.2013.05.007>

825 Franklin, J.F., Spies, T.A., Pelt, R.V., Carey, A.B., Thornburgh, D.A., Berg, D.R.,
826 Lindenmayer, D.B., Harmon, M.E., Keeton, W.S., Shaw, D.C., Bible, K., Chen, J.,
827 2002. Disturbances and structural development of natural forest ecosystems with
828 silvicultural implications, using Douglas-fir forests as an example. *Forest Ecology and*
829 *Management*, 155, 399–423. [https://doi.org/10.1016/S0378-1127\(01\)00575-8](https://doi.org/10.1016/S0378-1127(01)00575-8)

830 Fraterrigo, J.M., Rusak, J.A., 2008. Disturbance-driven changes in the variability of
831 ecological patterns and processes. *Ecology Letters* 11, 756–770.
832 <https://doi.org/10.1111/j.1461-0248.2008.01191.x>

833 Füssel, H.-M., Klein, R.J.T., 2006. Climate change vulnerability assessments: An evolution of
834 conceptual thinking. *Climatic Change* 75, 301–329. <https://doi.org/10.1007/s10584-006-0329-3>

836 Future Earth. 2014. Future Earth 2025 Vision. ICS Paris, France. ISBN 978-0-9330357-95-5

837 Gaucherel, C., Pommereau, F., 2019. Using discrete systems to exhaustively characterize the
838 dynamics of an integrated ecosystem. *Methods Ecol Evol* 10, 1615–1627.
839 <https://doi.org/10.1111/2041-210X.13242>

840 Gaucherel, C., Théro, H., Puiseux, A., Bonhomme, V., 2017. Understand ecosystem regime
841 shifts by modelling ecosystem development using Boolean networks. *Ecological
842 Complexity* 31, 104–114. <https://doi.org/10.1016/j.ecocom.2017.06.001>

843 Gössling, S., 2002. Global environmental consequences of tourism. *Global environmental
844 change* 12.4: 283–302. [https://doi.org/10.1016/S0959-3780\(02\)00044-4](https://doi.org/10.1016/S0959-3780(02)00044-4)

845 Hartl-Meier, C., Dittmar, C., Zang, C., Rothe, A., 2014. Mountain forest growth response to
846 climate change in the Northern Limestone Alps. *Trees* 28, 819–829.
847 <https://doi.org/10.1007/s00468-014-0994-1>

848 Hooper, D.U., Adair, E.C., Cardinale, B.J., Byrnes, J.E.K., Hungate, B.A., Matulich, K.L.,
849 Gonzalez, A., Duffy, J.E., Gamfeldt, L., O’Connor, M.I., 2012. A global synthesis
850 reveals biodiversity loss as a major driver of ecosystem change. *Nature* 486, 105–108.
851 <https://doi.org/10.1038/nature11118>

852 Huss, M., Bookhagen, B., Huggel, C., Jacobsen, D., Bradley, R.S., Clague, J.J., Vuille, M.,
853 Buytaert, W., Cayan, D.R., Greenwood, G., Mark, B.G., Milner, A.M., Weingartner, R.,
854 Winder, M., 2017. Toward mountains without permanent snow and ice. *Earth’s Future*
855 5, 418–435. <https://doi.org/10.1002/2016EF000514>

856 Kormos, P.R., Marks, D., McNamara, J.P., Marshall, H.P., Winstral, A., Flores, A.N., 2014.
857 Snow distribution, melt and surface water inputs to the soil in the mountain rain–snow
858 transition zone. *Journal of Hydrology* 519, 190–204.
859 <https://doi.org/10.1016/j.jhydrol.2014.06.051>

860 Kristensen, N.P., Chisholm, R.A., McDonald - Madden, E., 2019. Dealing with high
861 uncertainty in qualitative network models using Boolean analysis. *Methods Ecol Evol*
862 10, 1048 - 1061. <https://doi.org/10.1111/2041-210X.13179>

863 Kumar, P., 2010. *The Economics of Ecosystems and Biodiversity: Ecological and Economic
864 Foundations*. Earthscan, London.

865 Lafond, V., Cordonnier, T., Mao, Z., Courbaud, B., 2017. Trade-offs and synergies between
866 ecosystem services in uneven-aged mountain forests: evidences using Pareto fronts. *Eur
867 J Forest Res* 136, 997–1012. <https://doi.org/10.1007/s10342-016-1022-3>

868 Landuyt, D., Broekx, S., D’hondt, R., Engelen, G., Aertsens, J., Goethals, P.L.M., 2013. A
869 review of Bayesian belief networks in ecosystem service modelling. *Environmental
870 Modelling & Software* 46, 1–11. <https://doi.org/10.1016/j.envsoft.2013.03.011>

871 Larsen, P.E., Field, D., Gilbert, J.A., 2012. Predicting bacterial community assemblages using
872 an artificial neural network approach. *Nat Methods* 9, 621–625.
873 <https://doi.org/10.1038/nmeth.1975>

874 Lescourret, F., Magda, D., Richard, G., Adam-Blondon, A.-F., Bardy, M., Baudry, J.,
875 Doussan, I., Dumont, B., Lefèvre, F., Litrico, I., Martin-Clouaire, R., Montuelle, B.,
876 Pellerin, S., Plantegenest, M., Tancoigne, E., Thomas, A., Guyomard, H., Soussana, J.-
877 F., 2015. A social–ecological approach to managing multiple agro-ecosystem services.

878 Current Opinion in Environmental Sustainability, Open Issue 14, 68–75.
879 <https://doi.org/10.1016/j.cosust.2015.04.001>

880 Littlewood, N., Anderson, P., Artz, R., Bragg, O., Lunt, P., 2010. Peatland Biodiversity.
881 IUCN UK Peatland Programme, Edinburgh

882 Loreau, M., NAEEM, S., Inchausti, P., Bengtsson, J., Grime, J. P., Hector, A., Hooper, D.U.,
883 Huston, M. A., Raffaelli, D., Schmid, B., Tilman, D., Wardle D. A. 2001. Biodiversity
884 and Ecosystem Functioning: Current Knowledge and Future Challenges. *Science* 294,
885 804–808. <https://doi.org/10.1126/science.1064088>

886 Mace, G.M., Norris, K., Fitter, A.H., 2012. Biodiversity and ecosystem services: a
887 multilayered relationship. *Trends in Ecology & Evolution* 27, 19–26.
888 <https://doi.org/10.1016/j.tree.2011.08.006>

889 Mao, Z., Bonis, M.-L., Rey, H., Saint-André, L., Stokes, A., Jourdan, C., 2013. Which
890 processes drive fine root elongation in a natural mountain forest ecosystem? *Plant*
891 *Ecology & Diversity* 6, 231–243. <https://doi.org/10.1080/17550874.2013.788567>

892 Mao, Z., Derrien, D., Didion, M., Liski, J., Eglin, T., Nicolas, M., Jonard, M., Saint-André,
893 L., 2019. Modeling soil organic carbon dynamics in temperate forests with Yasso07.
894 *Biogeosciences* 16, 1955–1973. <https://doi.org/10.5194/bg-16-1955-2019>

895 Manzoni, S., Porporato, A., 2009. Soil carbon and nitrogen mineralization: Theory and
896 models across scales. *Soil Biology and Biochemistry* 41, 1355–1379.
897 <https://doi.org/10.1016/j.soilbio.2009.02.031>

898 McCarthy, J. J., Canziani, O. F., Leary, N. A., Dokken, D. J., & White, K. S. (Eds.), 2001.
899 Climate change 2001: impacts, adaptation, and vulnerability: contribution of Working
900 Group II to the third assessment report of the Intergovernmental Panel on Climate
901 Change (Vol. 2). Cambridge University Press.

902 McDonald-Madden, E., Sabbadin, R., Game, E.T., Baxter, P.W.J., Chadès, I., Possingham,
903 H.P., 2016. Using food-web theory to conserve ecosystems. *Nat Commun* 7, 10245.
904 <https://doi.org/10.1038/ncomms10245>

905 Merritt, W.S., Letcher, R.A., Jakeman, A.J., 2003. A review of erosion and sediment transport
906 models. *Environmental Modelling & Software, The Modelling of Hydrologic Systems*
907 18, 761–799. [https://doi.org/10.1016/S1364-8152\(03\)00078-1](https://doi.org/10.1016/S1364-8152(03)00078-1)

908 Millennium Ecosystem Assessment (2005). *Ecosystems and human well-being: synthesis*.
909 Washington, DC: Island Press. ISBN 1-59726-040-1.

910 Minayeva, T.Yu., Bragg, O.M., Sirin, A.A., 2017. Towards ecosystem-based restoration of
911 peatland biodiversity. *Mires and Peat* 1–36.
912 <https://doi.org/10.19189/MaP.2013.OMB.150>

913 Moore, P.D., 1989. The ecology of peat-forming processes: a review. *International Journal of*
914 *Coal Geology* 12, 89–103. [https://doi.org/10.1016/0166-5162\(89\)90048-7](https://doi.org/10.1016/0166-5162(89)90048-7)

915 Moser, D., Sauberer, N., Willner, W., 2011. Generalisation of drought effects on ecosystem
916 goods and services over the Alps. *AlpWaterScarce-WP7 “Optimal Ecological*
917 *Discharge”*. Project Report. Vienna, Austria

918 Negro, M., Isaia, M., Palestrini, C., Rolando, A., 2009. The impact of forest ski-pistes on
919 diversity of ground-dwelling arthropods and small mammals in the Alps. *Biodivers*
920 *Conserv* 18, 2799–2821. <https://doi.org/10.1007/s10531-009-9608-4>

921 Nelson, E., Mendoza, G., Regetz, J., Polasky, S., Tallis, H., Cameron, Dr., Chan, K.M., Daily,
922 G.C., Goldstein, J., Kareiva, P.M., Lonsdorf, E., Naidoo, R., Ricketts, T.H., Shaw, Mr.,
923 2009. Modeling multiple ecosystem services, biodiversity conservation, commodity
924 production, and tradeoffs at landscape scales. *Frontiers in Ecology and the Environment*
925 7, 4–11. <https://doi.org/10.1890/080023>

926 Neugarten, R.A., Langhammer, P.F., Osipova, E., Bagstad, K.J., Bhagabati, N., Butchart,
927 S.H.M., Dudley, N., Elliott, V., Gerber, L.R., Gutierrez Arrellano, C., Ivanić, K.-Z.,
928 Kettunen, M., Mandle, L., Merriman, J.C., Mulligan, M., Peh, K.S.-H., Raudsepp-
929 Hearne, C., Semmens, D.J., Stolton, S., Willcock, S., 2018. Tools for measuring,
930 modelling, and valuing ecosystem services: guidance for Key Biodiversity Areas,
931 natural World Heritage sites, and protected areas, 1st ed. IUCN, International Union for
932 Conservation of Nature. <https://doi.org/10.2305/IUCN.CH.2018.PAG.28.en>

933 Pagès, J.-P., Michalet, R., 2006. Contrasted responses of two understorey species to direct and
934 indirect effects of a canopy gap. *Plant Ecol* 187, 179–187.
935 <https://doi.org/10.1007/s11258-005-0976-x>

936 Pérez-Miñana, E., 2016. Improving ecosystem services modelling: Insights from a Bayesian
937 network tools review. *Environmental Modelling & Software* 85, 184–201.
938 <https://doi.org/10.1016/j.envsoft.2016.07.007>

939 Persha, L., Agrawal, A., Chhatre, A., 2011. Social and Ecological Synergy: Local
940 Rulemaking, Forest Livelihoods, and Biodiversity Conservation. *Science* 331, 1606–
941 1608. <https://doi.org/10.1126/science.1199343>

942 Petri, CA (1966) Communication with Automata. DTIC Research Report AD0630125.

943 Puga-Gonzalez, I., Sueur, C., 2017. Emergence of complex social networks from spatial
944 structure and rules of thumb: a modelling approach. *Ecological Complexity* 31, 189–
945 200. <https://doi.org/10.1016/j.ecocom.2017.07.004>

946 R Core Team. 2015. R: a language and environment for statistical computing. R Foundation
947 for Statistical Computing, Vienna, Austria. <http://www.R-project.org/>

948 Rissman, A.R., Gillon, S., 2017. Where are Ecology and Biodiversity in Social–Ecological
949 Systems Research? A Review of Research Methods and Applied Recommendations.
950 *Conservation Letters* 10, 86–93. <https://doi.org/10.1111/conl.12250>

951 Rixen, C., Haeberli, W., Stoeckli, V., 2004. Ground Temperatures under Ski Pistes with
952 Artificial and Natural Snow. *Arctic, Antarctic, and Alpine Research* 36, 419–427.
953 <https://doi.org/10.1657/1523-0430>

954 Rixen, C., Rolando, A. (Eds.), 2013. The impacts of skiing and related winter recreational
955 activities on mountain environments. Soest, the Netherlands: Bentham Science Publishers

956 Rixen, C., Stoeckli, V., Ammann, W., 2003. Does artificial snow production affect soil and
957 vegetation of ski pistes? A review. *Perspectives in Plant Ecology, Evolution and*
958 *Systematics* 5, 219–230. <https://doi.org/10.1078/1433-8319-00036>

959 Rouault, G., Candau, J.-N., Lieutier, F., Nageleisen, L.-M., Martin, J.-C., Warzée, N., 2006.
960 Effects of drought and heat on forest insect populations in relation to the 2003 drought
961 in Western Europe. *Ann. For. Sci.* 63, 613–624. <https://doi.org/10.1051/forest:2006044>

962 Roux-Fouillet, P., Wipf, S., Rixen, C., 2011. Long-term impacts of ski piste management on
963 alpine vegetation and soils. *Journal of Applied Ecology* 48, 906 – 915.
964 <https://doi.org/10.1111/j.1365-2664.2011.01964.x>

965 Ruess, R.W., Hendrick, R.L., Burton, A.J., Pregitzer, K.S., Sveinbjornsson, B., Allen, M.F.,
966 Maurer, G.E., 2003. Coupling fine root dynamics with ecosystem carbon cycling in
967 black spruce forests of Interior Alaska. *Ecological Monographs* 73, 643–662.
968 <https://doi.org/10.1890/02-4032>

969 Sagot, C., Brun, J.-J., Grossi, J.-L., Chauchat, J.H., Boudin, G., 1999. Earthworm distribution
970 and humus forms in the development of a semi-natural alpine spruce forest. *European*
971 *Journal of Soil Biology* 35, 163–169. [https://doi.org/10.1016/S1164-5563\(10\)70002-9](https://doi.org/10.1016/S1164-5563(10)70002-9)

972 Schirpke, U., Leitinger, G., Tasser, E., Schermer, M., Steinbacher, M., Tappeiner, U., 2013.
973 Multiple ecosystem services of a changing Alpine landscape: past, present and future.

- 974 Int. J. Biodivers. Sci. Ecosyst. Serv. Manag. 9, 123-135.
975 <https://doi.org/10.1080/21513732.2012.751936>
- 976 Schröter, D., Cramer, W., Leemans, R., Prentice, I.C., Araújo, M.B., Arnell, N.W., Bondeau,
977 A., Bugmann, H., Carter, T.R., Gracia, C.A., De La Vega-Leinert, A.C., Erhard, M.,
978 Ewert, F., Glendining, M., House, J.I., Kankaanpää, S., Klein, R.J.T., Lavorel, S.,
979 Lindner, M., Metzger, M.J., Meyer, J., Mitchell, T.D., Reginster, I., Rounsevell, M.,
980 Sabate, S., Sitch, S., Smith, B., Smith, J., Smith, P., Sykes, M.T., Thonicke, K.,
981 Thuiller, W., Tuck, G., Zaehle, S., Zierl, B., 2005. Ecosystem service supply and
982 vulnerability to global change in Europe. *Science* 310, 1333–1337.
983 <https://doi.org/10.1126/science.1115233>
- 984 Seidl, R., Albrich, K., Erb, K., Formayer, H., Leidinger, D., Leitinger, G., Tappeiner, U.,
985 Tasser, E., Rammer, W., 2019. What drives the future supply of regulating ecosystem
986 services in a mountain forest landscape? *For. Ecol. Manage.* 445, 37-47.
987 <https://doi.org/10.1016/j.foreco.2019.03.047>
- 988 Shoyama, K., Kamiyama, C., Morimoto, J., Ooba, M., Okuro, T., 2017. A review of modeling
989 approaches for ecosystem services assessment in the Asian region. *Ecosystem Services*
990 26, 316–328. <https://doi.org/10.1016/j.ecoser.2017.03.013>
- 991 Spandre, P., François, H., Morin, S., George-Marcelpoil, E., 2015. Snowmaking in the French
992 Alps: Climatic context, existing facilities and outlook. *rga*.
993 <https://doi.org/10.4000/rga.2913>
- 994 Spitzer, K., Bezděk, A., Jaroš, J., 1999. Ecological succession of a relict central European
995 peat bog and variability of its insect biodiversity. *Journal of Insect Conservation* 3, 97–
996 106. <https://doi.org/10.1023/A:1009634611130>
- 997 Sun, F., Lyu, Y., Fu, B., Hu, J., 2016. Hydrological services by mountain ecosystems in
998 Qilian Mountain of China: A review. *Chin. Geogr. Sci.* 26, 174–187.
999 <https://doi.org/10.1007/s11769-015-0791-9>
- 1000 Strahler, A.N., 1952. Hypsometric (area-altitude) analysis of erosional topography. *GSA*
1001 *Bulletin* 63, 1117–1142. <https://doi.org/10.1130/0016-7606>
- 1002 Thomas, R., Kaufman, M., 2001. Multistationarity, the basis of cell differentiation and
1003 memory. II. Logical analysis of regulatory networks in terms of feedback circuits.
1004 *Chaos* 11, 180–195. <https://doi.org/10.1063/1.1349893>
- 1005 van der Plas, F., Manning, P., Allan, E., Scherer-Lorenzen, M., Verheyen, K., Wirth, C.,
1006 Zavala, M.A., Hector, A., Ampoorter, E., Baeten, L., Barbaro, L., Bauhus, J.,
1007 Benavides, R., Benneter, A., Berthold, F., Bonal, D., Bouriaud, O., Bruelheide, H.,
1008 Bussotti, F., Carnol, M., Castagnyrol, B., Charbonnier, Y., Coomes, D., Coppi, A.,
1009 Bastias, C.C., Muhie Dawud, S., De Wandeler, H., Domisch, T., Finér, L., Gessler, A.,
1010 Granier, A., Grossiord, C., Guyot, V., Hättenschwiler, S., Jactel, H., Jaroszewicz, B.,
1011 Joly, F.-X., Jucker, T., Koricheva, J., Milligan, H., Müller, S., Muys, B., Nguyen, D.,
1012 Pollastrini, M., Raulund-Rasmussen, K., Selvi, F., Stenlid, J., Valladares, F., Vesterdal,
1013 L., Zielinski, D., Fischer, M., 2016. Jack-of-all-trades effects drive biodiversity–
1014 ecosystem multifunctionality relationships in European forests. *Nat Commun* 7, 11109.
1015 <https://doi.org/10.1038/ncomms11109>
- 1016 Wallén, B., 1986. Above and below ground dry mass of the three main vascular plants on
1017 hummocks on a subarctic peat bog. *Oikos* 46, 51–56. <https://doi.org/10.2307/3565379>
- 1018 Washbourne, C.-L., Goddard, M.A., Le Provost, G., Manning, D.A.C., Manning, P., 2020.
1019 Trade-offs and synergies in the ecosystem service demand of urban brownfield
1020 stakeholders. *Ecosystem Services* 42, 101074.
1021 <https://doi.org/10.1016/j.ecoser.2020.101074>

- 1022 Woo, M., Valverde, J., 1981. Summer streamflow and water level in a midlatitude forested
1023 swamp. *Fr Sci* 27, 177–189. <https://doi.org/10.1093/forestscience/27.1.177>
- 1024 Xiao, H., Dee, L.E., Chadès, I., Peyrard, N., Sabbadin, R., Stringer, M., McDonald-Madden,
1025 E., 2018. Win-wins for biodiversity and ecosystem service conservation depend on the
1026 trophic levels of the species providing services. *J Appl Ecol* 55, 2160–2170.
1027 <https://doi.org/10.1111/1365-2664.13192>
- 1028 Xiao, H., McDonald-Madden, E., Sabbadin, R., Peyrard, N., Dee, L.E., Chadès, I., 2019. The
1029 value of understanding feedbacks from ecosystem functions to species for managing
1030 ecosystems. *Nature Communications* 10, 3901. [https://doi.org/10.1038/s41467-019-
1031 11890-7](https://doi.org/10.1038/s41467-019-11890-7)
- 1032 Zerbe, S., Steffenhagen, P., Parakenings, K., Timmermann, T., Frick, A., Gelbrecht, J., Zak,
1033 D., 2013. Ecosystem service restoration after 10 years of rewetting peatlands in NE
1034 Germany. *Environmental Management* 51, 1194–1209. [https://doi.org/10.1007/s00267-
1035 013-0048-2](https://doi.org/10.1007/s00267-013-0048-2)
- 1036

1037 **Tables**

1038 Table 1 Nodes and initial states set for each simulation scenario for the case study of
1039 Chamrousse

1040 Table 2 Rules (R) and Constraints (C) for the case study of Chamrousse

1041 Table 3 Biodiversity and ecosystem service list and their triggering conditions

1042 Table 4 Comparison of ecosystem service proxies between control (no climate change) and
1043 treatment (climate change) scenarios

1044

1045 **Figures**

1046 Figure 1 An example of a state space (a), strongly connected component (SCC) space (b),
1047 calculation of confluential indices (in text) and sequence orders (in circles) of SCC (c) and
1048 evolution between states within and across SCC (d). In (c), CI_x and SO_x represent the
1049 confluential index and sequence order of the SCC x , respectively. In (d): purple dots represent
1050 natural components and orange dots represent human components. Squares represent status
1051 (red for presence and grey for absence) of components in each of the five states (0, 1, 3, 2 and
1052 4) from Scenario 3. The curves on the top of spectra represent the evolution between states,
1053 and arrows indicate their directions. The text in italics and red colour beside each curve
1054 represents the rule/constraint or rules/constraints conducting the evolution between two states,
1055 including R1 (*Win+ >> Win-*); R2 (*Win- >> Win+*); R10 (*Res+, Win-, For+ >> Tou+*); R14
1056 (*For+, Res+ >> Tim+, Gap+*); R16 (*Win-, Res+, Bog+ >> Tou+*); R19 (*For+, Tim- >> Gap-*)
1057 and C5 (*Win+, Ski- >> Tou-*). States 0, 1 and 3 belong to the same SCC (i.e., SCC F), as they
1058 can shift between each other. States 2 and 4 belong to the other SCC, as they are irreversible
1059 to the states in SCC F.

1060 Figure 2 Evolution of itineraries of strongly connected components (SCC) per scenario.
1061 Subplots from (a) to (f): each SCC has a unique label (in capital or small Latin letters);
1062 identical SCC in different scenarios share the same label (e.g., SCC P in scenarios 4 and 6);
1063 the arrows with arrow head in the middle represent the evolution of itineraries from one SCC
1064 to another. Subplot (g) summarizes the number of states contained in each SCC. The filled
1065 colour in each of the circles in (a-f) and bars in (g) represents the average of the total ES
1066 scores of all states in a SCC (0 as minimum and 20 as maximum among all the states). The
1067 negative direction along the y-axis is the sequence order (SO) of SCC reflecting SCC
1068 evolution.

1069 Figure 3 Analysis of state spectra with ecosystem services (ES) and components. The figure
1070 shows an example of scenario 4 containing 1614 states of out of all the 1814 states appearing
1071 in the social-ecological system of Chamrousse. The figure consists of three parts (marked on
1072 the right from top to bottom): (I) – spectrum with biodiversity and ES proxies (red: present;
1073 grey: absent), (II) – evolution of total ES score and trajectories among the states and (III) –
1074 spectrum with the status of components (red: ON; grey: OFF). In (I) and (III), the order of the
1075 states from left to right represents the descending order of the total ES score; the hollow parts

1076 signify the absence of the states in the present scenario; values on the right are percentages of
1077 a proxy or a component appearing in all the states of the scenario 4 and are ranged in a
1078 descending order from top to bottom. Regarding the evolution of the total ES score in (II),
1079 thick and thin sections correspond to the metric of the present scenario and of all the six
1080 scenarios, respectively; the vertical dashed blue line of the state ID 948 at $P_{50} = 10$ splits the
1081 pools of healthy and degraded states; translucent grey arcs represent degraded evolution
1082 trajectories between two states (only paths crossing the line at state ID 948 are shown).

1083 Figure 4 Variations of biodiversity and ecosystem service (ES) scores (total ES, economy-
1084 and ecology-related ES) per scenario. For each boxplot, the thick horizontal line and point
1085 “X” inside the box represent the median and mean of data points, respectively. Low and top
1086 edges of the box correspond to the 25th and 75th percentile data points, respectively. Low and
1087 top horizontal lines correspond to the 10th and 90th percentile data points, respectively. Point
1088 clouds over boxplots allow a visual check of the quantity of states, each of which corresponds
1089 to one point. In (a), the total number of states per scenario is shown on the top of each
1090 boxplot.

1091 Figure 5 Variations of ecosystem service (ES) scores (total ES, economy- and ecology-related
1092 ES) as a function of biodiversity gradient. For each boxplot, the thick horizontal line and point
1093 “X” inside the box represent the median and mean of data points, respectively. Lower and top
1094 edges of the box correspond to the 25th and 75th percentile data points, respectively. Lower
1095 and top horizontal lines correspond to the 10th and 90th percentile data points, respectively.
1096 Point clouds over boxplots allow a visual check of the quantity of states, each of which
1097 corresponds to one point. Points of different colours represent different scenarios. In (a), total
1098 numbers of states per scenario are shown on the top of each boxplot.

1099

1100 **Supplementary tables and figures**

1101 Table S1 Terminology and acronyms related to the model

1102 Table S2. List of questions prepared for town hall employees and private stakeholders at
1103 Chamrousse

1104 Table S3 Ecosystem services (ES) included in the case study based on the full ES list of MEA
1105 (2005)

1106 Table S4 Comparison of state conditions between control and treatment scenarios

1107 Table S5 Percentage of states with water stress (%) according to different scenarios (S1 – S6),
1108 health condition (healthy, degraded and all together) and season (summer (*Win-*) and winter
1109 (*Win+*))

1110 Figure S1 Relationship between semantics (rules and constraints) and nodes for the case of
1111 Chamrousse

1112 Figure S2 Scatter plot between total ecosystem service (ES) score and confluential index of
1113 all the strongly connected components (SCC)

1114 Figure S3 Analysis of state spectra with ecosystem services and components of for each of the
1115 six scenarios along all the 1814 states appearing in the social-ecological system of
1116 Chamrousse. Each subplot presenting one scenario consists of two parts. The lower part
1117 shows the spectrum of states with the status of components (red: ON; grey: OFF). The order
1118 of the states from left to right represents the descending order of the total ecosystem service
1119 (ES) score. The hollow parts signify the absence of the states in the present scenario. The
1120 order of components from top to bottom represents the descending order of the percentages of
1121 nodes in status ON calculated with the data of all the six scenarios. Values on the right of the
1122 spectrum indicate the percentage of the nodes for the present scenario. The upper part shows
1123 the evolution of total ES score, where thick and thin sections correspond to the metric of the
1124 present scenario and of all the six scenarios, respectively. The vertical dashed blue line of the
1125 state ID 948 at $P_{50} = 10$ splits the pools of healthy and degraded states. Translucent grey arcs
1126 represent degraded evolution trajectories between two states (only paths crossing the line at
1127 state ID 948 are shown)

1128 Figure S4 Analysis of state spectra for components and ecosystem service (ES) of all the
1129 strongly connected components (SCC), as well as the states that they contain, of the social-
1130 ecological system of Chamrousse. The figure consists of four parts (marked on the right from
1131 top to bottom): I – spectrum of biodiversity and ES proxies (red: present; grey: absent), II –
1132 score of ES and composition between economy- and ecology-related ES, III –evolution
1133 trajectories among the states belonging to different SCC, IV – spectrum of components. In I
1134 and IV, every thin vertical slice corresponds to a state (4202 states in all for 27 SCC); the
1135 colours represent the presence (red) and absence (grey) of the component in each state;
1136 numbers on the right are percentage of a proxy or a component appearing in all the states and
1137 are ranging in a descending order from top to bottom. In II, numbers on the top of each bar
1138 refer to total ES and the colours in the bar represents the proportion of ecology-related ES
1139 (light pink) against economy-related ES (deep pink). In III, only degraded trajectories (i.e., a
1140 path linking a healthy state and a degraded state) are shown. In IV, numbers below the
1141 spectrum indicate the numbers of states in SCC

1142 Figure S5 Variations of biodiversity and ecosystem service (ES) scores (total, provisioning,
1143 cultural, regulating and supporting) per scenario. For each boxplot, the thick horizontal line
1144 and point “X” inside the box represent the median and mean of data points, respectively. Low
1145 and top edges of the box correspond to the 25th and 75th percentile data points, respectively.
1146 Low and top horizontal lines correspond to the 10th and 90th percentile data points,
1147 respectively. Point clouds over boxplots allow a visual check of the quantity of states, each of
1148 which corresponds to one point. In (b), the total number of states per scenario is shown on the
1149 top of each boxplot

1150 Figure S6 Variations of ecosystem service (ES) scores (total ES, economy- and ecology-
1151 related ES) as a function of biodiversity gradient and climate change. For each boxplot, the
1152 thick horizontal line and point “X” inside the box represent the median and mean of data

1153 points, respectively. Lower and top edges of the box correspond to the 25th and 75th percentile
1154 data points, respectively. Lower and top horizontal lines correspond to the 10th and 90th
1155 percentile data points, respectively. Point clouds over boxplots allow a visual check of the
1156 quantity of states, each of which corresponds to one point. Points of different colours
1157 represent different scenarios. S1, S3 and S5 correspond to control scenarios with no climate
1158 change effect, while S2, S4 and S6 correspond to treatment scenarios with climate change
1159 effect

1160 Figure S7 Principle component analysis (PCA) of biodiversity and ecosystem service (ES)
1161 variables at both state and strongly connected component (SCC) levels. Hull convex polygons
1162 represent the ranges of scenarios (S1 – S6). Letters represent the names of SCC

1163 **Table 1**

Category	Nodes			Scenarios	
	ID	Name	Acronym	1 & 2	3, 4, 5 & 6
Natural	1	Winter or summer	<i>Win</i>	-	-
	2	Natural snow	<i>Nsn</i>	-	-
	3	Water	<i>Wat</i>	+	+
	4	Topsoil with organic horizon	<i>Soh</i>	+	+
	5	Bogs	<i>Bog</i>	+	+
	6	Dense forest	<i>For</i>	+	+
	7	Forest gaps	<i>Gap</i>	+	+
	8	Forest fauna	<i>Ffau</i>	+	+
	9	Forest flora	<i>Fflo</i>	+	+
	10	Aquatic or open area fauna	<i>Ofau</i>	+	+
	11	Aquatic or open area flora	<i>Oflo</i>	+	+
Human	12	Residents	<i>Res</i>	-	+
	13	Timber	<i>Tim</i>	-	-
	14	Tourists	<i>Tou</i>	-	-
	15	Ski activities (including infrastructure and path)	<i>Ski</i>	-	-
	16	Artificial snow	<i>Asn</i>	-	-

1164 Note : + and - means the node is ON and OFF at initial state prior to simulation, respectively.

1165

Table 2

Category	ID	Semantics of edge	Explanation	Source of information
Constraint (C)	1	<i>Wat-</i> >> <i>Asn-</i>	Without water resources (water table), no artificial snow will be produced.	Common sense
	2	<i>Nsn-</i> , <i>Asn-</i> >> <i>Ski-</i>	Without (artificial or natural) snow, no skiing activities will be possible.	Common sense
	3	<i>Res-</i> >> <i>Tou-</i> , <i>Asn-</i> , <i>Ski-</i>	Without residents, no touristic winter activities will be possible.	Interview with stakeholders
	4	<i>Win-</i> >> <i>Ski-</i> , <i>Asn-</i>	In summer, no winter activities, no ski and no artificial snow will be possible.	Interview with stakeholders
	5	<i>Win+</i> , <i>Ski-</i> >> <i>Tou-</i>	In winter, tourists will be absent without the ski station and other winter activities.	Interview with stakeholders
	6	<i>For-</i> >> <i>Tim-</i> , <i>Ffau-</i> , <i>Fflo-</i> , <i>Gap-</i>	Without forest, no wood production (logging) and no associated fauna and flora will survive.	Common sense
	7	<i>Soh-</i> >> <i>For-</i> , <i>Bog-</i> , <i>Fflo-</i> , <i>Oflo-</i>	Without fertile soils, it will be impossible to maintain forests, bogs and flora.	Common sense
	8	<i>Fflo-</i> >> <i>Ffau-</i>	If forest fauna lacks forest flora, they will die or leave the system.	Common sense
	9	<i>Fflo-</i> , <i>Oflo-</i> >> <i>Ofau-</i>	If open area fauna lacks any kind of flora, they will die or leave the system.	Common sense
Rule (R)	1	<i>Win+</i> >> <i>Win-</i>	Winter can switch into summer (seasons).	Common sense
	2	<i>Win-</i> >> <i>Win+</i>	Summer can switch into winter.	Common sense
	3	<i>Win-</i> >> <i>Nsn-</i>	The arrival of summer can remove the natural snow within the study area.	Observed
	4	<i>Win+</i> >> <i>Nsn+</i>	In winter, natural snow can appear.	Observed
	5#	<i>Win+</i> >> <i>Nsn-</i>	Climate change can cause late snow events or snowless winter	Observed
	6#	<i>Win-</i> >> <i>Wat-</i>	Climate change can cause summer water shortage	Observed
	7	<i>Win-</i> , <i>For+</i> , <i>Bog+</i> >> <i>Wat+</i>	In summer, forest and bogs can conserve and renew water resources.	Academic knowledge ¹⁻³
	8	<i>Win+</i> , <i>Nsn+</i> >> <i>Wat+</i>	In winter, natural snow can enhance surface water resources.	Academic knowledge ⁴⁻⁵
	9	<i>Wat-</i> , <i>Soh-</i> , <i>For-</i> >> <i>Tou-</i> , <i>Res-</i>	Without fertile soils, forest and water, residents and tourists can leave the system.	Interview with stakeholders
	10	<i>Res+</i> , <i>Win-</i> , <i>For+</i> >> <i>Tou+</i>	In summer, residents can manage summer activities related to forest.	Interview with stakeholders
	11*	<i>Win+</i> , <i>Nsn+</i> , <i>Res+</i> >> <i>Ski+</i>	In winter, natural snow can make residents set up and operate ski stations.	Interview with stakeholders
	12*	<i>Res+</i> , <i>Wat+</i> , <i>Win+</i> , <i>Nsn-</i> >> <i>Asn+</i>	In winter, ski stations can produce artificial snow, when the natural snow is absent.	Interview with stakeholders
	13*	<i>Ski+</i> >> <i>Tou+</i>	Ski stations can attract tourists.	Observed

14	<i>For+</i> , <i>Res+</i> >> <i>Tim+</i> , <i>Gap+</i>	If forests are present, there can be timber production conducted by residents, resulting in forest gaps.	Interview with stakeholders
15	<i>Win-</i> , <i>Res+</i> , <i>For+</i> >> <i>Tou+</i>	In summer, residents and forest can make summer activities possible.	Interview with stakeholders
16	<i>Win-</i> , <i>Res+</i> , <i>Bog+</i> >> <i>Tou+</i>	In summer, residents and bogs can make summer activities possible.	Interview with stakeholders
17*	<i>Asn+</i> , <i>Win+</i> , <i>Res+</i> >> <i>Ski+</i>	In winter, residents can rely on artificial snow to maintain ski stations.	Interview with stakeholders
18*	<i>Ski+</i> , <i>Tou+</i> >> <i>For-</i>	Ski activities and tourists can impact forest in short or long terms.	Academic knowledge ⁶
19	<i>For+</i> , <i>Tim-</i> >> <i>Gap-</i>	Without logging, forest regeneration can close forest gaps.	Academic knowledge ⁷⁻⁸
20	<i>Tou+</i> >> <i>Bog-</i>	Tourists can unfavourably affect bog ecosystem over the long term.	Interview with stakeholders
21	<i>Tou+</i> >> <i>Ffau-</i> , <i>Fflo-</i>	Tourists can unfavourably affect forest fauna and flora over the long term.	Interview with stakeholders
22	<i>Tou+</i> >> <i>Ofau-</i> , <i>Oflo-</i>	Tourists can unfavourably affect the open area fauna and flora over the long term.	Interview with stakeholders
23	<i>Wat+</i> , <i>Soh+</i> >> <i>Fflo+</i> , <i>Oflo+</i>	Flora of forests and of open areas can both grow and prosper when fertile soils and water are present.	Common sense
24	<i>Wat+</i> , <i>Oflo+</i> >> <i>Ofau+</i>	Fauna of open areas can grow and prosper when vegetation and water are present.	Common sense
25	<i>Wat+</i> , <i>Gap+</i> , <i>Soh+</i> >> <i>Oflo+</i>	The presence of forest gaps and fertile soils can favour the arrival of open area fauna and flora.	Common sense
26	<i>Wat+</i> , <i>For+</i> , <i>Fflo+</i> >> <i>Ffau+</i>	Fauna of forest can grow and prosper when vegetation and water are all present.	Common sense
27	<i>Wat+</i> , <i>Soh+</i> >> <i>Bog+</i>	Bog can maintain as soon as fertile soils and water are present.	Common sense
28*	<i>Asn+</i> >> <i>Ffau-</i> , <i>Fflo-</i> , <i>Oflo-</i>	Ski with artificial snow and tourists can unfavourably affect forest fauna and flora.	Academic knowledge
29	<i>Nsn+</i> >> <i>Oflo-</i>	Natural snow can suppress flora growth and functioning and cause loss in flora when soil is frozen (of open areas only).	Academic knowledge ¹⁰⁻¹²
30	<i>Bog+</i> >> <i>Ffau+</i> , <i>Oflo+</i>	The presence of bogs can favor the recovery or enrichment of forest fauna and open area flora.	Academic knowledge ¹³⁻¹⁴
31	<i>Ffau+</i> >> <i>Oflo-</i>	Forest fauna can feed on open area flora.	Common sense
32	<i>Res+</i> >> <i>Ffau-</i>	Residents can hunt the forest fauna.	Interview with stakeholders
33	<i>Ffau+</i> >> <i>Fflo-</i>	Forest fauna can feed on forest flora.	Common sense
34	<i>Tou+</i> >> <i>Ffau-</i> , <i>Ofau-</i>	Winter activities can unfavourably affect forest and open area fauna.	Academic knowledge ^{6, 15-17}
35	<i>Gap+</i> >> <i>Fflo-</i> , <i>Ffau-</i>	Opening forest gaps can suppress the growth of forest fauna and flora.	Academic knowledge ¹⁸⁻¹⁹
36	<i>Wat+</i> , <i>Fflo+</i> , <i>Soh+</i> >> <i>For+</i>	Favourable soil and water conditions and presence of forest flora can help the forest to recover over the long term.	Academic knowledge ²⁰

37	<i>Tou+</i> >> <i>Soh-</i>	Tourists can impact the soil fertility over the long term.	Academic knowledge ⁶
38*	<i>Asn+</i> >> <i>Soh-</i>	Artificial snow can cause decline in soil fertility (organic horizon is degraded).	Academic knowledge ⁹
39	<i>Wat+</i> , <i>Bog+</i> , <i>Oflo+</i> , <i>Ofau+</i> >> <i>Soh+</i>	Healthy bog with rich open area fauna and flora can favour soil fertility.	Academic knowledge ²¹⁻²²
40	<i>Wat+</i> , <i>For+</i> , <i>Fflo+</i> , <i>Ffau+</i> >> <i>Soh+</i>	If the forest is present and healthy, soil fertility can be guaranteed over the long term.	Academic knowledge ²³⁻²⁴
41	<i>Wat-</i> >> <i>For-</i> , <i>Fflo-</i> , <i>Ffau-</i>	Water stress can damage forest ecosystems.	Academic knowledge ²⁵⁻²⁶
42	<i>Wat-</i> >> <i>Bog-</i> , <i>Oflo-</i> , <i>Ofau-</i>	Water stress can damage bog and open air ecosystems.	Academic knowledge ²⁷⁻²⁸

Notes: ID with “#” refers to the rule that is deactivated in Scenarios 1, 3 and 5 and activated in Scenarios 2, 4 and 6 to mimic the impact of climate change on snow; ID with “*” refers to the rules that are deactivated in Scenarios 5 and 6 to mimic the situation of no ski activity. Numbers in the column “Source of information” refer to the reference sources supporting the argument: 1 – Bragg (2015); 2 – Woo and Valverde (1981); 3 – Sun et al., (2016); 4 – Huss et al., (2017); 5 – Kormos et al., (2014); 6 – Rixen and Rolando (2013); 7 – Bugmann (2001); 8 – Franklin et al. (2002); 9 – Rixen et al., (2003); 10 – Ruesch et al., (2003); 11 – Mao et al., (2013); 12 – Drescher and Thomas (2013); 13 – Littlewood et al., (2010); 14 – Minayeva et al., (2017); 15 – Negro et al., (2009); 16 – Andereck (1995); 17 – Gössling (2002); 18 – Spitzer et al., (1999); 19 – Pagès and Michalet (2006); 20 – Diwold et al., (2010); 21 – Moore (1989); 22 – Wallén (1986); 23 – Aber et al., (1990); 24 – Sagot et al., (1999); 25 – Moser et al., (2011); 26 – Rouault et al., (2006); 27 – Bragazza (2008); 28 – Breeuwer et al., (2009).

Table 3

Class	Category	Ecosystem service	Subcategory	Accronym	Triggering conditions	No. of conditions	
Economy-related ES	Provisioning	Food	Livestock	livestock	<i>Oflo+</i> , <i>Res+</i> , <i>Win-</i>	1	
		Food	Wild plant / animal products	wild	<i>Res+</i> , <i>Ffau+</i> , <i>Win-</i> or <i>Res+</i> , <i>Flo+</i> , <i>Win-</i> or <i>Res+</i> , <i>Ofau+</i> , <i>Win-</i> or <i>Res+</i> , <i>Oflo+</i> , <i>Win-</i>	4	
		Food	Hunted products	hunted	<i>Ffau+</i> , <i>Res+</i> , <i>Win-</i>	1	
		Fiber	Timber	timber	<i>For+</i> , <i>Tim+</i> , <i>Win-</i>	1	
		Fiber	Wood fuel	fuel	<i>For+</i> , <i>Res+</i>	1	
		Fresh water supply		fresh water	<i>Wat+</i> or <i>Nsn+</i>	2	
		Cultural	Aesthetic values		aesthetic	<i>For+</i> , <i>Ski-</i> or <i>Bog+</i> , <i>Ski-</i>	2
		Recreation	Hunting	hunting	<i>Win</i> , <i>Tou+</i> , <i>Ffau+</i> , <i>Res+</i>	1	
		Recreation	Hiking	hiking	<i>For+</i> , <i>Tou+</i> , <i>Res+</i> or <i>Bog+</i> , <i>Tou+</i> , <i>Res+</i>	2	
		Recreation	Mountain bike	bike	<i>For+</i> , <i>Win-</i> , <i>Tou+</i> , <i>Res+</i>	1	
		Recreation	Skiing	skiing	<i>Tou+</i> , <i>Ski+</i> , <i>Res+</i> , <i>Win+</i>	1	
	Ecology-related ES	Regulating	Climate regulation	Global	clim. global	<i>For+</i> , <i>Wat+</i> or <i>Bog+</i> , <i>Wat+</i> or <i>Soh+</i> , <i>Wat+</i>	3
			Climate regulation	Regional and local	clim. local	<i>For+</i> , <i>Wat+</i> or <i>Bog+</i> , <i>Wat+</i>	2
			Water cycling regulation		water cycle	<i>For+</i> , <i>Soh+</i> , <i>Bog+</i> , <i>Wat+</i> , <i>Nsn+</i> , <i>Win+</i> or <i>For+</i> , <i>Soh+</i> , <i>Bog+</i> , <i>Wat+</i> , <i>Win-</i>	2
Erosion regulation				erosion	<i>For+</i> , <i>Ffau+</i> , <i>Soh+</i> or <i>Gap+</i> , <i>Oflo+</i> , <i>Soh+</i>	2	
Water purification and waste treatment				waste	<i>For+</i> , <i>Fflo+</i> , <i>Wat+</i> , <i>Soh+</i> or <i>Bog+</i> , <i>Oflo+</i> , <i>Wat+</i>	2	

		Pollination		pollination	<i>Fflo+</i> or <i>Oflo+</i>	2
		Natural hazard regulation		hazard	<i>For+,Gap-</i>	1
Supporting		Soil formation		soil form.	<i>For+,Wat+,Soh+</i>	1
		Photosynthesis and primary production		photosyn.	<i>For+,Wat+,Soh+</i> or <i>Bog+,Wat+</i>	2
		Nutrient cycling		nutri. cyc.	<i>For+,Wat+</i>	1
		Water cycling		water cyc.	<i>For+,Wat+</i> or <i>Bog+,Wat+</i>	2
Biodiversity	Biodiversity	Specific diversity	Forest species	forest div.	<i>For+,Ffau+,Fflo+,Wat+</i>	1
		Specific diversity	Open area species	open div.	<i>Ofau+,Oflo+,Gap+,Wat+</i>	1
		Specific diversity	Aquatic species	aquatic div.	<i>Bog+,Wat+</i>	1
		Specific diversity	Soil species	soil div.	<i>Soh+,Wat+</i>	1

Note: In the column “Triggering conditions,” there was no priority between conditions in case of multiple conditions; see Table 1 for the explanations of the components.

Table 4

Scenario pairs		Indicators (<i>i</i>)															
		Mean total ES score				Mean economy-related ES score				Mean ecology-related ES score				Mean p_e			
Control (C)	Treatment (T)	$M_{i,C}$	$M_{i,T}$	$\frac{M_{i,T}-M_{i,C}}{M_{i,C}}$	V_i	$M_{i,C}$	$M_{i,T}$	$\frac{M_{i,T}-M_{i,C}}{M_{i,C}}$	V_i	$M_{i,C}$	$M_{i,T}$	$\frac{M_{i,T}-M_{i,C}}{M_{i,C}}$	V_i	$M_{i,C}$	$M_{i,T}$	$\frac{M_{i,T}-M_{i,C}}{M_{i,C}}$	V_i
<i>Only healthy states included</i>																	
S1	S2	11.7 ± 0.1a	11.7 ± 0.1a	0.0	0.0	2.0 ± 0.0a	2.0 ± 0.0a	0.0	0.0	9.7 ± 0.1a	9.7 ± 0.1a	0.0	0.0	82.7 ± 0.2a	82.7 ± 0.2a	0.0	0.0
S3	S4	11.7 ± 0.1a	13.0 ± 0.1b	1.3	11.2	2.0 ± 0.0a	4.2 ± 0.1a	2.2	110.6	9.7 ± 0.1a	8.8 ± 0.1b	-0.9	-9.4	82.7 ± 0.2a	68.4 ± 0.4b	14.4	-17.4
S5	S6	13.0 ± 0.1a	14.1 ± 0.1b	1.1	8.3	4.1 ± 0.1a	5.6 ± 0.1b	1.5	38	9.0 ± 0.0a	8.5 ± 0.1b	-0.5	-5.1	69.9 ± 0.3a	60.7 ± 0.7b	-9.2	-13.2
S1+S3+S5	S2+S4+S6	13.3 ± 0.1a	13.2 ± 0.1a	-0.1	-0.7	4.3 ± 0.1a	4.5 ± 0.1b	0.2	4.5	9.0 ± 0.0a	8.7 ± 0.0b	-0.3	-3.1	69.0 ± 0.3a	67.0 ± 0.4b	-2	-2.9
<i>Only degraded states included</i>																	
S1	S2	8.9 ± 0.1a	4.0 ± 0.2b	-4.8	-54.5	2.0 ± 0.0a	1.6 ± 0.0a	-0.4	-21	6.9 ± 0.1a	2.5 ± 0.2b	-4.4	-64.2	77.4 ± 0.4a	55.4 ± 1.8b	-22	-28.5
S3	S4	4.0 ± 0.2a	5.8 ± 0.1b	1.7	43.3	1.6 ± 0.0a	3.4 ± 0.1b	1.8	113.2	2.5 ± 0.2a	2.4 ± 0.1a	0.0	-1.7	55.4 ± 1.8a	38.3 ± 0.8b	17.1	-30.8
S5	S6	7.0 ± 0.2a	5.9 ± 0.1b	-1.1	-15.8	2.3 ± 0.1a	3.8 ± 0.1b	1.5	67.7	4.7 ± 0.2a	2.1 ± 0.1b	-2.6	-56.1	61.2 ± 1.5a	33.0 ± 0.9b	28.1	-46
S1+S3+S5	S2+S4+S6	7.3 ± 0.2a	5.7 ± 0.1b	-1.6	-22.2	2.3 ± 0.1a	3.4 ± 0.1b	1	43.9	4.9 ± 0.2a	2.3 ± 0.0b	-2.6	-53.6	61.1 ± 1.4a	37.9 ± 0.6b	23.2	-38
<i>All states together</i>																	
S1	S2	11.4 ± 0.1a	7.1 ± 0.3b	-4.3	-37.7	2.0 ± 0.0a	1.7 ± 0.0a	-0.2	-12.5	9.4 ± 0.1a	5.4 ± 0.3b	-4.1	-43.1	82.3 ± 0.2a	66.4 ± 1.4b	15.9	-19.3
S3	S4	7.1 ± 0.3a	9.6 ± 0.1b	2.5	35.4	1.7 ± 0.0a	3.8 ± 0.0b	2.1	118.3	5.4 ± 0.3a	5.8 ± 0.1a	0.4	8.3	66.4 ± 1.4a	54.5 ± 0.6b	-12	-18.1
S5	S6	11.9 ± 0.1a	9.5 ± 0.2b	-2.4	-20	3.7 ± 0.1a	4.6 ± 0.1b	0.9	23.3	8.2 ± 0.1a	4.9 ± 0.1b	-3.3	-39.7	68.4 ± 0.4a	45.4 ± 0.7b	-23	-33.6
S1+S3+S5	S2+S4+S6	12.4 ± 0.1a	9.4 ± 0.1b	-3	-24	4.0 ± 0.1a	3.9 ± 0.0a	-0.1	-1.8	8.4 ± 0.1a	5.5 ± 0.1b	-2.9	-34.5	67.8 ± 0.3a	52.4 ± 0.4b	15.4	-22.8

Note: for each of the four indicators *i*, values of $V_i = (M_{i,T}-M_{i,C})/M_{i,C}$ are presented in % (see Eq. (3)); mean ± standard deviation were given for $M_{i,C}$ and $M_{i,T}$; different letters in each pair of columns ($M_{i,C}$ and $M_{i,T}$) represent the significance at $p<0.05$ level according to student test; letters are independent among rows and indicators. Grey zones highlight the cases where $M_{i,T}$ and $M_{i,C}$ were significantly different.

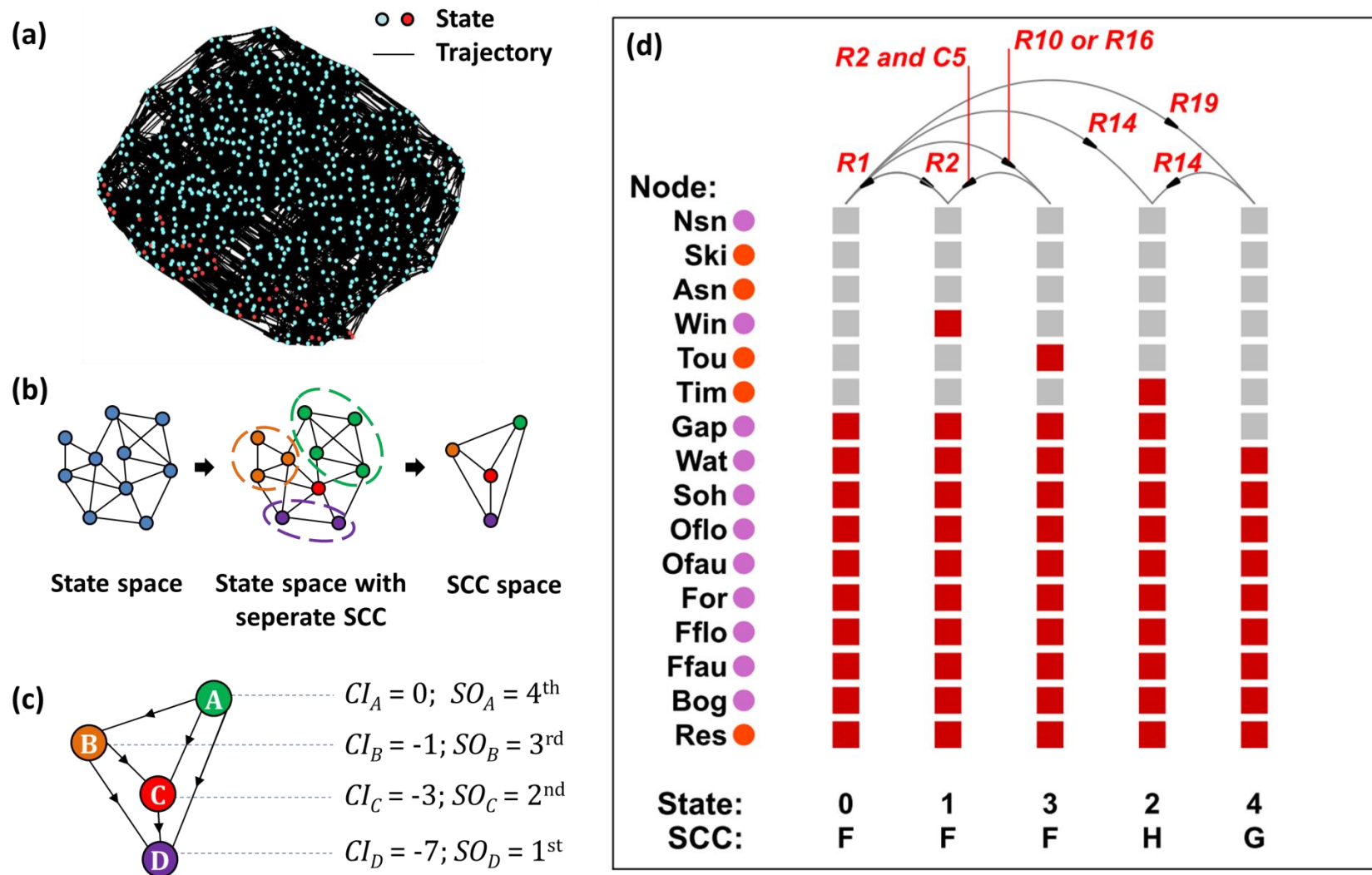


Figure 1

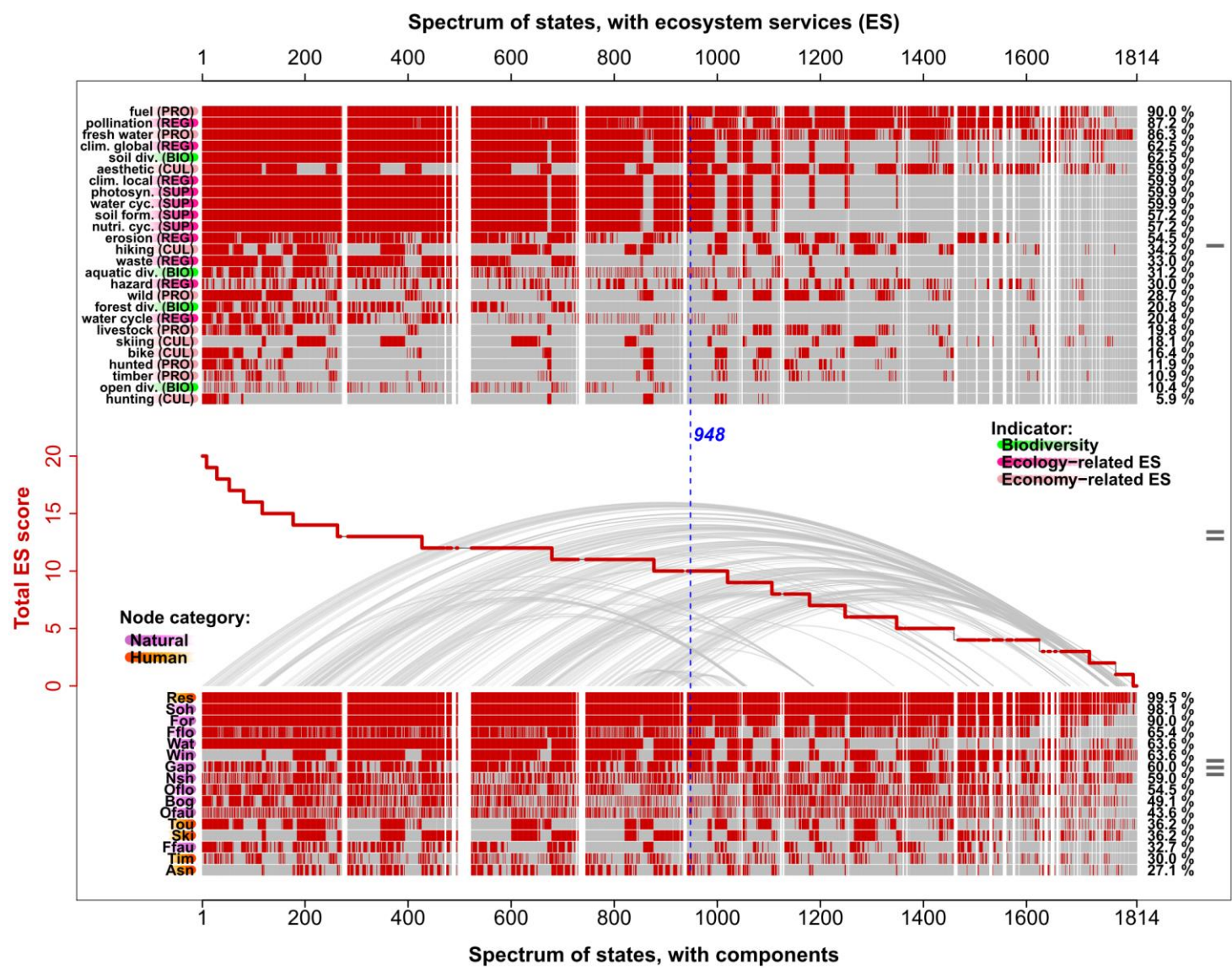
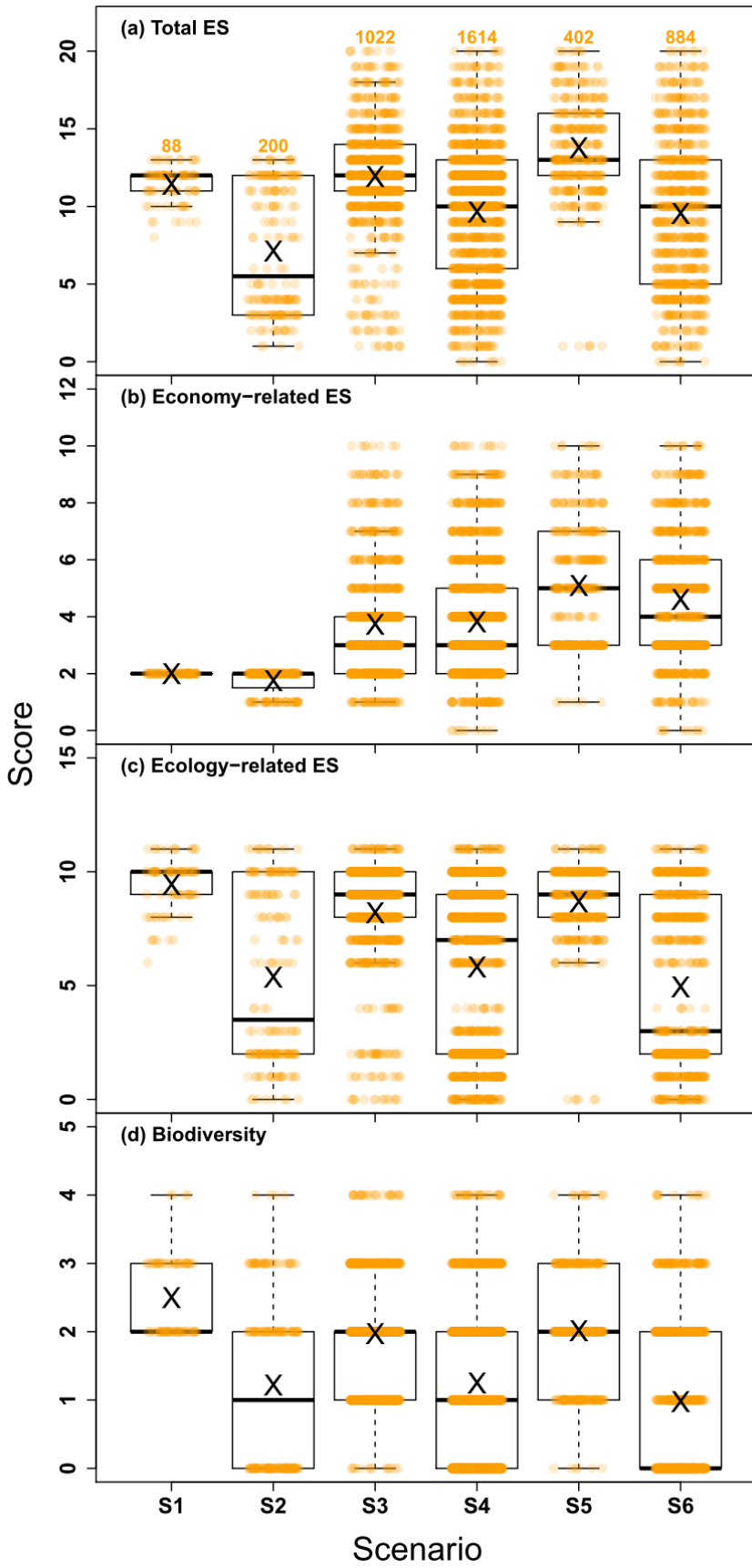
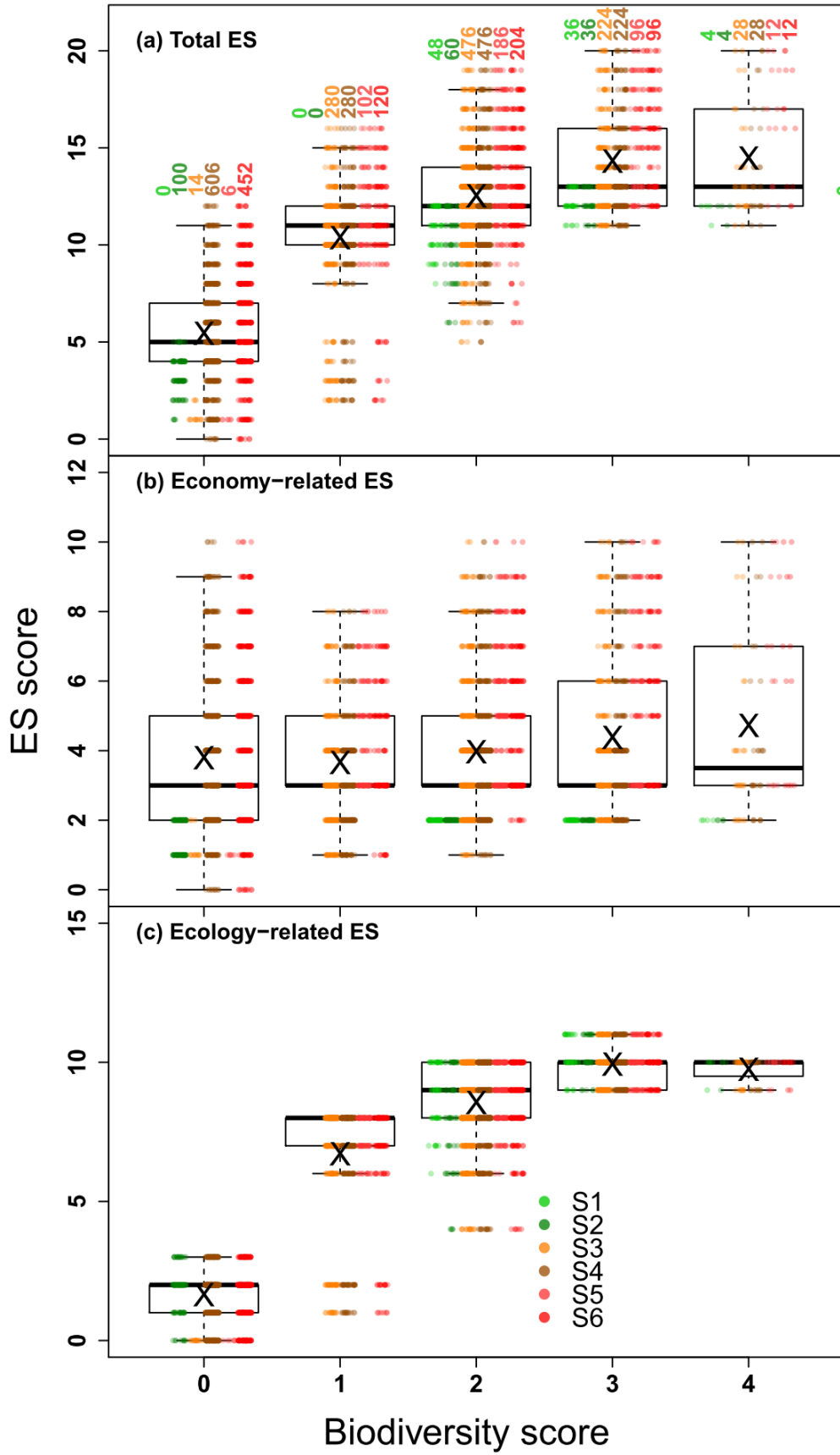


Figure 3



1

2 Figure 4



3
4 Figure 5