

## **Bridging Ostrom's governance theory to dynamic adaptive policy pathway (DAPP) maps: theory and application example**

Jean-Baptiste Pichancourt, Antoine Brias, Anne Bonis

### **To cite this version:**

Jean-Baptiste Pichancourt, Antoine Brias, Anne Bonis. Bridging Ostrom's governance theory to dynamic adaptive policy pathway (DAPP) maps: theory and application example.  $2024$ . hal-04680185

## **HAL Id: hal-04680185 <https://hal.science/hal-04680185>**

Preprint submitted on 2 Sep 2024

**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.



[Distributed under a Creative Commons Attribution 4.0 International License](http://creativecommons.org/licenses/by/4.0/)

## **Bridging Ostrom's governance theory to dynamic adaptive policy pathway (DAPP) maps: theory and application example (#100894)**

First submission

## Guidance from your Editor

Please submit by **5 Aug 2024** for the benefit of the authors (and your token reward) .



### **Structure and Criteria**

Please read the 'Structure and Criteria' page for guidance.



## **Raw data check**

Review the raw data.



### **Image check**

Check that figures and images have not been inappropriately manipulated.

If this article is published your review will be made public. You can choose whether to sign your review. If uploading a PDF please remove any identifiable information (if you want to remain anonymous).

### **Files**

Download and review all files from the [materials page](https://peerj.com/submissions/100894/reviews/1647283/materials/).

11 Figure file(s) 3 Table file(s)

## **Bridging Ostrom's governance theory to dynamic adaptive policy pathway (DAPP) maps: theory and application example**

**Jean-Baptiste Pichancourt** Corresp., Equal first author, <sup>1</sup> , **Antoine Brias** Equal first author, <sup>2</sup> , **Anne Bonis** <sup>2</sup>

1 Université Clermont Auvergne (UCA), INRAE, UR 1465 LISC, Clermont-Ferrand, France

2 Université Clermont Auvergne (UCA), CNRS, UMR 6042 GEOLAB, Clermont-Ferrand, France

Corresponding Author: Jean-Baptiste Pichancourt Email address: jean-baptiste.pichancourt@inrae.fr

Dynamic Adaptive Policy Pathway (DAPP) maps help guide management decisions when the future of a critical asset is deeply uncertain due to environmental changes. Recent discussions have highlighted the importance of creating DAPPs that better consider social-ecological factors for managing common-pool ecosystem services adaptively. Our focus was on evaluating how DAPPs could address three key challenges identified by Ostrom in adaptive governance of social-ecological systems (SES): (i) avoiding one-size-ûts-all solutions (i.e. the panacea dilemma), (ii) ensuring resilience to system-wide shocks (i.e. systemic robustness), and (iii) coordinating different levels of governance initiatives effectively (i.e. operational, collective and constitutional-choice levels).

Here, we demonstrate that balancing these three goals hinges upon understanding the connection between DAPP and other key analytical frameworks: Ostrom's SES framework, the Coupled Infrastructure System (CIS) framework, the Complex Dynamical Systems theory, and the Viable Control Theory.

We developed this connection and applied it to investigate potential governance transition pathways designed to manage hedgerow networks that provide a wide range of ecosystem services. Our focus was on two SES characterized by distinct community constraints and needs: a rural and a peri-urban SES located in the French Auvergne region. There, the viable delivery in hedgerows' ecosystem services faces threats from climate change, prompting our exploration of possible viable or optimal adaptation pathways between nine alternative nested governance arrangements. We developed indicators to pinpoint the key drivers influencing DAPP map differences, in response to changes in SES context and climate stress level.

Our research underscores the efficacy of this approach in addressing simultaneously the three adaptation problems. We discuss the advantages and limitations of this approach to accommodate increasingly complex SES and semi-natural infrastructures with diverse plant species, diverse stakeholders, and various ecosystem (dis)services. Additionally, we emphasize how this complexity may affect ease of use and testability in practical applications.

#### **Title** 1

- Bridging Ostrom's governance theory to dynamic adaptive policy pathway (DAPP) maps: theory 2
- and application example 3
- 4

#### **Authors** 5

- Jean-Baptiste Pichancourt\*<sup>1†</sup>, Antoine Brias\*<sup>2</sup>, and Anne Bonis<sup>2</sup> 6
- \*Co-first authors 7
- 1 Université Clermont Auvergne (UCA), INRAE, UR 1465 LISC, Clermont-Ferrand, France 8
- 2 Université Clermont Auvergne (UCA), CNRS, UMR 6042 GEOLAB, Clermont-Ferrand, France 9
- Corresponding author: [jean-baptiste.pichancourt@inrae.fr](mailto:jean-baptiste.pichancourt@inrae.fr) 10
- 11

#### **Abstract** 12

Dynamic Adaptive Policy Pathway (DAPP) maps help guide management decisions when the future of a critical asset is deeply uncertain due to environmental changes. Recent discussions have highlighted the importance of creating DAPPs that better consider social-ecological factors for managing common-pool ecosystem services adaptively. Our focus was on evaluating how DAPPs could address three key challenges identified by Ostrom in adaptive governance of socialecological systems (SES): (i) avoiding one-size-fits-all solutions (i.e. the panacea dilemma), (ii) ensuring resilience to system-wide shocks (i.e. systemic robustness), and (iii) coordinating different levels of governance initiatives effectively (i.e. operational, collective and constitutional-choice levels). 13 14 15 16 17 18 19 20 21

Here, we demonstrate that balancing these three goals hinges upon understanding the connection between DAPP and other key analytical frameworks: Ostrom's SES framework, the Coupled Infrastructure System (CIS) framework, the Complex Dynamical Systems theory, and the Viable Control Theory. 22 23 24 25

We developed this connection and applied it to investigate potential governance transition pathways designed to manage hedgerow networks that provide a wide range of ecosystem services. Our focus was on two SES characterized by distinct community constraints and needs: a rural and a peri-urban SES located in the French Auvergne region. There, the viable delivery in hedgerows' ecosystem services faces threats from climate change, prompting our exploration of possible viable or optimal adaptation pathways between nine alternative nested governance arrangements. We developed indicators to pinpoint the key drivers influencing DAPP map differences, in response to changes in SES context and climate stress level. 26 27 28 29 30 31 32 33

Our research underscores the efficacy of this approach in addressing simultaneously the three adaptation problems. We discuss the advantages and limitations of this approach to accommodate increasingly complex SES and semi-natural infrastructures with diverse plant species, diverse stakeholders, and various ecosystem (dis)services. Additionally, we emphasize how this complexity may affect ease of use and testability in practical applications. 34 35 36 37 38

#### **1. Introduction**  39

Ecosystem services (ES) represent common pool resources (CPR) that require collective management, due to their universal benefits, non-excludability, and susceptibility to depletion from changing circumstances (Ostrom, 2009; Allen et al., 2011). 40 41 42

The level of ES can be depleted locally due to various factors. Changes in species composition directly and shifts in their ecological environment indirectly impact ES (MEA, 2005). Stakeholder decisions regarding ecosystem infrastructure adaptation and changes in the socialecological context also influence ES. For example, rural and suburban areas may have different stakeholder needs (Lapointe et al., 2019). Climate change further affects the strategies required to govern and adapt ecosystems to meet ES demands (Lavorel et al., 2019). 43 44 45 46 47 48

Adapting to these contextual changes necessitates cost-effective managerial strategies capable of being implemented across diverse social-ecological contexts and management scales, while also mitigating unforeseen spillover effects that may affect various stakeholders and ecological elements. 49 50 51 52

The adaptation pathway framework (Wise et al., 2014; Werners et al., 2021), and particularly the Dynamic Adaptive Policy Pathway maps (aka. DAPP, as per Haasnoot et al., 2013; 2019) partly address this problem by facilitating the mapping of adaptation options, amid varying costs and benefits between them and uncertain disturbances. However, concerns have been raised regarding their effectiveness in addressing adaptation planning challenges when the complexity of the social-ecological systems (SES) need to be better emphasized (Hermans et al., 2017; Roelich & Giesekam, 2019; Stanton & Roelich, 2021). 53 54 55 56 57 58 59

In an attempt to improve on this, some studies have recently presented DAPP maps in order to adjust the delivery of the bundles of ES in agro-ecological landscapes (e.g. Colloff et al., 2016; Lavorel et al., 2019). These studies presented interesting qualitative information on how to sequentially transit between long-term visions of social-ecological transformations. However, their approach lacked quantitative predictive and explanatory power, and unambiguous links with E. Ostrom's theory of governance of common-pool resources (CPR). 60 61 62 63 64 65

Our research focuses on the nature of the best methodological formalism for creating DAPPs that best respected Ostrom's theory, with minimal ambiguity. Here we particularly focused on solving simultaneously three adaptive governance hurdles raised by Ostrom: namely the panacea vs SEScontext dilemma (Ostrom 2007), the systemic robustness/overflow problem (Anderies, Jansen & Ostrom), and the optimal sequencing of nested governance initiatives (Ostrom, 1990). We subsequently identify and describe each problem, and review methods along with their limits, prompting the development of a more cohesive method. To provide tangible insight, we evaluated the interest of this method through a real-world scenario in Central France, focusing on the sustaining of hedgerows' ES provisioning across two distinct SES types (rural and suburban) and under three varied climatic conditions. 66 67 68 69 70 71 72 73 74 75

76

#### **1.1. The panacea dilemma for adaptation.** 77

The first adaptation problem pertains to identifying the best targets for addressing ES risks of depletion. These targets can change with the social-ecological context, given the diverse elements within different SES. These may include actors, species, and shared or private infrastructures that can be of different nature: ecological infrastructures (e.g. hedgerows as a semi-natural infrastructures), physical infrastructures that support them or control their access, institutional infrastructures (i.e. laws, rules, property-rights), social infrastructures (i.e. associations, public spaces, communication networks) or cultural infrastructures (values, practices, knowledge, beliefs). Selecting the appropriate target necessitates a comprehensive description of the SES attributes, followed by the assessment and diagnosis of their state of good functioning and adaptability against empirical norms (Ostrom et al., 1989). 78 79 80 81 82 83 84 85 86 87

This class of problem has been addressed by the SES framework (Ostrom, 2007, 2009; Ostrom & Cox, 2010; McGinnis & Ostrom, 2014), that derives from Ostrom's (1990) theory of governance of Common Pool Resources (CPR) and the simplification of the 450 attributes presented in Ostrom's CPR codebook (Ostrom et al., 1989). The aim was to balance applying general principles of good governance with effective tools for designing specific adaptation plans. This ensured that diagnostic criteria could cover different socio-economic variables, issues, and potential targets for improvement in various contexts. As such, the SES framework provides a reduced list of SES attributes, but that can be further unpacked or modified if the context and data availability require it (e.g. see improvements of the SES framework by Basurto et al., 2013; McGinnis & Ostrom, 2014; Vogt et al., 2015). However, the SES framework has never been formally connected with the DAPP framework, and this leads frequently to less streamlined methods for constructing DAPP maps that incorporate SES elements (see e.g. Lavorel et al., 2019). 88 89 90 91 92 93 94 95 96 97 98 99 100

101

#### **1.2. The problem of systemic adaptive robustness and overflow** 102

The DAPP framework was initially designed with questions of systemic robustness in mind (Haasnoot et al., 2013; 2019). However, The underpinning modeling guidelines presented in the DAPP framework (see Haasnoot et al., 2019) was not designed to streamline complex SES adaptation problems. For instance, there is no guideline on how to model complex socialecological interactions, non-linearities, cascading chains and spillovers impacting different resource users and species (Anderies, 2016; Anderies, 2019; Houballah et al., 2020), or unexpected trade-offs and synergies between common and non-common pool ES (Fisher et al., 2009; Ban et al., 2015). 103 104 105 106 107 108 109 110

Various modeling frameworks address these systemic problems, synthesized by Binder et al. (2013) and Pulver et al. (2018). The Coupled-Infrastructure System and Robustness (CIS) framework (Anderies, Janssen and Ostrom, 2004; Anderies et al., 2019; Aggarwal & Anderies, 2023) tackles these problems effectively. It views adaptation actions as crucial for SES robustness, considering four interacting infrastructures and actors: ecological resource infrastructure (RI), public infrastructure (PI), resource users (RU), and public infrastructure providers (PIP). This framework offers guidance for translating systemic adaptation and spillover problems into equations, predicting infrastructural vulnerabilities related to ES production and external disturbances (Anderies, 2015; Muneepeerakul & Anderies, 2020). When combined with 111 112 113 114 115 116 117 118 119

the viable control theory (Aubin et al., 2011; Martin et al., 2011), the CIS framework estimates system-wide metrics of robustness or resilience (Muneepeerakul & Anderies, 2017; Homayounfar et al., 2018; Houbbalah et al., 2021), drawing from Holling (1973) and Walker et al. (2004). 120 121 122 123

Up to now, the CIS framework has however never been articulated with DAPP maps. Furthermore, its current stylized structure introduces ambiguities, as highlighted by Bernstein et al. (2019) and Pichancourt (2024). For instance to enhance its relevance, modifications are necessary to facilitate the independent analysis of the adaptation of infrastructures and actors' functions associated with every social compartments (RU, PI, and PIP). Additionally, there needs to be a clear articulation with the SES and DAPP frameworks to ensure unambiguous integration. 124 125 126 127 128 129

130

#### **1.3. The problem of nested adaptive governance initiatives** 131

The last adaptation problem pertains to orchestrating complementary initiatives across nested governance arrangements, each representing both targets and source of adaptation actions geared 132 133

towards enhancing the viability (robustness) of the SES over varying time frames. 134

DAPP maps are designed to help sequence different adaptation initiatives at different timescales, 135

but lack guidelines to plan nested governance initiatives and arrangements that are inextricably linked through complex linkages. 136 137

For instance, Ostrom (1990) described three such nested governance arrangements: short-term operational-choice arrangements (hereafter called OCA), mid-term collective-choice arrangements (KCA), and long-term constitutional-choice arrangements (CCA). 138 139 140

Adapting OCA can consist in changing the range of daily actions associated with e.g., resource exploitation, support, monitoring. Then adapting KCA can consist in adapting the functions of actors or way to articulate and trigger these different OCA simultaneously or sequentially. Finally adapting CCA can consist in changing radically i) who is the fundamental center of decisions and ii) what KCA are allowed to operate or be adapted. 141 142 143 144 145

The problem is that adapting a lower-level arrangement for shorter term viability benefits, may not secure long-term needs, and vice versa. Global governance adaptation may thus require complex nested adaptation trade-offs to stay viable at different time-scales. 146 147 148

The last challenge would thus be to define a way to organize these three nested governance initiatives in a way that we can maintain the robustness of the entire SES at any time scale. 149 150

151

#### **1.4. Objective and structure of the paper** 152

In this paper, we propose a method that can streamline the process of constructing socioecologically rich DAPP maps (cf. Stanton & Roelich, 2021), by linking them to the three mentioned frameworks, i.e. (i) with the SES framework (Ostrom, 2007) to balance universal adaptation principles with context-specific responses, (ii) with the CIS framework (Anderies et al., 2004) to balance adaptation actions and maximize robustness (or minimize risks of systemic 153 154 155 156 157

#### overflow), and (iii) with the model of nested governance arrangements (Ostrom, 1990) to balance adaptation sequences along the adaptation pathways. 158 159

In the methodology section, we elaborate on the formalism, detailing the workflow and necessary minor yet mandatory adjustments made to the three frameworks mentioned earlier. Our testing of the newly integrated method focuses on assessing a bundle of ES producedby hedgerow networks, alongside the pathways for adapting the hedgerow network, the associated network of actors and governance arrangements that can address the challenges posed by climate change, particularly drought stress. We specifically investigated two archetypal SES - peri-urban and rural - with the aim of crafting distinct DAPP maps tailored to each SES. We also introduce hedgerows contrasts regarding their height and plant species richness as they are both partly controlled by man-made management and impact ES level. The resulting maps reflect variations in how actors value the bundle of ES within their respective social-ecological contexts. We then pinpoint with specific indicators the key drivers influencing DAPP map differences, in response to changing SES context and climate stress level. 160 161 162 163 164 165 166 167 168 169 170 171

172

#### **2. Methodology** 173

We used a six-step workflow to connect the three previously mentioned frameworks and adaptation problems. **Step 1** extends Ostrom's SES framework to analyze the social-ecological attributes to facilitate the adaptation at different temporal scales of the governance of the hedgerow network and ES (CCA, KCA, OCA). **Step 2** explains how to deduce the SES structure using a **renewed** version of the CIS framework, and to apply it to model different nested levels of governance arrangements (CCA, KCA, OCA), and transitions between them characterized by different costs and benefits. **Step 3** explains how to transform the renewed CIS model into a system of equations, and the assumptions and parametrizations involved for our case study. **Step 4** shows how to apply the Viable Control Theory (Aubin, 2011) to to the system of equations and estimate the robustness limits of each CIS option under different climate stressors impacting the hedgerows and ES provisioning. **Step 5** consists in defining the DAPP framework within the CIS and viable control theory frameworks, and shows how to construct different classes of DAPP maps that emphasize different nested aspects of the adaptation problem. **Step 6** explains the quantitative indicators that are used to understand the sensitivity of these novel DAPP maps to changes in climate stress levels and SES contexts. 174 175 176 177 178 179 180 181 182 183 184 185 186 187 188

Supplementary details required to implement this method to our case study are presented in Supplementary S1 for the application of the SES framework analysis and associated data; in S2 for the ecological surveys and GIS analyses used to model the structure and dynamics of the hedgerow network; and in S3 for the model implementation including computer code. 189 190 191 192

#### **2.1. Definition of the social-ecological attributes of adaptation** 193

The version of the SES framework that we used for analyzing our study site is firstly based on Ostrom's (2009) on Basurto et al.'s (2013). Then on McGinnis & Ostrom's (2014) for the attributes allowing generalization from users to actors and multi-tiering of some variables per level of governance-choice arrangement (OCA, KCA, CCA). Finally on Vogt et al.'s (2015) for the integration of ecological and ecosystem services attributes. For example, we transformed the  $2<sup>nd</sup>$  tier attribute "externalities to other SES" (O3) into a 3<sup>rd</sup> tier attribute that emphasizes the role of ecological resource infrastructures and associated species. All the  $1<sup>st</sup>$  and  $2<sup>nd</sup>$  tier attributes that derived from these works can be targeted for adaptation (refer to table 1). 194 195 196 197 198 199 200 201

We further introduced new  $3<sup>rd</sup>$  and even  $4<sup>th</sup>$  tier attributes specific to our general adaptation problem, including in anticipation of the modifications planned for the CIS and DAPP frameworks. For instance, we subdivided certain  $2<sup>nd</sup>$  tier attributes (see table 1: S1:S3, RS4, RU1, RU3, GS2:GS10, A1:A9, I2:I10, O1) into three new 3<sup>rd</sup> tier functional attributes that are subject to adaptation, called "exploiting", "supporting" and "policy-making", such that: 202 203 204 205 206

(i) **Exploiting attributes**  $(3<sup>rd</sup>$  tier noted e.g. A1.1 in table 1 and Supplementary S1) refer to as the exploiting actors (A2.1), the associated social infrastructures (e.g. norms and social capital, A6.1), institutional infrastructures (e.g. rules-in use, strategies:  $GS1.1 \rightarrow GS10.1$ ) and physical infrastructures (such as supply chains or exploiting technologies, S7.1). These attributes involve various social-ecological interactions  $(11.1 \rightarrow 110.1)$  associated with the hedgerows' resource appropriation/provisioning, production, distribution/supply (chain), transformation, consumption/ use and monitoring of own cost-effectiveness. They also involve various resource outcomes  $(O1.1 \rightarrow O3.1)$  in relation with the production of the desired quantities of ecosystem services human livelihoods. Exploiting attributes can delineate actors, infrastructures, interactions and outcomes related with the sustainable dimension of this exploitation, provided they solely refer to utilitarian actions and objectives. In our case, it means conserving, monitoring and regulating the exploitation of only the hedgerows elements that are important for the delivery of the ES of direct selected interest for the exploiting and beneficiary actors. 207 208 209 210 211 212 213 214 215 216 217 218 219

(ii) **Supporting attributes**  $(3<sup>rd</sup>$  tier noted e.g. A1.2) refer to as the supporting actors, infrastructures, interactions and outcomes that contribute to maintain and monitor the resource system (hedgerows size and their plant species richness). They also contribute to regulate the resource access, or the flow of certain ecosystem disservices caused by the lack or the excess of hedgerows (e.g. fire spread, landslide). Furthermore, they can provide socio-economic or knowledge support the exploiting actors and end-users affected by these disservices. The motives of these actions includes thus both utilitarian and non-utilitarian considerations, such as ethical or aesthetical reasons (e.g. life for its own sake, landscape aesthetics) which may be positive or negative. 220 221 222 223 224 225 226 227 228

(iii) **Policy-making attributes** (3rd tier noted e.g. A1.3) refer first to the actors, infrastructures, interactions and outcomes associated with the institutional, social, financial and cultural support of the exploiting and/or the supporting actors and infrastructures. They also refer to the one involved in the arbitration and conflict-resolution between exploiting and supporting actors and infrastructures, when trade-offs emerge on how to best manage the resource (e.g. utility vs global), and how to best navigate the global process of adaptation through planning (i.e., 229 230 231 232 233 234



the DAPP). It is important to note that SES do not necessarily possess exploiting, supporting, and/or governing attributes, but all the associations can in theory be found. 235 236

Following the third adaptation problem, relative to the balance the timing between nested governance initiatives, we further subset the exploiting, supporting, and policy-making attributes into fourth-tier attributes to record the three possible levels of governance actions operating at different time scales: i.e. CCA, KCA and OCA (see definition in the introduction and table 1). 237 238 239 240

241

#### **2.2. Relations between SES attributes and the CIS model** 242

243

#### *2.2.1. Translation of the SES framework into a renewed CIS framework* 244

Step 2 sets the transformation of the SES framework analysis into a Coupled-Infrastructure System (CIS) model originally proposed by Anderies, Janssen & Ostrom (2004). It aims to formalize the functional relation among the attributes of the SES framework (figure 1). To achieve that, we modified the original CIS framework structure, following Bernstein et al. (2019) and Pichancourt (2024), who particularly raised limitations in relation with our arguments for creating our  $3<sup>rd</sup>$  and  $4<sup>th</sup>$  tier attributes in step 1. 245 246 247 248 249 250

251

Four modifications were made on the original CIS framework, building upon a previous small modification introduced by Pichancourt (2023, 2024) to study social-ecological coexistence in forest SES. 252 253 254

*(i) First modification concerning the three social compartments*. The original CIS framework separated infrastructural compartments (natural infrastructures NI and public infrastructures PI) and **actor compartments** (resource users RU and public infrastructure providers PIP). As a result, all the infrastructures (physical, social, institutional, economic, cultural) were grouped under PI, regardless of their function (exploitation, support, policy-making, arbitration). Similarly, all the organizational actors and economic capacities were grouped under PIP, and all the perception models of nature were grouped under RU and PIP (cf. Aggarwal & Anderies, 2023). In the modified version, we rather defined the three social compartments into three classes of functions or capacities of action outlined in the SES framework (see step 1): the one associated with exploiting actors & infrastructures (EAI), with supporting actors & infrastructures (SAI), and with policy-making / arbitrating actors & infrastructures (PAI). This way, we can now explicitly model collaborating, competitive, or subordinating interactions occurring between functions, actors and/or infrastructures of the three compartments (cf. figure 1). 255 256 257 258 259 260 261 262 263 264 265 266 267

*(ii) Second modification concerning the actors*. Given the first modification, a given actor can now assume different functions (as suggested by McGinnis & Ostrom, 2014) and thus may participate and increase the capacity of action of EAI, SAI, and PAI, if relevant. This can now be modeled using any of the following linking arrows from figure 1: 2a, 2b, 3a, 3b, 6a, 6b. For example, in our case study, an organic farmer can simultaneously be: 268 269 270 271 272

273

an independent exploiting ES benefits and/or owner of some hedgerows (EAI),



274 275

- a member of a local group of organic farmers providing more collective supporting roles for broader conservation purposes (SAI),
- 276 277

278

• a board member of a governing body of an NGO or private association (PAI) that is buying lands and renting them to farmers, under specific organic farming rules and granting schemes (cf. SES analysis in Supplementary S1).

*(iii)* Third modification concerning the compartments' interactions with their external settings. A given external agent, institution or environmental driver can now more clearly interact uniquely with every social compartment (using any of the links 7d, 7f, 7h). For instance, the NGO "Mission Haie" (hedgerow mission) offers three different training schemes to increase actors' capacities of action. One for individual or collective of farmers on how to sustainably harvest and manage their hedgerows for private or club ES benefits (EAI link 7d), another for groups of farmers on how to collectively monitor or restore the state of hedgerow networks for broader public and common ES outcomes (SAI link 7f), and a third for helping governing bodies to establishing DAPP rules (PAI link 7h). 279 280 281 282 283 284 285 286 287

*(iv) The fourth modification concerning the modeling of the adaptation of nesting governing structures and actions.* The original CIS framework allowed for modeling some forms of operational and collective-choice arrangements (Anderies et al., 2019), but less at a constitutional-choice level. The three suggested modifications (i, ii, iii) are useful to understand and model nested adaptations in governance arrangements: at an operational-choice (OCA), collective-choice (KCA), and constitutional-choice (CCA) levels (cf. SES framework analysis in step 1 and table 1). This capacity is exemplified next. 288 289 290 291 292 293 294

295

#### *2.2.2. Defining potential adaptation options at three nested levels of governance arrangements: constitutional-choice (CCA), collective-choice (KCA), and operational-choice (OCA).* 296 297 298

Setting up steps #1 and #2, and following the spirit of the method described by Ban et al. (2015) and Anderies et al. (2016, 2019), we designed various renewed CIS structures that represent different options for adaptation across the three levels of governance arrangements identified in the SES framework analysis of our case study of the Auvergne region (CCA, KCA, OCA). 299 300 301 302

We first defined four CCAs that each represent a unique distribution of authority between possible functional actors when governing the common pool of ES (see figure 2). For every CCA, we defined that different KCA could be used, involving different forms of coordination between actors and infrastructures within and between the four compartments (denoted as  $KCA<sub>EAI</sub>$ , KCA<sub>PAI</sub>, KCA<sub>SAI</sub>), and thus resulting in different chains of actions (table 2). In our case study, and for reducing complexity, every KCA resulted into one and only one OCA. Every combination of KCA/OCA involved a unique set of constraints on the permissible range and intensity of exploitation and management actions on hedgerows (cf. links 1a and 1b in figure 1 and in table 2), of supporting actions between SAI and RSI or EAI (cf. links 4 to 6), and of policy-making actions between PAI and other social compartments (cf. links 2 and 3, and table 2). 303 304 305 306 307 308 309 310 311 312

313

314

#### **2.3. Transformation of the renewed CIS model into a set of equations** 315

#### **2.3.1 System of equations representing the most generic scenario**  316

Each CIS state variable (RSI, EAI, SAI, PAI) and linking parameter (0a  $\rightarrow$  7g) can denote various SES attributes, potentially leading to distinct mathematical formulations and interpretations (cf. figure 2). Consequently, we had to make deliberate choices regarding their specific meanings in this study. 317 318 319 320

RSI was defined through the hedgerows' potential for producing ES, ranging from 0 to  $+1$  for each of them. The associated links (0a, 1a, 4b, 7b) directed toward RSI represented ecological process (0a, 7b) or actions by actors (1a, 4b, 7b) impacting this ES potential, ranging from -1 to +1 (see details in figure 1). Similarly, for each social compartment (EAI, SAI, and PAI), the links directed toward them were defined as the relative capacity of action gained and potentially lost, within the range of -1 to +1 or 0 to +1. Self-loops (0b, 0c, 0d: -1 to +1) denoted the natural growth or decay of the capacity of action of the compartment. This could be negative (loss through natural death or socio-cultural or economic instability), positive (e.g., gain through internal creativity), or neutral based on precise definitions. 321 322 323 324 325 326 327 328 329

For clarity, link 1a represented the management rate (0 to 1) by EAI on hedgerows from RSI, while 1b represented the effective EAI action capacity gain or loss per resource unit (ES) flowing from RSI (-1 to +1). Similarly, 2a and 2b denoted PAI action capacity ratios gained from monitoring EAI elements  $(0 \tto +1)$  and SAI action capacity ratios gained or lost from contextualizing with PAI  $(-1 \text{ to } +1)$ , respectively. 4a represented the SAI action capacity ratio gained by monitoring RSI elements (0 to 1), and 4b denoting the collective SAI support rate on RSI (0 to 1). Links like 6a and 6b reflected the SAI capacity of action gained or lost through EAI actors joining the SAI and the extra one gained or lost by EAI from the support or sanctions received from SAI (-1 to +1). 5a and 5b denote the action capacity gained from monitoring 1a and 1b, respectively, within the range of  $[0, 1]$ . Similarly, 5a' and 5b' represented the regulation rate on action 1a and the action capacity gain 1b (0 to 1). We defined that 7b signified the impact of the settings on RSI (climate stress rate on the survival of various hedgerow types producing ES (-1 to 0)). Additionally, 7d, 7f, and 7h indicated the action capacity gained by EAI, PAI, and SAI, respectively, resulting from external socio-economic or climate factors. Finally, 7a, 7c, 7e, and 7g represented externalities of ES flowing to other SES outside the one studied (-1 to 1). 330 331 332 333 334 335 336 337 338 339 340 341 342 343 344

Altogether, the total weight of all linking variables (which includes self-loops) directed toward each of the four compartments, adds up to 1, such that: EAI:  $0b + 1b + 2b + 6b + 7d = 1$ , PAI: 0c  $+ 2a + 3b + 7f = 1$ , SAI: 0d + 3a + 4a + 6a + 7h = 1. 345 346 347

Given the selected meanings and CIS structure (figure 1), we then represented the CIS model as a set of equations, following the methodology described by Anderies et al. (2016), Muneepeerakul & Anderies (2017; 2020), and Houballah et al. (2021; 2023). This way, we obtained the most general system of equations (eq. 1) describing the processes affecting the dynamics in the RSI state (hedgerow network and ES) and of the overall action capacities of EAI, PAI and SAI: 348 349 350 351 352

# Peer I

## Manuscript to be reviewed

$dRSI$	Natural ES Growth	Import of SES Settings	ES Externalities	(1a)
$dH$	SAT Support ES Access or Flow Regulated Access & Management Regulated			
$+4a.RSI.SAI - 1b.RSI.EAI$	5b.SAI + 1a.EAI.RSI	5a.SAI		
$dEAI$	Natural EAI Growth/Decay	Import of SES Settings	Extremalities	
$dEAI$	+\n $\frac{1}{10.RSI.EAI}$ \n	\n        ± 7d.EAI - 7c.EAI (1b)		
Access & ES Flow Regulated	SAI Support & Regulations	PAI Support & Sanctions		
$+ 1b.RSI.EAI$	5b.SAI ± 6b'.EAI.SAI ± 2b.EAI.PAI			
$dSAI$	Natural Loss/Decay	Import of SES Settings	Extremalities	
$dI$	RAT Joining/leaving	PAI Support/Sanction + (6a-6b).EAI.SAI ± 7h.SAI - 7g.SAI (1c)		
$EMI$ Join/Suport/Saux	PAI Support/Sanction + (6a-6b).EAI.SAI ± 3a.PAI.SAI - 7e.SAI			
$dPAI$	Natural Loss/Decay	Import of SES settings	Extremalities	
$dPAI$	Natural Loss/Decay	Import of SES settings	Extremalities	
$dPAI$	Natural Loss/Decay	Import/Sanction - 7e.SAI		
$dPAI$	15a.I.AII + 3a.PAI.SAI + 3a.PAI.SAI + 7f.SAI + 7f.SAI + 7			

In this system of equations, the  $\pm$  sign reflects the fact that some parameters associated with the action capacities of EAI, SAI, PAI may have positive or negative impacts on the dynamics of RSI, depending on the context. 354 355 356

357

#### **2.3.2 Model parametrization and simplifications to match our case study**  358

In the study area, situated in the Auvergne region (central France), we focused on the impact of the hedgerow dynamics of various ecosystem (dis)services. The implementation of the renewed CIS resulted in further parametrizations and simplifications. 359 360 361

2.3.2.1 RSI Model of hedgerows network dynamics 362

The RSI represented the hedgerow network. It was decomposed into four hedgerow types (and a fifth extra empty state), each characterized by their height (short, tall) and biodiversity states (rich, poor plant species richness) (see Supplementary S1). The height and extent of hedgerows were defined through a GIS analysis of aerial photographs of representative parts of the studied areas in 1958, 1989, 2009 and 2019, together with field observations for plant species richness (cf. Supplementary S2). We deduced the annual average transition and stasis rates between the five hedgerow states (Supplementary S1), and then the transition matrix *M* that was used as a baseline model for projection of our scenarios of hedgerow network dynamics, associated with CCA-A (figure 2). Given the discrete nature of this model, the RSI dynamics in eq. 1 was also discretized. 363 364 365 366 367 368 369 370 371 372

2.3.2.2 Model of ecosystem services, costs & benefits of adaptation actions 373

Each hedgerow state was characterized by the production of different levels of seven ecosystem (dis)services, postulated as shown in table 3. We made the assumption that the entire ES produced by hedgerows equals the ES outflow effectively enjoyed by EAI, such that  $1b = 1$  in eq. 1. Based on interviews with local stakeholders and regional strategic documents (Supplementary S2), we characterized archetypal needs and expectations of stakeholders in each SES. We found 374 375 376 377 378

that two rural and peri-urban areas had somehow different needs and expectations regarding ecosystem (dis)services (table 3). 379

380

381

- 2.3.2.2 Specific parametrization for the different governance arrangements and actions 382
- At an operational-choice (OCA) level, the actions changed with the different types of hedgerows, affecting the level of production of the seven studied ecosystem (dis)service (Supplementary S1, table 3). 383 384 385
- At a collective-choice level (KCA), not all the information could be obtained from interviews for 386
- the chains of actions presented in table 2. The same applied for the constitutional-choice (CCA) level (table 3). We thus made further simplifying assumptions to eq. 1 as followed: 387 388
- At a constitutional-choice (CCA) level, we assumed perfect community grouping for the CCA-C 389
- and -D ( $6a = 1$  and  $6b = 0$  in equation 1). For CCA-B and -D, we also assumed perfect feedback from farmers to the European union (EU-CAP) and/or the NGO *Terre-de-Lien* TdL (2a = 1). For 390 391
- CCA-C and -D, we assumed a perfect monitoring of the resource state  $(4a = 1)$ , and a perfect 392
- monitoring  $(5b = 1)$  of the access rate 1b of EAI (farmers, local population) to get some of the 393
- ES, or to manage hedgerows to produce ES ( $5a' = 1$  on 1a). Finally, for CCA-D, we assumed a perfect feedback of the SAI to the PAI  $(3b = 1)$ . In our case, this simplification applied to the 394 395
- TdL and DAPP board comities. We finally assumed a perfect human or economic support to the 396
- SAI from PAI  $(3a = 1)$ . 397
- We also considered qualitative rather than quantitative change in EAI, SAI and PAI attributes in eq. 1. We accordingly simplified eq. 1, by considering constant EAI, SAI and PAI population number or finances (dEAI/dt = 0, EAI = 1, 0b = 0; dPAI/dt = 0, PAI = 1, 0c = 0, dPAI/dt = 0). 398 399 400
- 401
- 2.3.2.2 Resulting context-specific model after simplifications 402
- These assumptions led to the simplified model that we used for our case study, as per eq. 2 below: 403 404

405

## Manuscript to be reviewed

**2.4.** 406

#### **Analysis of the viability of various CIS arrangements under different levels of climate stressors.** 407 408

#### **2.4.1. Model of climate stress impact on the hedgerow network** 409

We assumed the drought stress to evenly affect the four types of hedgerows from the RSI, through variable 7b in eq. 1 (or see figure 1). We assumed an increased mortality rate of the hedgerow woody plant species with increasing drought stress (Barros, 2017). Level 0 represented no additional climate stress (7b = 0), level 1 a moderate drought stress causing 1.2% annual mortality rate ( $7b = -1.2\%$ .0a), and level 2 a high drought stress causing 2.4% annual mortality rate  $(7b = -2.4\%, 0a)$ . 410 411 412 413 414 415

416

#### **2.4.2. Definition of the constraint domain of satisfaction for the levels of ES** 417

This step consists in evaluating the congruence between costs and benefits for all the possible scenarios of CIS arrangements (CCA, KCA and OCA), as specified by Ostrom's second design principle of good governance (Ostrom, 1990). To achieve this, we must respect the basic condition that the turnover of hedgerow biodiversity, biomass and ES produced are equal or greater than their exploitation rate, such that: 418 419 420 421 422

423

424 
$$
\frac{dRIS}{dt} = \frac{dES_i}{dt} \ge 0 \Rightarrow 0 \ a + (1 \ a \ .5 \ a \ ' + 4 \ b) SAI \ge 7 \ b + 1 \ b \ .5 \ a
$$
 equation 3

425

From eq. 3 and figure 2, it can be seen that the potential ES turn-over rate (dES/dt) depends on both the intrinsic rate of increase of the resource (link 0a), the supporting actions coming from either the EAI (link 1a) or SAI (link 4b). 426 427 428

If population needs differ between ecosystem services  $(ES<sup>+</sup>)$  or disservices  $(ES<sup>+</sup>)$ , viability is achieved when  $ES^+$ <sub>i</sub>  $\geq ES^+$ <sub>i,min</sub> and  $ES^-$ <sub>j</sub>  $\leq ES^-$ <sub>j,max</sub>, where  $ES^+$ <sub>i,min</sub> represents the minimal value of ecosystem service *i* and ES<sup>-</sup><sub>j,max</sub> the maximal value of ecosystem disservice *j*. They represent the different dimensions of the thresholds of a constraint domain  $K$  that defines all actors' ES needs, that we refer to as the *ES satisfactory domain.* In our case, *K* differed between rural and periurban SES, and ES levels from *K* were rescaled [0-1] to its analysis (cf. table 3 and Supplementary S1). 429 430 431 432 433 434 435

436

#### **2.4.3. Definition of the set of robust trajectories that respect** *K* 437

Based on the eq. 3 and *K*, we define robustness, resilience, or lack thereof for every nested combination of trajectories of adaptation action (CCA, KCA, OCA), and for different climate stress levels. Following Aubin (2011)'s Viable Control Theory, and then Martin et al. (2011), we can distinguish three sets of controlled trajectories: (i) the set of robust trajectories of governance structural change that permanently stay within *K* during the time horizon *T*, (ii) the set of resilient trajectories that temporarily cross *K* at time *t*, to then permanently come back within at *t+n* until *T*, and (iii) the set of non-viable trajectories that leave *K* at time *t* and inevitably lead to permanently cross the *K* limits. We used this method to anticipate the different stages of robustness loss before reaching a tipping point, and to define the desired adaptation actions (CCA, KCA, OCA) that can be triggered to restore long-term viability within *K*. 438 439 440 441 442 443 444 445 446 447

Here we defined the viability kernel *Viab(K)* as the set of the state space for which there is at least one viable (robust or resilient) sequence of adaptive governance action *a(t)* at time *t*, selected among a set of possible controlled actions *A,* starting from the initial *RSI0* states (hedgerow or ES states). In the most general case defined by Ostrom (1990), *A* assumed a nested group of sets of adaptive actions of governance changes, such that  $A_{OCA} \in A_{KCA} \in A_{CCA} \in A$ . These represent respectively the set of actions of changing or not the OCA  $(A<sub>oCA</sub>)$ , within the set of possible change in KCA  $(A_{KCA})$ , itself within the set of possible change in CCA  $(A_{CCA})$ . Given this nested structure, *Viab(K)* for the robust case can be defined in discrete time for any time horizon *T* as follows: 448 449 450 451 452 453 454 455 456

457

458 
$$
Viab_K(T) = [RIS_0 \lor \forall t \in [0, T], \exists a(t) \in A_{OCA}(T) \in A_{KCA}(T) \in A_{CCA}(T) \in A(T), ES_t \in K]
$$
eq. 5

459

Without changing the implications, and as specified in step #3, we simplified eq. 5 for our case study to only consider the viability estimation involving adaptive controls between two levels (CCA and KCA). It means that triggering an action that changed a KCA automatically led to a unique change in the OCA (cf. table 2 and 3). We then computed *Viab(K)* for every SES type (rural, peri-urban) and climate stress level (0, 1, 2), using the Saint-Pierre backward algorithm on a discrete grid of the state space (Aubin et al., 2011). 460 461 462 463 464 465

466

#### **2.5. Deducing DAPP maps from the viability kernel**  467

468

#### **2.5.1. Defining the DAPP framework within the CIS and viable control frameworks** 469

Once the sets of viable (robust) trajectories are defined within  $Viab<sub>K</sub>$  (figure 3a), we need to provide a way to represent the possible sequences of adaptation options that can be used (figure 3b). Every time step *t* within *T*, there can be different options of robust or resilient adaptation, and the choice made by actors depends on their respective costs and benefits in term of ES provisioning, but also governance constraints that they each imply. This can lead to possible conflicts. 470 471 472 473 474 475

DAPP maps (Haasnoot et al., 2019) help visualize these robust, resilient and non-viable options, as a temporarily organized succession of decision nodes at every time step *t.* Based on this foundation, a decision may arise regarding whether to alter the governance structure between two successive decision nodes. DAPP maps empower stakeholders to select their preferred adaptive governance arrangement, either one that aligns with  $Viab<sub>K</sub>$ , or of resilient options if temporary non-viable transitions are selected (figure 3). This way, conflicts between actors and options can be solved sequentially, from one node to another. 476 477 478 479 480 481 482

In our case study, governance arrangements and pathways are nested (CCA, KCA, OCA). We thus defined adaptation pathways as a sequence of actions a(.) combining nested CCA, KCA and OCA actions at every time step, such that: 483 484 485

486

 $a(.) = (a_{CCA} a_{QCA} a_{OCA}(0), a_{CCA} a_{QCA} a_{OCA}(1), ..., a_{CCA} a_{OCA} a_{OCA}(T))$  equation 6 487

488

All the possible  $a(.) \in A(T)$  represent the entire control map (Aubin, 2011) and therefore the DAPP map of possible viable and nonviable adaptation pathways.  $a^K(.) \in A(T)$  represents the subset and DAPP maps of only the viable ones respecting *K*. 489 490 491

For argument sake, the DAPP map presented in figure 3 can be used to plan for a CCA adaptation, when all KCA/OCA adaptation options lose viability of a given CCA. This situation can happen when external stressors are too strong. In such cases, adaptation is still possible but more transformative adaptation involving new CCA are required. Given the nested structure, the temporal nested succession of controlled adaptation transitions (CCA, KCA, OCA) can collectively form a global viability kernel at a CCA level (figure 3a), and thus new viable trajectories according to eq. 3 (cf. figure 3b). 492 493 494 495 496 497 498

499

#### **2.5.2. Deduction of different DAPP maps that emphasize different priorities** 500

In our case study, once the existence of viable pathways is proved, three different types of DAPP 501

maps were produced for the two SES types (peri-urban, rural), and the three climate stress levels 502

(0, 1, 2). Each DAPP map emphasized different priorities of actors: 503



(i) C*ertainty DAPP maps* (figure 4) emphasize the probability of finding long-term 30 years viable pathways of adaptation, passing by all the possible 5 years sequence between two successive decision nodes; 504 505 506

(ii) *Most secured DAPP maps* (figure 5*)* result in this work from the selection of the subset of the 10 most secured options of viable adaptation pathways; 507 508

(iii) *Optimal DAPP maps* (figure 6) as the subset comprised of the seven pathways that maximize only one of the five  $ES<sup>+</sup>$  and minimized only one of the two  $ES<sup>-</sup>$ . We supplemented this analysis 509 510

by decomposing the effect of optimizing every ES on the other ES (figure 7). 511

512

#### **2.6. Understanding the sensitivity of these DAPP maps to social-ecological changes** 513

514

We aimed to understand which factors explained differences in viable pathways implied within every DAPP map, for different SES and climate stress levels. To this purpose, we would have liked to represent and compare  $Viab<sub>K</sub>$  calculated in the ES state-space and then deduce DAPP maps accordingly. However, the estimation of the former was not possible for computational reasons, and only *Viab*<sub>K</sub> in the state space of the hedgerow types could be calculated (cf. Supplementary S3). To get information regarding ES, we thus had to separate the analysis in to two sub-steps. Frstly, analyzing **Viab**<sub>*K*</sub> into the hedgerow space, and secondly perform a retrospective sensitivity analysis of the impact of changing the hedgerow types on the provisioning of every ecosystem services. The method to achieve this is described below. 515 516 517 518 519 520 521 522 523

524

#### **2.6.1. Evaluating the viability impact of changing hedgerow types on pathway viability** 525

For the two SES types (rural, peri-urban) and the three climate stress levels (0, 1, 2), we first analyzed the size and shape of **Viab**<sub>*K*</sub> (eq. 5) within the state-space associated with the four hedgerow types: tall hedgerows (TH), short hedgerows (SH), species rich (RH) and species poor (PH), via eq. 5. The state-space's size and shape are good indicators of the number and types of adaptation pathways. We thereafter produced bi-dimensional slices of **Viab**<sub>K</sub> within the fourdimensional state-space, to represent *Viab*<sub>*K*</sub> for TH vs SH (figures 8) and for RH vs PH (figures 9). They describe the combinations of hedgerow types, expressed as percentages, necessary to ensure the viability of adaptation pathways 526 527 528 529 530 531 532 533

We further pinpointed the initial state's position at *t0* (i.e. time when we did the SES analysis of the study sites in 2020) within  $Viab<sub>K</sub>$ , as an indication of whether the current SES state is inside, outside or near the frontier of *ViabK*, and therefore requires governance adaptation. For example, a small volume, asymmetrically shape *ViabK* (CCA|KCA|OCA) and an ES state very close to *K* within, both suggest that the SES is not secured, as stakeholders need to adapt CCA, KCA, OCA to stay viable, but with more limited options of new hedgerow type proportions at hand. 534 535 536 537 538 539

540

#### **2.6.2. Evaluating the ES security gains when changing hedgerow types** 541

We retrospectively analyzed for all the adaptive governance pathways *a(.) (eq 6)*, how much security gains (i.e. increase in the distance from the constraint *K* for every  $ES^{+}_{i,min}$  or  $ES^{-}_{j,max}$ ) were gained by switching operational actions from one hedgerow type to another (TH, SH, RH, PH). 542 543 544

For instance for the pathways that assume a set of operational actions on tall hedgerows (TH) (i.e.  $a_{OCA}^{TH}$ .)), we first estimated the distance  $\Delta ES$  between the value of  $ES^{+}_{i}$  under action pathways on TH, and the threshold  $ES^+_{i,min}$ , such that: 545 546 547

548

549 
$$
\Delta ES_i^{TH} = ES_i \Big( a_{OCA}^{TH}(.) \Big) - ES_{i,min}
$$
 equation 7

550

The more positive this distance was from zero, the more secure the ES was for a given adaptation pathway, i.e. allowing to reduce the risks to cross  $ES^{+}_{i, min}$  and not be viable. A greater and negative distance signifies dissatisfaction, i.e. non-viability. 551 552 553

We compared these distances pair-by-pair to analyze the relative effect of acting on i) tall hedgerows (TH) vs short hedgerows (SH) and ii) species-rich hedgerows (RH) versus speciespoor (PH). For instance, based on the (i) comparison, the relative effect on acting on (i) was estimated this way: 554 555 556 557

558 
$$
\Delta ES_{TH-SH} = \Delta ES_{TH} - \Delta ES_{SH} = \left[ ES\left(a_{OCA}^{TH}(.)\right) - ES_{i,min} \right] - \left[ ES\left(a_{OCA}^{SH}(.)\right) - ES_{i,min} \right]
$$
 equation 8

Assuming the resulting metric is the result of the same unit of action on every hedgerow type (i.e.  $\Delta a = 1$ ), then eq. 8 becomes strictly equivalent to: 559 560

561

562 
$$
\left(\frac{\Delta ES_{TH-SH}}{\Delta a_{OCA}^{TH-SH}(\cdot)}\right) = \Delta ES_{TH-SH}
$$
 equation 9

563

Under this assumption, eq. 9 (and thus eq.8) represents a retrospective sensitivity analysis, where the numerator is the cause and the denominator the effect. It is a way to study causality and understand retrospectively every adaptation pathway and the entire DAPP maps. It particularly measures how much ES security can be gained for any given adaptation pathway a(.) (from the satisfactory baseline defined in eq. 7, 8), that operationally consisted in increasing TH over SH. So when  $\Delta ES$ <sub>*TH*-SH</sub> > 0, it means that an adaptive governance pathway a(.), consisting in increasing TH over SH, has contributed to secure more  $ES_i$  viability; and that the greater this value, the greater its security. Conversely, when  $\Delta ES_{TH-SH}$  < 0, then it tells that a(.) consisting in increasing SH over TH actually contributed to secure more *ESi* viability*.*  564 565 566 567 568 569 570 571 572

Eq. 9 was estimated to compare the effect between TH and SH (figure 10) and between RH and PH (figure 11). These comparisons were summarized by i) a global statistic estimated for the entire set of pathways (viable and non-viable) and ii) for the viable set of pathways only. 573 574 575

576

#### **3. Results** 577

578

#### **3.1. Five-year time step evaluation of the viability and its security for every governance pathway option** 579 580

DAPP maps presented in figure 4 globally confirm our expectation that keeping the same governance arrangement for 30 years (especially CCA-A, the one most frequently observed in our study site) is not predicted to be viable. They show on the contrary, that multiple adaptations are required, involving sequences of transitions between various combinations of CCA/KCA/OCA. 581 582 583 584 585

Decomposing the possible 30-year pathways into succession of 5-year pathway segments between two decision steps/nodes, we show that some of these segments are crossed by many unique 30-year pathway options (darker color). These pathways segments are thus more likely to offer a broader range of adaptation options for the subsequent 5-year time step. The darker segments on figure 4 seem less sensitive to an increase in climate stress level (0, 1, 2), , but are sensitive to change in the SES context (peri-urban, rural). 586 587 588 589 590 591

The diversity of viable pathway segments and transitions options changed with the SES type. More specifically, peri-urban SES (Figure 4a,b,c) offered a greater choice of viable pathways than rural SES, especially between viable KCA options within CCA-B, -C or -D options. This pattern was pretty insensitive to the increase in the level of climate stress. This matched with the greater constrains on the satisfactory space that characterizes rural SES (see table 3). Accordingly, in rural SES, fewer satisfactory options of KCA transitions per CCA option were predicted (figures 4d,e,f). There, actors would have to accept more drastic CCA transitions in order to respect the limits of the ES satisfactory domain. This is true in particular with no additional climate stress (figure 4d), as actors do have to first transit through CCA-B.2. This first transition, corresponds to contracting with the state government to be eligible for payments for ecosystem services or PES (figure 4d, see links 2a,b in figure 2b). Then, 20 years later, we predict that viability maintenance of the rural SES requires to transform CCA-B.2 into CCA-D.1 (i.e. KCA.1). This transformation is more demanding than from CCA-A to CCA-B.2, as it involves the setting of a new PAI supervising group of actors and infrastructures for arbitration, collective rules and economic support between SAI and EAI (see figure 2d). Unexpectedly, increased drought stress is predicted to diversify the number of KCA options, especially within the CCA-C option (figure 4e,f). This may be favorable for the viability of rural SES, while this larger choice is expected to come at the expense of the security level for every KCA choice (lighter gray shade), making those KCA transitions riskier. 592 593 594 595 596 597 598 599 600 601 602 603 604 605 606 607 608 609 610

611

#### **3.2. The most secured 30-year viable decision pathways** 612

We then selected the top 10% most secured options of viable 30-years adaptation pathways within the ES satisfactory domain out of the options in figure 5. This selection reduced in some cases drastically the number of viable pathways. For instance, for peri-urban SES, the most secured viable pathways require to transit as fast as possible toward a combination of CCA-D and KCA-D2 when climate stress level is the lowest (figure 6a, option of arrangement D.2: see table 613 614 615 616 617

2 for details); or to transit through KCA-D1 when climate stress level is the greatest (figure 5c, option D.1). Such drastic transformations are predicted to have large benefits, as they lead to a state where all the other governance pathway options become viable by 2040-2050. Interestingly, at climate stress level 1 (figure 5b), there is still a great diversity of highly secured viable pathways that sustain the required levels for all ES to be viable. 618 619 620 621 622

Similarly, in the rural SES, we predict that the most secured options can be found by first shortening the time of transition toward B.2 for climate stress level 0 (figure 5d) or toward C.2 for climate stress level 2 (figure 5f). Then similar benefits are achieved by shortening the remaining time for transiting to D.2 (figure 5d,f). 623 624 625 626

The model unexpectedly predicts that actors from the two SES will have a larger range of secured options at different time scales under climate stress level 1, as opposed to milder or harsher conditions (Figure 6b,e). This appears particularly true for peri-urban SES (Figure 6e). 627 628 629

630

#### **3.3 Switching between pathway options to change ES priority and arbitrate conflicts between actors** 631 632

Optimal DAPP maps (figure 6) were derived from figure 5, and showed viable adaptation pathways that maximize one  $ES^+$  at a time (or minimize one  $ES$ ). For example, in peri-urban  $SES$ with minimal level of climate stress (figure 6a), we predict that transiting directly to CCA-D.2 (as figure 5a would suggest to do to be more secured) will minimize the costs of maintenance but without maximizing the other  $ES<sup>+</sup>$  (or minimizing the other  $ES<sup>-</sup>$ ). The target of minimizing environmental hazards rather requires to delay the transition to CCA-C.4 (i.e. by creating a collective SAI) then the arrangement CCA-B.2 (i.e. contracting for PES). Maximizing all the other  $ES<sup>+</sup>$  would require to transit first through the arrangement C.4 and then either B.2 or D.1. 633 634 635 636 637 638 639 640

These results highlighted how the choices of pathways optimizing one  $ES^{\dagger}/ES^{\dagger}$  can impact other ES level through trade-off effects (figure 7). For instance, the pathway that maximizes pollination as priority objective (i.e. through pathway  $A.1_{(2020)} \rightarrow C.4_{(2020-2030)} \rightarrow B.2_{(2030-2040)} \rightarrow D.1_{(2040-2050)}$  in figure 6a), is expected to produce positive, thus synergistic, effects by reducing environmental hazards (brown line) and maximizing fruit production (figure 7a). This pathway is also predicted to have negative impacts on wood biomass production (green line), sunlight protection (blue line) and landscape aesthetics (orange line). Consequently, new winners and losers relative to the ES are expected to emerge with changing pathways and thus according to the ES+ or ES- that are prioritized. Conversely, if actors seek to minimize the ES<sup>-</sup> "cost of maintenance" (figure 7f), then the most optimal adaptation pathway involves the following transition:  $A.1_{(2020)} \rightarrow D.2_{(2020)}$  $_{2040)} \rightarrow A.1_{(2040-2050)}$  (figure 6a). This should result in a continual parallel decline of all the other ES<sup>+</sup> and ES<sup>-</sup> over the next 30 years (figure 7f), alleviating the risks of ES trade-offs. 641 642 643 644 645 646 647 648 649 650 651 652

653

#### **3.4. Understanding the sensitivity of DAPP maps to changes in climate stress, SES and hedgerow types** 654 655

656

#### **3.4.1 Set of viability solutions according to the proportions of hedgerow types** 657

As presented in the method section, we could not calculate the viability kernel within the actors' ES state-space, and rather expressed it in the hedgerow state-space (figure 8). We then considered how its size and shape (proxy of the number and types of adaptation pathways) were influenced by the hedgerow type proportion: i.e. tall hedgerows (TH) vs short ones (SH); and species-poor hedgerows (PH) *versus* species-rich ones (RH). 658 659 660 661 662

We found that its shape and size was bounded by minimal and maximal proportions of every hedgerow type, but that the proportions differed with climatic stress levels and SES types. For peri-urban SES, viable pathways were possible under greater climatic stress, with a large range of proportions of SH, but a narrower one for TH. By contrast in rural SES, greater climatic stress levels fit with viable pathways with much narrower ranges of proportion of both SH and TH. Patterns were somehow similar when considering species diversity to describe hedgerow types (figure 9). 663 664 665 666 667 668 669

Overall, as climate stress increases, maintaining large diversity of viable pathway options should require relatively more TH than SH (figure 8) and more RH than PH (figure 9), regardless of the type of SES. If the state of the hedgerows remain constant (blue dots in figures 8 and 9), then greater climate change is likely to put both SES types in an unsecured state: they would likely be very close to the threshold, reducing drastically the number of possible adaptive actions, and increasing their risk of being trapped into a non-viable state (figures 8c,f and 9c,f). 670 671 672 673 674 675

676

#### **3.4.2 Expected security gains per ES from switching the target of management from one type of hedgerow to another** 677 678

ES<sup>+</sup> and ES<sup>-</sup> depended for a large part on the hedgerow height and species richness (see table 3). We analyzed whether switching actions from one hedgerow type to another may lead to more or less security, expressed as a distance to the limits of the ES satisfactory domain for every  $ES^+$  and ES, as per method section 2.6.2. This was done for both the viable and non-viable adaptation pathways. We then analyzed whether the results contrasted when changing SES type and climatic stress level. The analysis revealed three consistent patterns of ES security shared between the two SES types (figures 10, 11). 679 680 681 682 683 684 685

Firstly, we found that viable pathways (green violins) that increased relatively more the proportion of SH (figure 10) and RH (figure 11) than TH or PH were likely to build greater security in the viable  $ES^+$  provisioning within the minimal thresholds (for pollination, fruit production, biomass production and sunlight protection). 686 687 688 689

Secondly, viable pathways that increased relatively more the proportion of TH (figure 10) and PH (Figure 11) than SH and RH were also likely to build greater security for keeping ES (i.e. 690 691

maintenance costs, environmental hazards) within the satisfactory threshold. 692

Thirdly, the ES landscape aesthetics was not impacted by changing hedgerow types, as aesthetics was designed as a Shannon index reflecting the diversity of all hedgerows, and was thus insensitive to changing any one type of hedgerow (see table 3). 693 694 695

In absence of additional climate stress, we found only limited contrasts between viable and nonviable pathways (figures 10a,d and 11a,d). With climate stress increased to level 1, viable adaptation pathways with greater  $ES<sup>+</sup>$  security were the one with greater TH than SH. The one with increased ES<sup>-</sup> security were the one with greater SH with TH. For the maximum climate stress (level 2), the priorities between hedgerow types were reversed to maximize ES security (see e.g. figure 10c for environmental hazards). 696 697 698 699 700 701

For RH vs PH proportions (figure 11), pushing for even more RH for ES<sup>+</sup> and even more PH for ES- was predicted to rather amplify existing patterns of ES security, under increased climate stress levels. 702 703 704

705

#### **4. Discussion** 706

Our goal was to produce different DAPP maps to select the best set of viable adaptation pathways that can govern the long-term sustainable provision of ES associated with hedgerows from two rural and peri-urban SES, amid climate change. We intended to investigate how well the proposed DAPP maps captured the essence of three adaptation challenges: (i) the panacea dilemma, (ii) the systemic overflow, and (iii) the sequencing of nested governance initiatives. To solve the three simultaneously, we suggested that a more cohesive approach could be developed from three existing methodological frameworks: namely Ostrom's SES framework, Anderies' CIS framework and Ostrom's nested governance structuring. We succeeded in mathematically linking these three frameworks, which required some modifications. We now discuss whether and how the method translated into practical successes when analyzing the results. 707 708 709 710 711 712 713 714 715 716

717

#### **4.1. Did we solve the panacea problem associated with adaptation?** 718

#### *4.1.1. DAPP maps provided access to rich understanding of the social-ecological context of adaptation* 719 720

Previous syntheses on the use of the DAPP framework showed that a way to integrate rich information on the social-ecological context was missing (Stanton & Roelich, 2021). Here we developed a integrated and general method to indirectly produce various types of socialecologically rich DAPP maps from the results of our SES framework analysis. The results emphasized the influence of the SES type (rural vs per-urban) and climate stress level (three drought levels) on the possible pathways of nested governance adaptation that supported the production of ES. Here we tested nine possible scenarios of nested governance, with possible adaptations between them every five years, for a total of  $9^7 = 4,782,969$  possible pathways of governance changes over a 30-years period. 721 722 723 724 725 726 727 728 729

Our approach allowed (i) to identify the type of nested governance arrangement (CCA, KCA and OCA); then (ii) to understand what these adaptations assume in term of changes in the SES structure (through the CIS framework); and finally (iii) to check the underpinning definitions of the social-ecological attributes (using Ostrom's SES framework) that these adaptations imply. We achieved this for all the DAPP maps, at every decision node (i.e. the time step, i.e. when all the actors can collectively discuss the need to make a decision and trigger a new governance 730 731 732 733 734 735

sequence). We provided the needed information in the method section (and supplementary information), such that actors can pinpoint and discuss the practical SES elements or processes in 736 737

their daily life that would lead to the expected discrepancies. 738

#### *4.1.2. Perspective for understanding better complex emerging DAPP patterns* 739

The results provided by the link between the SES, CIS and DAPP maps confirm the potential of this renewed DAPP approach for tackling social-ecologically unique and complex adaptation problems, while keeping a sufficiently generic method. However, making such connections was a cumbersome process. So even if DAPP maps associated with the SES framework analysis are very useful combinations of representations, they are still not as straightforward for stakeholders to plan governance changes to respond to changing climate (cf. Stanton & Roelich, 2021). 740 741 742 743 744 745

One way to communicate in a more straightforward way with stakeholders may be to provide a more synthetic information than what we did in our method tables and figures, for every option of adaptation or decision node (like in the form of card-boards). The challenge would be to compare different co-constructions with actors in order to infer the best operational guidelines to work with these maps for solving practical governance problems. 746 747 748 749 750

751

#### **4.2. Did we solve the systemic robustness and overflow problem?**  752

#### *4.2.1. DAPP maps detected viable options that solved sequentially complex ES overflow*  753

The DAPP framework was initially designed with questions of systemic robustness in mind (Haasnoot et al., 2013; 2019), but not for levels of systemic robustness and spillovers required for complex SES as described here. 754 755 756

We found that the initial differentiation between the two complex SES (peri-urban and rural) primarily rested on the constraints of ES levels for actors' satisfaction and the impact of climate change on hedgerows between climate stress levels. All other factors were held similar, as we lacked sufficient confidence in our social-ecological data to distinguish between the two SES. 757 758 759 760

Surprisingly, by simply adjusting these factors (and climate stress impacts on hedgerows), we observed the emergence of entirely distinct DAPP maps with different complex patterns of transition pathways akin to the systemic nature of our renewed CIS framework model (as expected by Anderies et al., 2015). Analyses also emerged different patterns of viable (robust), resilient and nonviable pathways (figure 4). Among the viable pathways, we could also detect how these contexts impacted the most secured ones (figure 5), or optimal ones that max(min)imized one-at-a-time the level of different ecosystem (dis)services (figure 6). Furthermore, we detected unexpected trade-offs and synergies among ES along the pathways (figure 7), and thus different winners and losers. We also demonstrated how the adaptation choices derived from on-ground differences in the operational actions involved in changing the relative proportion of short/tall and species-rich/poor hedgerows (figures 8, 9, 10, 11). 761 762 763 764 765 766 767 768 769 770 771

Some of the emerging patterns were particularly unexpected given the inherent simplicity of the input data and underlying model. For instance, it was intriguing to note that elevating the climate stress level to an intermediate range expanded the number of viable and optimal options, albeit 772 773 774

with reduced security. Conversely, the model showed that the choices of adaptation pathways was narrowed down for more severe climate stress scenarios. Additionally, for a given climate stress level, a minor shift in ES preferences resulted in even more pronounced differences in pathway options and ES dynamics. 775 776 777 778

Another interesting finding was the fact that the best options to secure the viability of peri-urban SES involved a swift transition to the more intricate constitutional choices (CCA-D), involving joint private, community, and public arrangements (see table 2 for details). This emerging property, and others presented in supplementary results S4, could not yet be fully comprehended yet. This underlines the need for developing complementary indicators to the one we developed (see method section 2.6.2) to understand the interplay between hedgerow dynamics, ES, and action pathways. This could be achieved through the direct calculation of the viability kernel into the ES state-space or the control space. 779 780 781 782 783 784 785 786

787

#### *4.2.2 Perspectives for using this approach for more complex networks of ES* 788

Following the Millennium Ecosystem Assessment (MEA, 2005), the flow of resource units from RSI to EAI (link 1b in figure 1) represented two classes of ES, namely the provisioning and cultural ES, which we considered in our study. However, two other ES categories are worth considering following the MEA, namely supporting and regulating ES. The interest of the renewed CIS framework model is to offer a new way to streamline the integration of all the MEA typology of ES into the CIS. By doing so, we could and study systemic problems and DAPP maps associated with them, which some researchers found problematic (La Notte et al., 2017). For instance, ecological infrastructures such as hedgerows or grass strip margins could be modeled as SAI that provide *supporting ES*, such as pollinators and pest control agents (link 4a). Indeed, they may enhance the growth of nearby crop fields (self-loop 0a), the latter conceptualized as RSI providing food and other (dis)services. Moreover, these infrastructures can provide *regulating ES*, understood now through link 5a as helping to regulate the flow of (di)services from RSI to EAI (link 1b). We can think of hedgerows regulating water flow and quality from adjacent fields (or other flows of services). 789 790 791 792 793 794 795 796 797 798 799 800 801 802

Using this method, we can also think of improving past qualitative DAPP studies (that use the concept of "adaptation services", cf. Colloff et al., 2016; Lavorel et al., 2019) into richer quantitative DAPP map studies like we did. For example, consider the adaptation services used in qualitative DAPP map studies defined in Lavorel et al. (2019): the ES called *erosion control* could be integrated in the renewed CIS model as link 5a (figure 2), *carbon storage* as a self-loop 0a, *fodder resilience* as link 4a if fodder is regarded as a RSI, and ES called *fodder*, *aesthetics*, and *shade* as link 1b. For the latter, link 6b could be considered if both RSI and SAI are deemed pivotal landscape elements for these services. Furthermore, the ES denoted as *connectivity* and *transformability* are intricately linked in the renewed CIS model to the potential transformation of structural or compositional variables associated with RSI or SAI, and thus with variables 0a and 0d. In this case, transformability could be defined as the range of acceptable rates of structural or compositional entropic change of the RSI (cf. Greek term "tropos" signifies transformation) that actors from EAI, SAI and PAI can tolerate. 803 804 805 806 807 808 809 810 811 812 813 814 815

These examples suggest that the renewed CIS approach could more flexibly and effectively model potentially more complex DAPP problems involving inextricable links between ecological 816 817

infrastructures, functions, biodiversity, and ES; as described in e.g. Vogt et al., (2015), Partelow 818

& Winkler (2016) or Rova & Pranovi (2017). 819

820

#### **4.3. Did we solve the nested governance adaptation problem?** 821

#### 4.3.1. DAPP maps solve some ... but! 822

We now need to consider whether the resulting DAPP maps captured and solved the essence of the nested adaptive governance initiative problem initially raised by Ostrom (1990). 823 824

In the most general case, our novel concept of DAPP maps present, at every decision node, options of transitions between OCA, within and between different KCA and then CCA. Changing OCA require less drastic investments for adaptation, and thus are expected to be adapted more regularly; whereas changing KCA and even more CCA would need to be maintained preferably for longer time as they would require more costly transformations. 825 826 827 828 829

In the archetypical SES we presented, most actors that possessed hedgerows from the two SES primarily used CCA-A. Our results revealed that this arrangement may not be sustainable in the long term, especially if climate change affects hedgerows that are especially tall and biodiverse. For rural actors, the most secured option to stay in a viable pathway (figure 5) would be to transform CCA-A into the most complex and polycentric CCA-D (see details in figure 2 and table 2). However, even if we predict a permitted delay of few decades for this transition, in practice a direct  $A \rightarrow D$  transformation should be very costly (for economic, technical, social or even cultural reasons). This was revealed by the semi-structured interviews of actors in our study region (Supplementary S2), but could also be deduced from the required substantial disparities between A and D in collaboration skills, mutual trust, and the willingness to delegate power and roles among EAI, SAI, and PAI (Ostrom, 1995; Ban et al., 2015; Anderies, 2019). 830 831 832 833 834 835 836 837 838 839 840

We lacked sufficient data to evaluate the specific costs involved in the direct  $A \rightarrow D$  transition. But by factoring in the relative costs of transforming CCA, and eventually KCA, our analysis may yield DAPP maps that could conform to the need to use more incremental transitions in the range of viable adaptive pathway, such as through CCA-B or CCA-C first, rather than opting for a direct transition from CCA-A to CCA-D. 841 842 843 844 845

846

#### *4.3.2. Perspectives for more detailed decomposition of the social system* 847

To align with the changes operated in the SES framework (see method section), we elaborated a modified version of Anderies' CIS. This version explicitly emphasizes the dual function of infrastructures and agents (i.e. actors or species) for every compartment, opening avenue to extend it to produce multi-tier DAPP maps involving both the infrastructures and agents. 848 849 850 851

One possible approach to do so may be to utilize Archer's (1995) morphogenetic framework, that 852

is extensively used to analyze the progression of causal relations between agents and structures 853

(social and cultural ones) over time. 854

Archer's analysis consists of three causal relations organized sequentially, that in fact match quite well the functioning of Ostrom  $(1990)'s$  IAD framework and thus potentially the CIS (cf. Anderies et al., 2019). In the first step of Archer's framework, ecological or social infrastructures (from RIS, EAI, PAI, or SAI) would condition the agents (actors or species) within the same or other (infra)structure  $(I \rightarrow A)$ . In the second step, the conditioned agents generate new social or ecological interactions  $(A \rightarrow A)$ , similar to Ostrom's action arena and CIS links. Finally in the third step, new (infra)structures  $(A \rightarrow I)$  emerge or reproduce through morphogenesis or morphostasis, respectively. 855 856 857 858 859 860 861 862

We propose that integrating Archer's framework would be a first natural extension of the modified version of the CIS, and may enable the creation of enriched nested DAPP maps that can distinguish, when needed, actors and structures for every level of governance arrangement (CCA, KCA, OCA). 863 864 865 866

867

#### **Conclusion & perspectives** 868

Overall, our results highlight the importance of climate stress levels, SES types and pathways of governance in determining the long-term viability of ES provisioning. Acquiring information on SES targets, system-level spill-over risks, and critical decision nodes is crucial when planning adaptation strategies for sustaining ES. 869 870 871 872

Once these informations have been gathered, we show that novel DAPP maps – that derive from the articulation between renewed versions of Ostrom's SES and CIS framework, and the complex dynamical system and viable control theories  $-$  could streamline the discovery of robust adaptive governance pathways. These DAPP maps stroke a balance between three dimensions of the SES adaptation problem described by Ostrom: namely the panacea dilemma, the systemic robustness and spill-over problem, and the problem of sequencing adaptation initiatives between nested governance arrangements. 873 874 875 876 877 878 879

The results we produced highlighted the possibility to emerge complex patterns of DAPP maps and ES, even from the quite simple dynamical SES models, ES objectives and constraints on control. We developed subsequent analytical representation to understand these complex patterns through the role of operational actions on the hedgerow network. However, we acknowledge further developments, involving other representations and multi-tier analyses, may improve the framework to test this approach to make sure stakeholders can use DAPP maps with clear knowledge of the consequences of their choices on their everyday life. 880 881 882 883 884 885 886

With this method, we targeted logical completeness between Ostrom's theory and DAPP maps to help produce scientific laws of adaptive governance of common pool ES. The question is whether they represent what local actors, legislators and policy-makers expect. This question is legitimate given the increasingly more frequent use of DAPP maps by policy makers. Testing this approach with the entire chain of actors as part of a Living-Lab would provide is of any use. 887 888 889 890 891

892

#### **Acknowledgements** 893

We express our gratitude to Pr. J. Marty Anderies for engaging in fruitful discussions regarding the minor adjustments of the CIS framework, ensuring its alignment with our present objectives. 894 895

We thank Dr. Magali Weissgerber, and master students Elise Krief, Lisa Minaca, Quentin Guillois and Loïc Montel for their contribution to, respectively, interviews with stakeholders, field hedgerows surveys, aerial photographs analyses and GIS maps elaboration, as well as SES 896 897 898

framework analyses. 899

900

#### **Supplementary Information** 901

- Supplementary S1: Spreadsheet detailing the SES framework analysis and associated original data for the rural and peri-urban sites: [te](https://rb.gy/g7xizx)mporary anonymous url:<https://rb.gy/dnize1> 902 903
- Supplementary S2: detailed data, GIS analysis and survey documents used for analyzing and modeling the structure and dynamics of the hedgerow network: [te](https://rb.gy/g7xizx)mporary anonymous url: <https://rb.gy/dnize1> 904 905 906
- Supplementary S3: Link to the repository to access details of the model and code to reproduce the results: [te](https://rb.gy/g7xizx)mporary anonymous url:<https://rb.gy/dnize1> 907 908
- Supplementary S4: Supplementary results: [te](https://rb.gy/g7xizx)mporary anonymous url:<https://rb.gy/dnize1> 909

910

#### **References** 911

- Allen, J., DuVander, J., Kubiszewski, I., & Ostrom, E. (2011). Institutions for Managing Ecosystem Services. Solutions, 2, 44-48. 912 913
- Aggarwal, R. M., & Anderies, J. M. (2023). Understanding how governance emerges in socialecological systems: insights from archetype analysis. Ecology and Society, 28(2). 914 915
- Anderies, J. M., Janssen, M. A., and Ostrom, E. (2004). A framework to analyze the robustness of social-ecological systems from an institutional perspective. Ecology and society, 9(1). 916 917
- Anderies, J. M., & Janssen, M. A. (2013). Robustness of social ecological systems: implications for public policy. Policy Studies Journal, 41(3), 513-536. 918 919
- Anderies, J. M. (2015). Understanding the dynamics of sustainable social-ecological systems: human behavior, institutions, and regulatory feedback networks. Bulletin of mathematical biology, 77, 259-280. 920 921 922
- Anderies, J., Janssen, M., & Schlager, E. (2016). Institutions and the performance of coupled infrastructure systems. International Journal of the Commons, 10(2). 923 924
- Anderies, J. M., Barreteau, O., & Brady, U. (2019). Refining the robustness of social-ecological systems framework for comparative analysis of coastal system adaptation to global change. Regional Environmental Change, 19, 1891-1908. 925 926 927
- Archer, M.S. Realist social theory: The morphogenetic approach. Cambridge university press, 1995. 928 929
- Aubin, J. P., Bayen, A. M., & Saint-Pierre, P. (2011). Viability theory. Springer Berlin, Heidelberg. 2<sup>nd</sup> Edition. 803 pp. 930 931

- Ban, N. C., L. S. Evans, M. Nenadovic, and M. Schoon. 2015. Interplay of multiple goods, ecosystem services, and property rights in large social-ecological marine protected areas. Ecology and Society 20(4):2. 932 933 934

- Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B. and Kissel, E.S., 2017. Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, CB Field and others (eds.), Cambridge, Cambridge University Press. 935 936 937 938 939

- Basurto, X., Gelcich, S., & Ostrom, E. (2013). The social–ecological system framework as a knowledge classificatory system for benthic small-scale fisheries. Global environmental change, 23(6), 1366-1380. 940 941 942
- Bernstein, M., del Mar Mancha-Cisneros, M., Tyson, M., Brady, U., Rubiños, C., Shin, H.C., Vallury, S., Smith-Heisters, S. and Ratajczyk, E. (2019). Mapping Ostrom's common-pool resource systems coding handbook to the coupled infrastructure systems framework to enable comparative research. International Journal of the Commons, 13(1). 943 944 945 946
- Binder, C. R., J. Hinkel, P. W. Bots, and C. Pahl-Wostl. 2013. Comparison of Frameworks for Analyzing Social-Ecological Systems. Ecology and Society 18(4):26 947 948
- Buurman, J., & Babovic, V. (2016). Adaptation Pathways and Real Options Analysis: An approach to deep uncertainty in climate change adaptation policies. Policy and Society, 35(2), 137-150. 949 950 951
- Colloff, M.J., Doherty, M.D., Lavorel, S., Dunlop, M., Wise, R.M., Prober, S.M., 2016. Adaptation services and pathways for the management of temperate montane forests under transformational climate change. Clim. Change 138, 267-282. 952 953 954
- Haasnoot, M., Kwakkel, J. H., Walker, W. E., & Ter Maat, J. (2013). Dynamic adaptive policy pathways: A method for crafting robust decisions for a deeply uncertain world. Global environmental change, 23(2), 485-498. 955 956 957
- Haasnoot, M., Warren, A., & Kwakkel, J. H. (2019). Dynamic adaptive policy pathways (DAPP). Decision making under deep uncertainty: From theory to practice, 71-92. 958 959
- Hermans, L. M., Haasnoot, M., ter Maat, J., & Kwakkel, J. H. (2017). Designing monitoring arrangements for collaborative learning about adaptation pathways. Environmental Science & Policy, 69, 29-38. 960 961 962
- Holling, C. S. (1973). Resilience and stability of ecological systems. Annual review of ecology and systematics, 4(1), 1-23. 963 964
- Homayounfar, M., Muneepeerakul, R., Anderies, J.M. and Muneepeerakul, C.P., 2018. Linking resilience and robustness and uncovering their trade-offs in coupled infrastructure systems. Earth System Dynamics, 9(4). 965 966 967
- Houballah, M., Cordonnier, T., & Mathias, J. D. (2020). Which infrastructures for which forest function? Analyzing multifunctionality through the social-ecological system framework. Ecology and Society, 25(1). 968 969 970
- Houbbalah, M, Mathias J.-D. And T. Cordonnier. (2021). An infrastructure perspective for 971
- enhancing multi functionality of forests: A conceptual modeling approach. Earth's Future. 972

- Houballah, M., Cordonnier, T., & Mathias, J. D. (2023). Maintaining or building roads? An adaptive management approach for preserving forest multifunctionality. Forest Ecology and Management, 537, 120957. 973 974 975
- La Notte, A., D'Amato, D., Mäkinen, H., Paracchini, M.L., Liquete, C., Egoh, B., Geneletti, D. and Crossman, N.D. (2017). Ecosystem services classification: A systems ecology perspective of the cascade framework. Ecological indicators, 74, pp.392-402. 976 977 978
- Lapointe, M., Cumming, G. S., & Gurney, G. G. (2019). Comparing ecosystem service preferences between urban and rural dwellers. Bioscience, 69(2), 108-116. 979 980
- Lavorel, S., Colloff, M.J., Locatelli, B., Gorddard, R., Prober, S.M., Gabillet, M., Devaux, C., Laforgue, D. and Peyrache-Gadeau, V. (2019). Mustering the power of ecosystems for adaptation to climate change. Environmental Science & Policy, 92, pp.87-97. 981 982 983
- Martin, S., Deffuant, G., & Calabrese, J. M. (2011). Defining resilience mathematically: from attractors to viability. Viability and resilience of complex systems: concepts, methods and case studies from ecology and society, 15-36. 984 985 986
- McGinnis, M. D., & Ostrom, E. (2014). Social-ecological system framework: initial changes and continuing challenges. Ecology and society, 19(2). 987 988
- Millennium Ecosystem Assessment (MEA). 2005. Ecosystems and Human Well-being : General Synthesis. Washington, D.C.: Island Press 989 990
- Muneepeerakul, R. and Anderies, J.M., 2017. Strategic behaviors and governance challenges in social ecological systems. Earth's Future, 5(8), pp.865-876. 991 992
- Ostrom, E., Agrawal, A., Blomquist, W., Schlager, E., and Tang, S. Y. (1989). CPR coding manual. Ostrom Workshop in Political Theory and Policy Analysis. 993 994
- Ostrom, E. (1990). Governing the commons: The evolution of institutions for collective action. Cambridge university press. 995 996
- Ostrom, E., 2007. A diagnostic approach for going beyond panaceas. Proceedings of the national Academy of sciences, 104(39), pp.15181-15187. 997 998
- Ostrom, E. (2009). A general framework for analyzing sustainability of social-ecological systems. Science, 325, 419-422 999 1000
- Ostrom, E., & Cox, M. (2010). Moving beyond panaceas: a multi-tiered diagnostic approach for social-ecological analysis. Environmental conservation, 37(4), 451-463. 1001 1002
- Partelow, S., & Winkler, K. J. (2016). Interlinking ecosystem services and Ostrom's framework through orientation in sustainability research. Ecology and Society, 21(3). 1003 1004
- Pichancourt, J. B. (2023). Some fundamental elements for studying social-ecological coexistence in forest common pool resources. PeerJ, 11, e14731. 1005 1006
- Pichancourt, J. B. (2024). Navigating the complexities of the forest land sharing vs sparing 1007
- logging dilemma: analytical insights through the governance theory of social-ecological systems dynamics. PeerJ. 12:e16809 1008 1009
- Pulver, S., N. Ulibarri, K. L. Sobocinski, S. M. Alexander, M. L. Johnson, P. F. McCord, and J. 1010
- Dell'Angelo. 2018. Frontiers in Socio-Environmental Research: Components, Connections, 1011

- Scale, and Context. Ecology and Society 23(3):23. DOI: https://doi.org/10.5751/ES-10280- 230323. 1012 1013
- Ramm, T. D., Watson, C. S., & White, C. J. (2018). Strategic adaptation pathway planning to manage sea-level rise and changing coastal flood risk. Environmental Science & Policy, 87, 92- 101. 1014 1015 1016
- Roelich, K., Giesekam, J., 2019. Decision making under uncertainty in climate change mitigation: introducing multiple actor motivations, agency and influence. Clim. Polic. 19, 175– 188 1017 1018 1019
- Rougé, C., Mathias, J. D., & Deffuant, G. (2015). Vulnerability: From the conceptual to the operational using a dynamical system perspective. Environmental Modelling & Software, 73, 218-230. 1020 1021 1022
- Rova, S., & Pranovi, F. (2017). Analysis and management of multiple ecosystem services within a social-ecological context. Ecological Indicators, 72, 436-443. 1023 1024
- Stanton, M. C. B., & Roelich, K. (2021). Decision making under deep uncertainties: A review of the applicability of methods in practice. Technological Forecasting and Social Change, 171, 120939. 1025 1026 1027
- Vogt, J. M., Epstein, G. B., Mincey, S. K., Fischer, B. C., & McCord, P. (2015). Putting the" E" in SES: unpacking the ecology in the Ostrom sociale-cological system framework. Ecology and Society, 20(1). 1028 1029 1030
- Walker, B., Holling, C. S., Carpenter, S. R., & Kinzig, A. (2004). Resilience, adaptability and transformability in social-ecological systems. Ecology and society, 9(2). 1031 1032
- Werners, S. E., Wise, R. M., Butler, J. R., Totin, E., & Vincent, K. (2021). Adaptation pathways: A review of approaches and a learning framework. Environmental Science & Policy, 116, 266-275. 1033 1034 1035
- Wise, R. M., Fazey, I., Smith, M. S., Park, S. E., Eakin, H. C., Van Garderen, E. A., & Campbell, B. (2014). Reconceptualising adaptation to climate change as part of pathways of change and response. Global environmental change, 28, 325-336 1036 1037 1038

## **Table 1(on next page)**

2<sup>nd</sup> tier attributes of the version of the Social-Ecological System (SES) framework The SES analysis was used to elaborate the ecological survey, social interview guides, qualitative and quantitative analyses of the study sites.  $*$  indicates that the  $2^{nd}$  tier attributes are decomposed into three  $3<sup>rd</sup>$  tier functional attributes representing capacities of action: action capacities of the exploiting actors & infrastructures (EAI), of the supporting actors & infrastructures (SAI) and of the policy-making actors  $\&$  infrastructures (PAI). \*\* signifies that the previous  $3<sup>rd</sup>$  tier attributes are extended to account for the directional influences of one 3<sup>rd</sup> tier attribute on the other, or also the resource system (RS). † indicates the decomposition of the  $3^{rd}$  tier attributes the following  $4^{th}$  tier attributes: Operational-choice arrangement (OCA), Collective-choice arrangement (KCA), Constitutional-choice arrangements (CCA). The  $3<sup>rd</sup>$  and 4<sup>th</sup>-tier analyses of the study area are presented in Supplementary S1.

## Manuscript to be reviewed



**Version of the SES Framework used to predict the possible targets of adaptation**



## **Table 2(on next page)**

Set of constitutional, collective, and operational choice arrangements (respectively referred to as CCA, KCA and OCA in the table) for the study site located in the Auvergne region of France.

The four CCA refer to the one presented in figure 2. For every CCA, several KCA are associated with different objectives, constrains, chains of actions, costs and benefits, and one OCA. The codes 1a, 0a, and others in the chains of actions refer to the CIS encoding presented in figure 1.

## Manuscript to be reviewed





## **Table 3(on next page)**

Model for seven ecosystem (dis)services produced by four types of hedgerows, along with the costs of operational maintenance actions and the differing needs in rural and peri-urban areas

Ecosystem (dis)services were evaluated using simple, semi-quantitative metrics from the literature. See details in Supplementary S1 and S2.

## Manuscript to be reviewed



Peer.

Systemic representation of the Social-Ecological System (SES)

Systemic representation of the Social-Ecological System (SES) as a renewed version of the Coupled Infrastructure System (CIS) framework originally developed by Anderies et al. (2004, 2019), and presented in Step 2 of the method section. Within this representation, the internal dynamics of the capacity of action of each compartment in absence of external factors are depicted through self-loops, denoted with bold numbers (0a  $\rightarrow$  d). Arrows labeled with bold numbers (1a  $\rightarrow$  b to 6a  $\rightarrow$  b) signify various actions, checks and balances, spillovers, gains or loss of capacity of actions, or the movement of actors between compartments. Bold arrows labeled as  $7a \rightarrow q$  symbolize external relations with the broader environmental settings. Accompanying these numbers, between brackets are the references to the SES framework attributes from table 1. These references offer insights into the functional grouping and interconnections of these attributes, illuminate the potential spillover effects among them. As in table 1, symbols are used to indicate that the same SES framework attribute can serve different roles within this model: as a variable or parameter of one of the four compartments (\*), to describe their interconnections (\*\*), or to delineate their relationship with the external environment (†).

## Manuscript to be reviewed





Illustration of the four scenarios of constitutional-choice arrangements (CCA)

Illustration of the four scenarios of constitutional-choice arrangements (CCA) used as a basis for defining possible adaptations of the distribution of authority, and using the renewed CIS model presented in figure 1. The four scenarios were defined from interviews of local actors and documents associated with the study sites. CCA-A was the dominant scenario recorded/present in the studied SES, while the other three were sporadically detected but frequently suggested for implementation based on interviews with local actors, or on strategic territorial planning documents. Each CCA has its own structural and time constraints, and permit different forms of collective-choice (KCA) and operational choice (OCA) arrangements (see table 2). RSI means resource species and infrastructures. EAI, SAI and PAI respectively refer to exploiting, supporting and policy-making actors and infrastructures. The red-colored compartments and arrows indicate the PAI involved in the DAPP process; while the black or blue-colored ones refer to those involved in other supporting actions (CCA-B and D) or arbitration (CCA-D).

## Manuscript to be reviewed



# Figure 3

Link between viable control theory and DAPP maps

(a) illustrates the sensitivity to climate change of the laws governing the OCA/KCA governance adaptation trajectories for two different CCA (cf. figure 2 for examples), and plotted within the ecosystem services state space after applying viable control theory (Aubin et al., 2011). (b) illustrates the corresponding set of viable 30-year governance trajectories (black lines) plotted along the decision node space using the dynamic adaptation policy pathway (DAPP) framework. In the latter, controlled trajectories represent the DAPP adaptation pathways. Pathway segments between two consecutive nodes (yellow circles) represent controlled trajectories at a CCA level that can be viable (blacklines), non-viable (grey lines), and the resilient ones (a succession of grey then black). Each CCA trajectory implies a specific combination of KCA and OCA actions, which could themselves be adapted, justifying further the decomposition of the viability analysis and DAPP map into as many subtrajectories as there are nested structures of governing adaptation.

## Manuscript to be reviewed



# Figure 4

## Uncertainty DAPP maps

Probability to find viable pathways of governance adaptation that meet the set of satisfaction constraints for all ecosystem services (ES), for two types of SES, three climate stress levels, and nine governance scenarios. Each governance scenario represents a combination of one constitutional choice arrangement (among four CCA), one collective-choice arrangement (among a maximum of four KCA per CCA), and one specific operational-choice arrangement OCA per KCA (cf. table 2). The letters (A-D) refer to the four possible CCA (cf. figure 2 and table 2), and the associated numbers (1-4) refer to the different KCA (cf. table 2). Every panel provides the percentage of total viable trajectories starting from the state of the SES in 2020. A total of  $9^7$  = 4,782, 969 possible pathways were constructed by combining CCA and KCA over the 30-years period and transitions every five years, i.e. between two successive decision nodes. Pathway sequences that are not represented in dark represent (irreversibly) unviable five years sequences regarding the studied ES. A dark line between a five-year sequence between two successive decision nodes means that at least one viable entire 30 year long pathway passing between these two nodes was found. Darker segments (on a 0-1 white and black scale) mean greater number of such unique 30-year long viable pathways crossing the 5-year segment.

## Manuscript to be reviewed



# Figure 5

### Secured DAPP maps

The secured DAPP maps represent the 10% most secured options of viable trajectories that respected the (normalized) sum of constraints for every ecosystem services. The letters (A-D) refer to the four possible CCA (cf. figure 2 and table 2), and the associated numbers  $(1-4)$ refer to the different collective choice arrangements (KCA) that can be used for every CCA (cf. table 2).



# Figure 6

### Optimal DAPP maps

Optimal DAPP maps are constructed using the subset of the most optimal sequence constitutional-choice arrangement (CCA) adaptation for six different SE, with every color showing a different prioritization to either maximize or minimize a specific ecosystem (dis)services. The letters (A-D) refer to the four possible CCA, and the associated numbers  $(1-4)$  refer to the different collective choice arrangements (KCA) that can be used for every CCA, as defined in table 2.



Temporal dynamics of all seven studied ecosystem (dis)services

Predicted temporal dynamics of all seven studied ecosystem services  $ES<sup>+</sup>$  and disservices (ES) when selecting the most optimal adaptation pathway aiming to either maximizing  $ES^+$  or minimizing ES<sup>-</sup>, as listed in the labels. For instance, panel (a) reads as the maximized ES<sup>+</sup> is resource for pollinators (prominent trend line) and the other ES<sup>+</sup>/ES<sup>-</sup> were set free (thinner trend lines). Results are derived from the optimal DAPP map presented in figure 5a for a peri-Urban SES under minimal climate stress level. Supplementary S4 presents similar results but corresponding to all the other five DAPP maps described in figure 6 (b:f).



PeerJ

Influence of hedgerow height on the size and shape of the viability kernel

2D cut of the four dimensional viability kernel, and expressed as a function of only small hedgerows (SH) and tall hedgerows (TH) for the two types of social-ecological systems (rural, peri-urban), and the three levels of environmental stress. The blue dots represent the initial state of hedgerow types in both rural and peri-urban social-ecological system (SES), and were selected to be the same to facilitate comparison. Blue dots close to the viability kernel limit mean that there are less options to adapt the hedgerow network through different nested governance arrangements changes, and thus are less secured. Method of calculation is described in section 2.5.3.



PeerJ

Influence of level of species richness in hedgerows on the size and shape of the viability kernel

2D cut of the four-dimensional viability kernel, expressed as a function of species-poor hedgerows (PH) and species-rich hedgerows (RH) for the two types of social-ecological systems (rural, peri-urban) and the three levels of climate stress. The blue dot represents the initial state of hedgerow types and were selected to be the same in the two SES to facilitate comparison. Viability kernel limit closer to the blue dot means less options to adapt the hedgerow network through different nested governance arrangements changes, and thus are less secured. Method of calculation is described in section 2.5.3



Peer.

Security gains  $\Delta ES_{TH-SH}$  relative to the limits of the ES satisfactory domain

Security gains  $\Delta ES_{TH-SH}$  relative to the limits of the ES satisfactory domain (i.e. distance from the blue baseline) for every ecosystem service (ES+) and disservice (ES-), when switching the target of management from short hedgerows (SH) to tall ones (TH), during an adaptive governance pathway. Panels a,b,c are for peri-urban SES and d,e,f for rural SES, along with increasing climatic stress. As per explanation in method section 2.6.2,  $\Delta ES_{\tau H-SH} > 0$  means greater security gains (and thus incentives) when acting more on TH than on SH; whereas  $\Delta ES_{TH-SH}$  < 0 means greater incentives to act more on SH than on TH. The violins represent the probability density of  $\Delta ES$  values (with median in red) associated with all the adaptation pathways that are both viable and non-viable (yellow violins), or viable only (green violins). ES full name are provided in table 3.

## Manuscript to be reviewed



Peer.

Security gains  $\Delta ES_{\text{RH-PH}}$  relative to the limits of the ES satisfactory domain

Security gains  $\Delta ES_{BH-PH}$  relative to the limits of the ES satisfactory domain (i.e. distance from the blue baseline), when switching the target of management from species-poor hedgerows (PH) to species-rich hedgerows (RH) during an adaptation pathway. As per explanation in method section 2.6.2,  $\Delta ES_{RH-PH} > 0$  means greater security gains when acting more on RH than on PH; whereas  $\Delta ES_{RH-PH}$  < 0 means greater security to act more on SH than on TH. The violins represent the probability density of  $\Delta ES$  values (with median in red) associated with all the adaptation pathways that are both viable and non-viable (yellow violins), or viable only (green violins). ES full name are provided in table 3.

## Manuscript to be reviewed





### wnload Review PDF

**wnload your review PDF** and use the line numbers in your review F when reading the comments from your editor and reviewers, and en writing your response letter.

### **ur peer-review comments: Editor's Decision MAJOR REVISIONS**

Two expert reviewers have evaluated your manuscript and their comments can be seen below and in an attached PDF. As you will see both comment on the length and the complexity of the dcoument and have made a number of suggestions that should help you to improve the presentation and content of the manuscript. Please ensure that you follow their suggestions and prepare a revised manuscript. Also, provide a rebuttal letter that clearly identifies what modifications have been made and where they can be found.

## **Comments from the reviewers**

Reviewer 1

### **Basic reporting**

Generally, the paper is very comprehensive in my view employing multiple theories and concepts (SES, CIS and nested governance) to enhance the existing DAPP framework for potential pathway simulations of hedgerows. I think the paper is rather long (about 50 pages!) and quite hard to follow probably due to the current writing structure. While i try appreciate the emphasis and contribution of the paper, the current structure or writing style needs to be improved.

Firstly, is current DAPP framework insufficient? not adequate to tackle current adaptation issues? clearer and strong rationales are required to justify the study's need particularly highlighting the real and tangible issues of the current framework which have propelled the authors to use various models and theories to hopefully provide pragmatic solutions to policymakers, not just remain theoretical. Below are some specific concerns that need to be addressed.

## Reviewer 2

### **Basic reporting**

The paper is long and complex with lots of ideas - combining multiple frameworks, mathematical models and viability theory. This is a lot to digest. The main messages of the paper need to be made more clearly and earlier. Some of the material might best be moved to a supplementary materials section.

Also, please put the figures in line for review purposes or send a "review version" of the manuscript as it is very difficult to review with the figures at the end.

### **Experimental design**

Not applicable - the study does not involve an experiment.

### **Validity of the findings**

The article suggests the need for "renewal" or "extensions" of the SES and CIS Frameworks. Perhaps this is a matter of word choice, but the text

reflects some lack of clarity regarding what is meant by "framework",

### **SECTION**

Environmental Science

### **SUBJECTS**

BiodiversityEcologyMathematical BiologyCoupled Natural and Human SystemsNatural Resource Management

### **KEYWORDS**

Social-Ecological System

(SES)AgroecosystemHedgerowsBiodiversityEcosystem ServicesSES AnalysisRobustness FrameworkComplex Dynamical SystemViability TheoryAdaptation Pathways

### **ABSTRACT**

Dynamic Adaptive Policy Pathway (DAPP) maps help guide management decisions when the future of a critical asset is deeply uncertain due to environmental changes. Recent discussions have highlighted the importance of creating DAPPs that better consider social-ecological factors for managing common-pool ecosystem services adaptively. Our focus was on evaluating how DAPPs could address three key challenges identified by Ostrom in adaptive governance of social-ecological systems (SES): (i) avoiding one-size-fits-all solutions (i.e. the panacea dilemma), (ii) ensuring resilience to system-wide shocks (i.e. systemic robustness), and (iii) coordinating different levels of governance initiatives effectively (i.e. operational, collective and constitutionalchoice levels).

Here, we demonstrate that balancing these three goals hinges upon understanding the connection between DAPP and other key analytical frameworks: Ostrom's SES framework, the Coupled Infrastructure System (CIS) framework, the Complex Dynamical Systems theory, and the Viable Control Theory.

We developed this connection and applied it to investigate potential governance transition pathways designed to manage hedgerow networks that provide a wide range of ecosystem services. Our focus was on two SES characterized by distinct community constraints and needs: a rural and a peri-urban SES located in the French Auvergne region. There, the viable delivery in hedgerows' ecosystem services faces threats from climate change, prompting our exploration of possible viable or optimal adaptation pathways between nine alternative nested governance arrangements. We developed indicators to pinpoint the key drivers influencing DAPP map differences, in response to changes in SES context and climate stress level.

Our research underscores the efficacy of this approach in addressing simultaneously the three adaptation problems. We discuss the advantages and limitations of this approach to accommodate increasingly complex SES and semi-natural infrastructures with diverse plant species, diverse stakeholders, and various ecosystem (dis)services. Additionally, we emphasize how this complexity may affect ease of use and testability in practical applications.

### **AUTHOR NOTE TO STAFF (CONFIDENTIAL)**

I accept the additional charge associated with a longer manuscript and would like to proceed with the submission

### **AUTHORS**

Jean-Baptiste Pichancourt

Accepted Has premium plan, ok to publish **Last 12 months (excludes rejected/withdrawn):** Published: 1, Submitted/In review: 1 **Last 36 months (excludes rejected/withdrawn):** Published: 2, Submitted/In review: 1 Université Clermont Auvergne (UCA), INRAE, UR 1465 LISC, Clermont-Ferrand, France

### Antoine Brias

Accepted Has free plan, needs upgrade to basic plan **Last 12 months (excludes rejected/withdrawn):** Submitted/In review: 1 **Last 36 months (excludes rejected/withdrawn):** Submitted/In review: 1 Université Clermont Auvergne (UCA), CNRS, UMR 6042 GEOLAB, Clermont-Ferrand, France

### Anne Bonis

Accepted Has free plan, needs upgrade to basic plan **Last 12 months (excludes rejected/withdrawn):** Submitted/In review: 1 **Last 36 months (excludes rejected/withdrawn):** Submitted/In review: 1 Université Clermont Auvergne (UCA), CNRS, UMR 6042 GEOLAB, Clermont-Ferrand, France

### **FILES**

### **Download all files Primary Files**

### **Manuscript.Text.Only.PEERJ.odt**

2abb083fd395e1798d36498e347a492381ae08c4

MANUSCRIPT (581KB)

**...** ...

### **Table.1.PEERJ.odt**

e5461b9a262ecd8ac793b5ecee8adbac60929d9b

### TABLE (169KB)

### 2<sup>nd</sup> tier attributes of the version of the Social-Ecological S **ystem (SES) framework**

The SES analysis was used to elaborate the ecological survey, social interview guides, qualitative and quantitative analyses of the study sites. \* indicates that the 2<sup>nd</sup> tier attributes are decomposed into three 3<sup>rd</sup> tier functional attributes representing capacities of action: action capacities of the exploiting actors & infrastructures (EAI), of the supporting actors & infrastructures (SAI) and of the policy-making actors & infrastructures (PAI). \*\* signifies that the previous 3<sup>rd</sup> tier attributes are extended to account for the directional influences of one  $3<sup>rd</sup>$  tier attribute on the other, or also the resource system (RS).  $\dagger$ indicates the decomposition of the 3<sup>rd</sup> tier attributes the following 4<sup>th</sup> tier attributes: Operational-choice arrangement (OCA), Collectivechoice arrangement (KCA), Constitutional-choice arrangements (CCA). The  $3<sup>rd</sup>$  and  $4<sup>th</sup>$ -tier analyses of the study area are presented in Supplementary S1.

### **Table.2.PEERJ.odt**

8578c048eb2b02a213acbcbf18a5b867d97e0ecb

### TABLE (115KB)

**Set of constitutional, collective, and operational choice ar rangements (respectively referred to as CCA, KCA and O CA in the table) for the study site located in the Auvergne region of France.**

The four CCA refer to the one presented in figure 2. For every CCA, several KCA are associated with different objectives, constrains, chains of actions, costs and benefits, and one OCA. The codes 1a, 0a, and others in the chains of actions refer to the CIS encoding presented in figure 1.

### **Table.3.PEERJ.odt**

23c3a1f3eeaa304e1455eb22b070b79c5812e13a

### TABLE (129KB)

### **Model for seven ecosystem (dis)services produced by fo ur types of hedgerows, along with the costs of operationa l maintenance actions and the differing needs in rural and peri-urban areas**

Ecosystem (dis)services were evaluated using simple, semiquantitative metrics from the literature. See details in Supplementary S1 and S2.

### **Figure.1.pdf**

285468da54e8222ec3c5e21b2f54e1b68cc2273a

#### FIGURE (80KB)

### **Systemic representation of the Social-Ecological System (SES)**

Systemic representation of the Social-Ecological System (SES) as a renewed version of the Coupled Infrastructure System (CIS) framework originally developed by Anderies et al. (2004, 2019), and presented in Step 2 of the method section. Within this representation, the internal dynamics of the capacity of action of each compartment in absence of external factors are depicted through self-loops, denoted with bold numbers (0a  $\rightarrow$  d). Arrows labeled with bold numbers (1a  $\rightarrow$ b to  $6a \rightarrow b$ ) signify various actions, checks and balances, spillovers, gains or loss of capacity of actions, or the movement of actors between compartments. Bold arrows labeled as  $7a \rightarrow g$  symbolize external relations with the broader environmental settings. Accompanying these numbers, between brackets are the references to the SES framework attributes from table 1. These references offer insights into the functional grouping and interconnections of these attributes, illuminate the potential spillover effects among them. As in table 1, symbols are used to indicate that the same SES framework attribute can serve different roles within this model: as a variable or parameter of one of the four compartments (\*), to describe their interconnections (\*\*), or to delineate their relationship with the external environment (†).

### **Figure.2.pdf**

fcfd790c0c90bb2fb90313a9003755d34b4cb2fe

FIGURE (683KB)

### **Illustration of the four scenarios of constitutional-choice arrangements (CCA)**

Illustration of the four scenarios of constitutional-choice arrangements (CCA) used as a basis for defining possible adaptations of the

distribution of authority, and using the renewed CIS model presented in figure 1. The four scenarios were defined from interviews of local actors and documents associated with the study sites. CCA-A was the dominant scenario recorded/present in the studied SES, while the other three were sporadically detected but frequently suggested for implementation based on interviews with local actors, or on strategic territorial planning documents. Each CCA has its own structural and time constraints, and permit different forms of collective-choice (KCA) and operational choice (OCA) arrangements (see table 2). RSI means resource species and infrastructures. EAI, SAI and PAI respectively refer to exploiting, supporting and policy-making actors and infrastructures. The red-colored compartments and arrows indicate the PAI involved in the DAPP process; while the black or blue-colored ones refer to those involved in other supporting actions (CCA-B and D) or arbitration (CCA-D).

### **Figure.3.pdf**

b817a2ab89a46540fbb85faccf97ed5b71ece8c0

FIGURE (734KB)

### **Link between viable control theory and DAPP maps**

(a) illustrates the sensitivity to climate change of the laws governing the OCA/KCA governance adaptation trajectories for two different CCA (cf. figure 2 for examples), and plotted within the ecosystem services state space after applying viable control theory (Aubin et al., 2011). (b) illustrates the corresponding set of viable 30-year governance trajectories (black lines) plotted along the decision node space using the dynamic adaptation policy pathway (DAPP) framework. In the latter, controlled trajectories represent the DAPP adaptation pathways. Pathway segments between two consecutive nodes (yellow circles) represent controlled trajectories at a CCA level that can be viable (blacklines), non-viable (grey lines), and the resilient ones (a succession of grey then black). Each CCA trajectory implies a specific combination of KCA and OCA actions, which could themselves be adapted, justifying further the decomposition of the viability analysis and DAPP map into as many sub-trajectories as there are nested structures of governing adaptation.

### **Figure.4.pdf** 336d95ee3a3f9552354ebedf0fcf2edd846a3f9f

FIGURE (260KB)

### **Uncertainty DAPP maps**

Probability to find viable pathways of governance adaptation that meet the set of satisfaction constraints for all ecosystem services (ES), for two types of SES, three climate stress levels, and nine governance

scenarios. Each governance scenario represents a combination of one constitutional choice arrangement (among four CCA), one collective-choice arrangement (among a maximum of four KCA per CCA), and one specific operational-choice arrangement OCA per KCA (cf. table 2). The letters (A-D) refer to the four possible CCA (cf. figure 2 and table 2), and the associated numbers (1-4) refer to the different KCA (cf. table 2). Every panel provides the percentage of total viable trajectories starting from the state of the SES in 2020. A total of  $9^7$  = 4,782, 969 possible pathways were constructed by combining CCA and KCA over the 30-years period and transitions every five years, i.e. between two successive decision nodes. Pathway sequences that are not represented in dark represent (irreversibly) unviable five years sequences regarding the studied ES. A dark line between a five-year sequence between two successive decision nodes means that at least one viable entire 30-year long pathway passing between these two nodes was found. Darker segments (on a 0-1 white and black scale) mean greater number of such unique 30-year long viable pathways crossing the 5-year segment.

### **Figure.5.pdf**

43a7598ed92b1a87731101b14af9f443069d01e8

FIGURE (204KB)

### *Secured DAPP maps*

*The secured DAPP maps* represent the 10% most secured options of viable trajectories that respected the (normalized) sum of constraints for every ecosystem services. The letters (A-D) refer to the four possible CCA (cf. figure 2 and table 2), and the associated numbers (1-4) refer to the different collective choice arrangements (KCA) that can be used for every CCA (cf. table 2).

### **Figure.6.pdf**

1923b8f7c951ca1ff9eae1ffd1dcba80e24d5955

#### FIGURE (253KB)

### *Optimal DAPP maps*

Optimal DAPP maps are constructed using the subset of the most optimal sequence constitutional-choice arrangement (CCA) adaptation for six different SE, with every color showing a different prioritization to either maximize or minimize a specific ecosystem (dis)services. The letters (A-D) refer to the four possible CCA, and the associated numbers (1-4) refer to the different collective choice arrangements (KCA) that can be used for every CCA, as defined in table 2.

**Figure.7.pdf** 1723af8a0dc77d029ce6877352584fa4dd3b4a0c

### **Temporal dynamics of all seven studied ecosystem (dis) services**

Predicted temporal dynamics of all seven studied ecosystem services  $ES<sup>+</sup>$  and disservices ( $ES<sup>-</sup>$ ) when selecting the most optimal adaptation pathway aiming to either maximizing ES<sup>+</sup> or minimizing ES<sup>-</sup>, as listed in the labels. For instance, panel (a) reads as the maximized  $ES<sup>+</sup>$  is resource for pollinators (prominent trend line) and the other ES+/ESwere set free (thinner trend lines). Results are derived from the optimal DAPP map presented in figure 5a for a peri-Urban SES under minimal climate stress level. Supplementary S4 presents similar results but corresponding to all the other five DAPP maps described in figure 6 (b:f).

### **Figure.8.pdf**

ee9c4ea6a52813acdd1a870402bcee1240eb0cb1

FIGURE (206KB)

### **Influence of hedgerow height on the size and shape of the viability kernel**

2D cut of the four dimensional viability kernel, and expressed as a function of only small hedgerows (SH) and tall hedgerows (TH) for the two types of social-ecological systems (rural, peri-urban), and the three levels of environmental stress. The blue dots represent the initial state of hedgerow types in both rural and peri-urban social-ecological system (SES), and were selected to be the same to facilitate comparison. Blue dots close to the viability kernel limit mean that there are less options to adapt the hedgerow network through different nested governance arrangements changes, and thus are less secured. Method of calculation is described in section 2.5.3.

### **Figure.9.pdf**

f4f3d6390cbe2f5708af6e0918cefc635582c043

FIGURE (109KB)

### **Influence of level of species richness in hedgerows on th e size and shape of the viability kernel**

2D cut of the four-dimensional viability kernel, expressed as a function of species-poor hedgerows (PH) and species-rich hedgerows (RH) for the two types of social-ecological systems (rural, peri-urban) and the three levels of climate stress. The blue dot represents the initial state of hedgerow types and were selected to be the same in the two SES to facilitate comparison. Viability kernel limit closer to the blue dot means less options to adapt the hedgerow network through different nested governance arrangements changes, and thus are less secured. Method of calculation is described in section 2.5.3

### **Figure.10.pdf**

7ee5a5a9809ead34972840173f1aba67bf7b96d5

#### FIGURE (333KB)

### **Security gains** *ΔES* **relative to the limits of the ES sat** *TH-SH*  **isfactory domain**

Security gains  $\Delta ES_{TH\text{-}SH}$  relative to the limits of the ES satisfactory domain (i.e. distance from the blue baseline) for every ecosystem service (ES+) and disservice (ES-), when switching the target of management from short hedgerows (SH) to tall ones (TH), during an adaptive governance pathway. Panels a,b,c are for peri-urban SES and d,e,f for rural SES, along with increasing climatic stress. As per explanation in method section 2.6.2, *ΔES<sub>TH-SH</sub> > 0* means greater security gains (and thus incentives) when acting more on TH than on SH; whereas  $\Delta E S_{TH\text{-}SH}  $\ell$  means greater incentives to act more on$ SH than on TH. The violins represent the probability density of *ΔES* values (with median in red) associated with all the adaptation pathways that are both viable and non-viable (yellow violins), or viable only (green violins). ES full name are provided in table 3.

### **Figure.11.pdf**

f2aa0c1e669fc94c1d1ac76f0b234a403bc4c816

### **Security gains** *ΔES* **relative to the limits of the ES sa** *RH-PH*  **tisfactory domain**

Security gains  $\Delta ES_{RH-PH}$  relative to the limits of the ES satisfactory domain (i.e. distance from the blue baseline), when switching the target of management from species-poor hedgerows (PH) to speciesrich hedgerows (RH) during an adaptation pathway. As per explanation in method section 2.6.2, *ΔES<sub>RH-PH</sub> > 0* means greater security gains when acting more on RH than on PH; whereas  $\Delta E S_{RH}$ .  $_{PH}$   $<$  0 means greater security to act more on SH than on TH. The violins represent the probability density of *ΔES* values (with median in red) associated with all the adaptation pathways that are both viable and non-viable (yellow violins), or viable only (green violins). ES full name are provided in table 3.

### **DECLARATIONS**

Do you need to list a 'Group' as if they were a single author on the article?

Are any elements of this paper or text under consideration at any other journal, or have they been published elsewhere already? Please also use

FIGURE (286KB)

this space to tell us if a version of the manuscript has been published as a preprint.

Please provide your Competing Interest statement here using complete sentences. This may include financial, non-financial, professional or personal relationships, including serving as an Academic Editor for PeerJ. If there are no competing interests then you must explicitly state this fact. This text will be published alongside your accepted manuscript.

### **The authors declare that they have no competing interests.**

Funding Statement: Using full author names and complete sentences, declare all the external funding sources for your work. Name the funding source/grant agency and any grant or identification numbers. All funding must be declared completely here. No financial information (including funders) is permitted in the Acknowledgements and no thanks/Acknowledgements are permitted in the Funding Statement. This statement will be published in the final article. No changes are permitted after acceptance, no Corrections are permitted to change Funding after publication.

**The work, including the master's student and the post-doctoral fellowship of Antoine Brias, was supported by the PACSEN project (led by Anne Bonis) and funded by the European Regional Development Fund (European Union) and the FEDER Auvergne-Rhône-Alpes.**

Did the external funders have any role in study design, data collection and analysis, decision to publish, or preparation of the manuscript?

Do you name, or make use of, any patents in your text?

Do you report on any DNA/RNA/peptide etc. sequencing?

Did you perform any microarray experiments?

Is your article a Systematic Review or a Meta Analysis?

Did you study human participants or human tissue?

Do you make use of any cell lines?

Did your work involve vertebrate or cephalopod animals?

Did you conduct research or collect specimens/material at a field site other than at your institution or a permanent field station?

Did your study require the approval of an Institutional Review Board (or other relevant body) for any other reason not already described?

Does your paper describe a new taxon?

Your submission will be published using the CC BY 4.0 copyright license (the Open Access standard). Please consult with co-authors and employers to confirm all authors can publish with this license. Authors who are US government employees may be required to use the CC0 license, and UK government (Crown) employees may be required to use the OGL license. If necessary, you can select one of these alternative licenses. For assistance contact: editorial.support@peerj.com

**CC BY 4.0 - standard creative commons license**

How are you submitting your raw data or code?

### **Submit repository link(s) to data**

Describe the files you are providing repository access to. Include: 1. Repository/database name 2. Accession/id number 3. Link (please double-check) Your submission cannot be reviewed without your raw data or code

**Supplementary materials S1, S2, S3, and S4 are available for download at the following URL: https://rb.gy/dnize1**

All authors agree

to be accountable for all aspects of the work

to ensure that questions related to the accuracy or integrity of any part of

the work are appropriately investigated and resolved they have approved the final draft of the manuscript submitted for review and publication

### **Confirmed**

Which authors conceived and designed the experiments? For literature reviews, selecting search engines and search terms; defining inclusion/exclusion criteria qualifies as "designing the experiment."

### **Jean-Baptiste Pichancourt Anne Bonis**

Which authors performed the experiments? For literature reviews, searching the database qualifies as "performed the experiments."

**Jean-Baptiste Pichancourt Antoine Brias Anne Bonis**

Which authors analyzed the data? For literature reviews, analyzing database search results qualifies as "analyzing the data."

### **Antoine Brias**

Which authors prepared the figures and/or tables?

### **Jean-Baptiste Pichancourt Antoine Brias**

Which authors drafted the work or revised it critically for important content?

**Jean-Baptiste Pichancourt Anne Bonis**

Did any authors make other contributions that are not already listed above? If there was a contribution made that does not fit in any of the default contributions above but does qualify in place of an item from Categories 1 or 2 , please clearly state that contribution here. Note: *"contributed reagents, materials, analysis tools"* are NOT qualifying contributions.

**Jean-Baptiste Pichancourt (Wrote the paper) Antoine Brias (Wrote the code of the model)**

#### **kubmit**

Possible payments due

2 authors or pay Article Processing Charge –

Payment is not required for submission, but must be done before publication

View payments needed

**About us - Peerl team |** Our publications | Benefits | | Press room | Terms of use | Partnerships | Endorsements | Awards **Academic boards -** Advisors | Editors | Subject areas **Submission guides -** PeerJ Activities | Resources – Life and Environment | PeerJ Computer Science | **Peerl Chemistry Resources -** FAQ | Careers Privacy | Credits | Contact **Follow us -** PeerL blog | X | Facebook | LinkedIn | Instagram | Pinterest **Spread the word** - **PeerJ feeds -** Atom | RSS 1.0 | RSS 2.0 | JSON **PeerJ Computer Science feeds -** Atom | RSS 1.0 |

iss funds available for qualifying authors

RSS 2.0 | JSON

**Archives -** PeerJ – Life and

### d we'll waive your author fee

**Five new journals in Chemistry** Free to publish • Peer-reviewed <mark>om Peer-</mark> 4.0 unless © PeerJ, Inc. 2012-2024 | Public user content licensed otherwise specified.

**Environment | PeerJ** Computer Science

PeerJ ISSN: 2167-8359 PeerJ Comput. Sci. ISSN: 2376-5992 PeerJ Phys. Chem. ISSN: 2689-7733 PeerJ Analytical Chem. ISSN: 2691-6630 PeerJ Org. Chem. ISSN: 2831-6223 PeerJ Mat. Sci. ISSN: 2691-6657 PeerJ Preprints ISSN: 2167- 9843