



Linking Adaptation Pathways with Ostrom's Framework: A Novel Method for Governing Social-Ecological Systems Amid Global Change

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

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

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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 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.

1 Title

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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 constitutional-choice levels).

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1. Introduction

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).

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 social-ecological 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).

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.

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 & Gieseckam, 2019; Stanton & Roelich, 2021).

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).

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 SES-context 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.

1.1. The panacea dilemma for adaptation.

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).

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).

1.2. The problem of systemic adaptive robustness and overflow

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 social-ecological 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).

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; Muneeppeerakul & Anderies, 2020). When combined with

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).

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.

1.3. The problem of nested adaptive governance initiatives

The last adaptation problem pertains to orchestrating complementary initiatives across nested governance arrangements, each representing both targets and source of adaptation actions geared towards enhancing the viability (robustness) of the SES over varying time frames.

DAPP maps are designed to help sequence different adaptation initiatives at different timescales, but lack guidelines to plan nested governance initiatives and arrangements that are inextricably linked through complex linkages.

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).

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.

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.

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.

1.4. Objective and structure of the paper

In this paper, we propose a method that can streamline the process of constructing socio-ecologically 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

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

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

172

173 2. Methodology

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

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

2.1. Definition of the social-ecological attributes of adaptation

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 2nd tier attribute "externalities to other SES" (O3) into a 3rd tier attribute that emphasizes the role of ecological resource infrastructures and associated species. All the 1st and 2nd tier attributes that derived from these works can be targeted for adaptation (refer to table 1).

We further introduced new 3rd and even 4th 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 2nd tier attributes (see table 1: S1:S3, RS4, RU1, RU3, GS2:GS10, A1:A9, I2:I10, O1) into three new 3rd tier functional attributes that are subject to adaptation, called "exploiting", "supporting" and "policy-making", such that:

(i) **Exploiting attributes** (3rd 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 → GS10.1) and physical infrastructures (such as supply chains or exploiting technologies, S7.1). These attributes involve various social-ecological interactions (I1.1 → I10.1) 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 → 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.

(ii) **Supporting attributes** (3rd 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.

(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.,

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.

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).

2.2. Relations between SES attributes and the CIS model

2.2.1. Translation of the SES framework into a renewed CIS framework

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 3rd and 4th tier attributes in step 1.

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.

(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).

(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:

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



- 274 • a member of a local group of organic farmers providing more collective supporting roles
275 for broader conservation purposes (SAI),
- 276 • a board member of a governing body of an NGO or private association (PAI) that is
277 buying lands and renting them to farmers, under specific organic farming rules and
278 granting schemes (cf. SES analysis in Supplementary S1).

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

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

295

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

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

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

313

314

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

2.3.1 System of equations representing the most generic scenario

Each CIS state variable (RSI, EAI, SAI, PAI) and linking parameter (0a → 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.

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.

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 to +1) and SAI action capacity ratios gained or lost from contextualizing with PAI (-1 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).

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: $0d + 3a + 4a + 6a + 7h = 1$.

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), Muneeppeerakul & 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:

$$\begin{aligned}
 \left\{ \begin{aligned}
 \frac{dRSI}{dt} &= \underbrace{\text{Natural ES Growth}}_{0a.RSI} \pm \underbrace{\text{Impact of SES Settings}}_{7b.RSI} - \underbrace{\text{ES Externalities}}_{7a.RSI} \\
 &+ \underbrace{\text{SAI Support}}_{4a.RSI.SAI} - \underbrace{\text{ES Access or Flow Regulated}}_{1b.RSI.EAI} + \underbrace{\text{Access \& Management Regulated}}_{5b.SAI} + \underbrace{\text{SAI Support \& Regulations}}_{1a.EAI.RSI} - \underbrace{\text{PAI Support \& Sanctions}}_{5a.SAI} \\
 \frac{dEAI}{dt} &= \pm \underbrace{\text{Natural EAI Growth/Decay}}_{0b.EAI} \pm \underbrace{\text{Impact of SES Settings}}_{7d.EAI} - \underbrace{\text{Externalities}}_{7c.EAI} \\
 &+ \underbrace{\text{Access \& ES Flow Regulated}}_{1b.RSI.EAI} + \underbrace{\text{SAI Support \& Regulations}}_{5b.SAI} \pm \underbrace{\text{PAI Support \& Sanctions}}_{6b'.EAI.SAI} \pm \underbrace{\text{PAI Support \& Sanctions}}_{2b.EAI.PAI} \\
 \frac{dSAI}{dt} &= - \underbrace{\text{Natural Loss/Decay}}_{0d.SAI} \pm \underbrace{\text{Impact of SES Settings}}_{7h.SAI} - \underbrace{\text{Externalities}}_{7g.SAI} \\
 &+ \underbrace{\text{EAI Joining/leaving}}_{(6a-6c).EAI.SAI} \pm \underbrace{\text{PAI Support/Sanction}}_{3a.PAI.SAI} \\
 \frac{dPAI}{dt} &= - \underbrace{\text{Natural Loss/Decay}}_{0c.PAI} \pm \underbrace{\text{Impact of SES Settings}}_{7f.SAI} - \underbrace{\text{Externalities}}_{7e.SAI} \\
 &\pm \underbrace{\text{Join/Support/Sanction}}_{2a.EAI.PAI} \pm \underbrace{\text{Join/Support/Sanction}}_{3b.SAI.PAI}
 \end{aligned} \right.
 \end{aligned}
 \tag{1a}$$

$$\tag{1b}$$

$$\tag{1c}$$

$$\tag{1d}$$

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.

2.3.2 Model parametrization and simplifications to match our case study

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.

2.3.2.1 RSI Model of hedgerows network dynamics

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 \mathbf{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.

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

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

2.3.2.2 Specific parametrization for the different governance arrangements and actions

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).

At a collective-choice level (KCA), not all the information could be obtained from interviews for 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:

At a constitutional-choice (CCA) level, we assumed perfect community grouping for the CCA-C 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 CCA-C and -D, we assumed a perfect monitoring of the resource state ($4a = 1$), and a perfect monitoring ($5b = 1$) of the access rate $1b$ of EAI (farmers, local population) to get some of the 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 TdL and DAPP board comities. We finally assumed a perfect human or economic support to the SAI from PAI ($3a = 1$).

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 ($dEAI/dt = 0$, $EAI = 1$, $0b = 0$; $dPAI/dt = 0$, $PAI = 1$, $0c = 0$, $dPAI/dt = 0$).

2.3.2.2 Resulting context-specific model after simplifications

These assumptions led to the simplified model that we used for our case study, as per eq. 2 below:

405

$$\frac{dRSI}{dt} = \underbrace{0a.RSI}_{\text{Natural ES Growth}} - \underbrace{7b.RSI}_{\text{Climate Stress}} + \underbrace{4a.RSI.SAI}_{\text{SAI Support}} \quad (2a) \quad 2.4.$$

$$\frac{dEAI}{dt} = - \underbrace{RSI.EAI.SAI}_{\text{Perfect ES Access, Flow \& Regulation}} + \underbrace{1a.EAI.RSI}_{\text{Access \& Management}} + \underbrace{5a.SAI}_{\text{Regulated}}$$

$$\frac{dSAI}{dt} = - \underbrace{0d}_{\text{Natural EAI Growth/Decay}} + \underbrace{RSI.SAI}_{\text{Perfect ES Access, Flow \& Regulation}} + \underbrace{6b'.SAI}_{\text{EAI Support}} + \underbrace{2b.PAI}_{\text{PAI Support}} = 0$$

$$\frac{dPAI}{dt} = - \underbrace{0c}_{\text{Natural Loss/Decay}} + \underbrace{EAI}_{\text{Perfect EAI Participation}} + \underbrace{PAI}_{\text{Perfect PAI Support}} = 0 \quad (2c)$$

$$\frac{dPAI}{dt} = - \underbrace{0c}_{\text{Natural Loss/Decay}} + \underbrace{EAI}_{\text{Perfect EAI Feedback}} + \underbrace{SAI}_{\text{Perfect SAI Feedback}} = 0 \quad (2d)$$

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

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

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

416

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

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

423

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

425

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

If population needs differ between ecosystem services (ES^+) or disservices (ES^-), viability is achieved when $ES_i^+ \geq ES_{i,min}^+$ and $ES_j^- \leq ES_{j,max}^-$, where $ES_{i,min}^+$ represents the minimal value of ecosystem service i and $ES_{j,max}^-$ 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 peri-urban SES, and ES levels from K were rescaled [0-1] to its analysis (cf. table 3 and Supplementary S1).

2.4.3. Definition of the set of robust trajectories that respect K

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 .

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 RSI_0 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 $A_{OCA} \subseteq A_{KCA} \subseteq A_{CCA} \subseteq A$. These represent respectively the set of actions of changing or not the OCA (A_{OCA}), 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:

$$Viab_K(T) = \{ RSI_0 \mid \forall t \in [0, T], \exists a(t) \in A_{OCA}(T) \in A_{KCA}(T) \in A_{CCA}(T) \in A(T), ES_t \in K \} \quad \text{eq. 5}$$

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).

2.5. Deducing DAPP maps from the viability kernel

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

Once the sets of viable (robust) trajectories are defined within \mathbf{Viab}_K (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.

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 \mathbf{Viab}_K , 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.

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

$$a(\cdot) = (a_{CCA} a_{QCA} a_{OCA}(0), a_{CCA} a_{QCA} a_{OCA}(1), \dots, a_{CCA} a_{QCA} a_{OCA}(T)) \quad \text{equation 6}$$

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

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).

2.5.2. Deduction of different DAPP maps that emphasize different priorities

In our case study, once the existence of viable pathways is proved, three different types of DAPP maps were produced for the two SES types (peri-urban, rural), and the three climate stress levels (0, 1, 2). Each DAPP map emphasized different priorities of actors:

(i) *Certainty 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;

(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;

(iii) *Optimal DAPP maps* (figure 6) as the subset comprised of the seven pathways that maximize only one of the five ES^+ and minimized only one of the two ES^- . We supplemented this analysis by decomposing the effect of optimizing every ES on the other ES (figure 7).

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

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 $Viab_K$ 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 $Viab_K$ 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 two sub-steps. Firstly, analyzing $Viab_K$ 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.

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

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 $Viab_K$ (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 $Viab_K$ within the four-dimensional state-space, to represent $Viab_K$ 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

We further pinpointed the initial state's position at t_0 (i.e. time when we did the SES analysis of the study sites in 2020) within $Viab_K$, as an indication of whether the current SES state is inside, outside or near the frontier of $Viab_K$, and therefore requires governance adaptation. For example, a small volume, asymmetrically shape $Viab_K$ (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.

2.6.2. Evaluating the ES security gains when changing hedgerow types

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).

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 ΔES between the value of ES_i^+ under action pathways on TH, and the threshold $ES_{i,min}^+$, such that:

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

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.

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 species-poor (PH). For instance, based on the (i) comparison, the relative effect on acting on (i) was estimated this way:

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

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:

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

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 $\Delta ES_{TH-SH} > 0$, 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 ES_i viability.

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.

3. Results

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

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.

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).

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 constraints 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.

3.2. The most secured 30-year viable decision pathways

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

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.

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).

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).

3.3 Switching between pathway options to change ES priority and arbitrate conflicts between actors

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^+ (or minimizing the other ES^-). 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^+ would require to transit first through the arrangement C.4 and then either B.2 or D.1.

These results highlighted how the choices of pathways optimizing one ES^+/ES^- 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^- “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^+ and ES^- over the next 30 years (figure 7f), alleviating the risks of ES trade-offs.

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

3.4.1 Set of viability solutions according to the proportions of hedgerow types

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).

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).

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).

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

ES⁺ and ES⁻ 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).

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).

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

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).

In absence of additional climate stress, we found only limited contrasts between viable and non-viable pathways (figures 10a,d and 11a,d). With climate stress increased to level 1, viable adaptation pathways with greater ES⁺ security were the one with greater TH than SH. The one with increased ES⁻ 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).

For RH vs PH proportions (figure 11), pushing for even more RH for ES⁺ and even more PH for ES⁻ was predicted to rather amplify existing patterns of ES security, under increased climate stress levels.

4. Discussion

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.

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

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

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 social-ecologically 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.

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

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 their daily life that would lead to the expected discrepancies.

4.1.2. Perspective for understanding better complex emerging DAPP patterns

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).

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.

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

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

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.

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.

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).

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

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.

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.

4.2.2 Perspectives for using this approach for more complex networks of ES

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).

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.

These examples suggest that the renewed CIS approach could more flexibly and effectively model potentially more complex DAPP problems involving inextricable links between ecological infrastructures, functions, biodiversity, and ES; as described in e.g. Vogt et al., (2015), Partelow & Winkler (2016) or Rova & Pranovi (2017).

4.3. Did we solve the nested governance adaptation problem?

4.3.1. DAPP maps solve some ... but!

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).

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.

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 → 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).

We lacked sufficient data to evaluate the specific costs involved in the direct A → 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.

4.3.2. Perspectives for more detailed decomposition of the social system

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.

One possible approach to do so may be to utilize Archer's (1995) morphogenetic framework, that is extensively used to analyze the progression of causal relations between agents and structures (social and cultural ones) over time.

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.

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).

Conclusion & perspectives

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.

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.

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.

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.

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Supplementary Information

- Supplementary S1: Spreadsheet detailing the SES framework analysis and associated original data for the rural and peri-urban sites: temporary anonymous url: <https://rb.gy/dnize1>
- Supplementary S2: detailed data, GIS analysis and survey documents used for analyzing and modeling the structure and dynamics of the hedgerow network: temporary anonymous url: <https://rb.gy/dnize1>
- Supplementary S3: Link to the repository to access details of the model and code to reproduce the results: temporary anonymous url: <https://rb.gy/dnize1>
- Supplementary S4: Supplementary results: temporary anonymous url: <https://rb.gy/dnize1>

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Table 1 (on next page)

2nd 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 2nd tier attributes are decomposed into three 3rd 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 3rd tier attributes are extended to account for the directional influences of one 3rd tier attribute on the other, or also the resource system (RS). † indicates the decomposition of the 3rd tier attributes the following 4th tier attributes: Operational-choice arrangement (OCA), Collective-choice arrangement (KCA), Constitutional-choice arrangements (CCA). The 3rd and 4th-tier analyses of the study area are presented in Supplementary S1.

Version of the SES Framework used to predict the possible targets of adaptation			
Social, Economic and Political settings (S)			
S1	Economic development * †	S4	Other governance systems †
S2	Demographic trends * †	S5	Markets †
S3	Political stability (rate of political change) * †	S6	Media organizations †
		S7	Technology †
Resource Systems (RS)		Resource units (RU)	
RS1	Sector	RU1	Resource unit mobility ** †
RS2	Clarity of system boundaries	RU2	Growth or replacement rate of resource units
RS3	Size of resource system	RU3	Interactions among resource units * †
RS4	Human constructed facilities *	RU4	Economic value
RS5	Productivity of the system	RU5	Number of units
RS6	Equilibrium properties	RU6	Distinctive characteristics
RS7	Predictability of system dynamics	RU7	Spatial & temporal distribution
RS8	Storage characteristics		
RS9	Location		
RS10	Ecosystem history		
Governance Systems (GS)		Actors (A)	
GS1	Policy area	A1	Number of relevant actors *
GS2	Geographic scale of governance system *	A2	Socio-economic attributes *
GS3	Proportion of participating population **	A3	History of past experience **
GS4	Regime type (demo/auto-cratic, mono/poly-centric) *	A4	Location *
GS5	Rule-making organizations *	A5	Leadership / entrepreneurship *
GS6	Rules-in-Use *	A6	Norms /(trust-reciprocity) / social capital *
GS7	Property rights systems (relations among people in relation to resource units and infrastructures) *	A7	Knowledge of SES / mental models / beliefs *
GS8	Repertoire of cultural knowledge, beliefs, norms, practices (strategies) with no rules and sanctions *	A8	Proportion of resource dependent actors *
GS9	Network structure (connections among the rule-making organizations and the population subject to these rules) **	A9	Technologies available *
GS10	Historical continuity of the governance system (recent vs long-lasting, open vs close to internal adaptation) *		
Interactions (I)		Outcomes (O)	
I1	Harvesting / using resource units by divers users	O1	Social performance measures (e.g. efficiency, equity, accountability, sustainability) **
I2	Information sharing among actors **	O2	Ecological performance measures (e.g. overharvested, resilience, robustness, biodiversity) **
I3	Deliberation process * **	O3	Externalities to other SES †
I4	Conflicts among actors * **		
I5	Investment activities * **		
I6	Lobbying activities * ** †		
I7	Self-organizing activities * **		
I8	Networking activities * **		
I9	Monitoring activities * **		
I10	Evaluative activities * **		

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.

Constitutional-Choice arrangements (CCA)			Associated Collective-Choice Arrangements (KCA)			Consequences on the operational choice arrangement (OCA) for the EAI: proportion of every type of action for link 1a			Effect of the OCA on the resource infrastructure (Ia)	Relative cost reduction provided by the KCA to compensate the disservice cost of management (hedgerows).
Name	Description	Minimal duration	#	objectives	Method (chain of collective actions) to achieve the objective	No maintenance	Hedge-cutting (tractor mounted)	Integrative soft management		
(A) Private arrangement	Individualistic social organization (current dominant practice): no incentives or collective actions to support the hedgerow network or regulate actions. Most common practice is trimming. We assume that this action is included in the SES that was observed during the 1989-2019 period.	no	A1	Collective-choice arrangement for baseline monitoring and range of operational actions	#NA	0.2	0.6	0.2	Business-as-usual dynamics (I#NA)	0%
			B1	Compulsory planting of species- rich hedgerows to increase public & common-good ES	2b -> 1a -> 0a -> 1b	0.2	0.6	0.2	More planting of species-rich hedgerows: Tall: +5%, Short: +5%	-10%
(B) Joint Private-Public arrangement	Social organization and infrastructures around state- controlled scheme for the payments for ecosystem services (PES): The state pay farmers who enter a PES scheme, under the condition that they maintain hedgerows and associated ES	5 years	B2	Compulsory planting of species- rich hedgerows under integrated soft management (constrain the on tractor hedge-cutting use) to protect public & common-good ES	2b->1a->0a->1b	0.2	0.4	0.4	#NA	0%
			C1	Incentives to share material and reduce costs in order to reduce constraints on tractor hedge-cutting	6a->1a+1b	0.1	0.8	0.1	#NA	-10%
(C) Joint Private- Community arrangement	Social organization and infrastructures around the support and regulation of the hedgerow network, ecosystem services and exploiting actors: Neighboring farmers enter joint private-community arrangement by forming an auxiliary association (AIA) to set auxiliary practices regarding monitoring, the sharing of material/costs/knowledge, and set operational constraints on PIA appropriation practices (e.g. on planting new hedgerows, tractor hedge-cutting, integrated soft management).	no	C2	Regulate the planting to increase poor-species hedgerows in order to increase biomass production	5a->1a->0a->1b	0.2	0.6	0.2	More planting of productive species in species-poor hedgerows: Tall: +5%, Short+5%	0%
			C3	Regulate the use of tractor hedge- cutting + incentives on the planting of species-rich hedgerows + integrated soft management practices on these hedgerows	5a -> 1a -> 0a -> 1b	0.2	0.4	0.4	More planting of species-rich hedgerows: Tall: +5%, Short: +5%	0%
			C4	Strongly regulate maintenance activities for reducing costs and increase nature conservation	5a->1a->0a->1b	0.4	0.4	0.2	#NA	0%
			D1	Regulate the use of tractor hedge- cutting, set incentives to plant more species-rich hedgerows that require integrated soft management practices	5a -> 1a -> 0a -> 1b	0.2	0.4	0.4	More planting of species-rich hedgerows: Tall: +5%, Short: +5%	-20%
(D) Joint-Private- Community-Public arrangement	Social organisation and infrastructure for governing, arbitrating between exploiting and supporting actors and infrastructures: Farmers join organic farming NGO Terre-de-liens (TdL) and the EU-CAP sponsored PES scheme. Farmers lease land to TdL with extra individual regulations and benefits for the management of their own hedgerows. Farmers can join the TdL SAI group that receive funds from TdL to collectively protect the hedgerow network	10 years	D2	Strongly regulate maintenance activities & set cost sharing incentives to increase nature conservation	5a+6b -> 1a -> 0a -> 1b	0.4	0.4	0.2	#NA	-20%

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.

Ecosystem (dis)services (ES) (i.e. link 1b in the CIS model from figure 1)	Weighted limits of satisfaction for every ES deduced from the actors surveyed in the two SES [0-1]		Relative production of ES by type of hedgerow, on a [0-1] scale, with 1 corresponding to the observed maximal production or effect of the ES	Impact of maintenance operational action on ES, on a [0-1] scale, with 0 corresponding to a total degradation of the ES, whereas 1 meaning a perfect conservation of the ES.						Quantitative indicator of ecosystem services (and origin of indicator and measurement)		
	Rural SES Sauvetat)	(La Peri-urban SES (Veyre-Monton)		No hedgerow	Short hedgerow (SH)		Tall hedgerow (TH)		No maintenance		Hedge-cutting (tractor-mounted)	Integrative soft maintenance
					Species-poor (PH)	Species-rich (RH)	Species-poor (PH)	Species-rich (RH)				
Fruit production	0.9	0.95	0	0.553	1	0.3169	0.9859	0.5	0.25	0.75	Mean number of edible fruits species (based on ecological survey)	
Pollination	0.9	0.95	0	0.5204	0.9959	0.2353	1	0.5	0.25	0.75	Mean number of species attacking pollinators (based on ecological survey)	
Biomass Production	0.95	0.5	0	0.25	0.25	1	0.75	1	0.5	0.75	Aerial carbon (Open data from Carbocage	
Sunlight Protection	0.95	0.5	0	0.3231	0.3508	0.938	1	0.75	0.25	0.5	Mean height (based on ecological survey)	
Landscape aesthetics	0.5	0.95	Aesthetic opinion of actors changes with the diversity of hedgerow present in the landscape.					0.5	0.25	0.75	Shannon index (calculated from the relative proportion of the four hedgerow types present in the landscape, and confronted to opinions of actors based on social survey)	
Maintenance cost (social- economic cost)	0.1	0.1	0	0.25	0.25	0.75	1	0	0.5	0.75	Mean annual maintenance cost	
Environmental hazards: fire, lateral encumbrance, snag fall, etc. ...	0.15	0.2	0	0.25	0.25	0.75	1	1	0.5	0.5	Based on expert knowledge	

Figure 1

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 → d). Arrows labeled with bold numbers (1a → b to 6a → 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 → 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 (†).

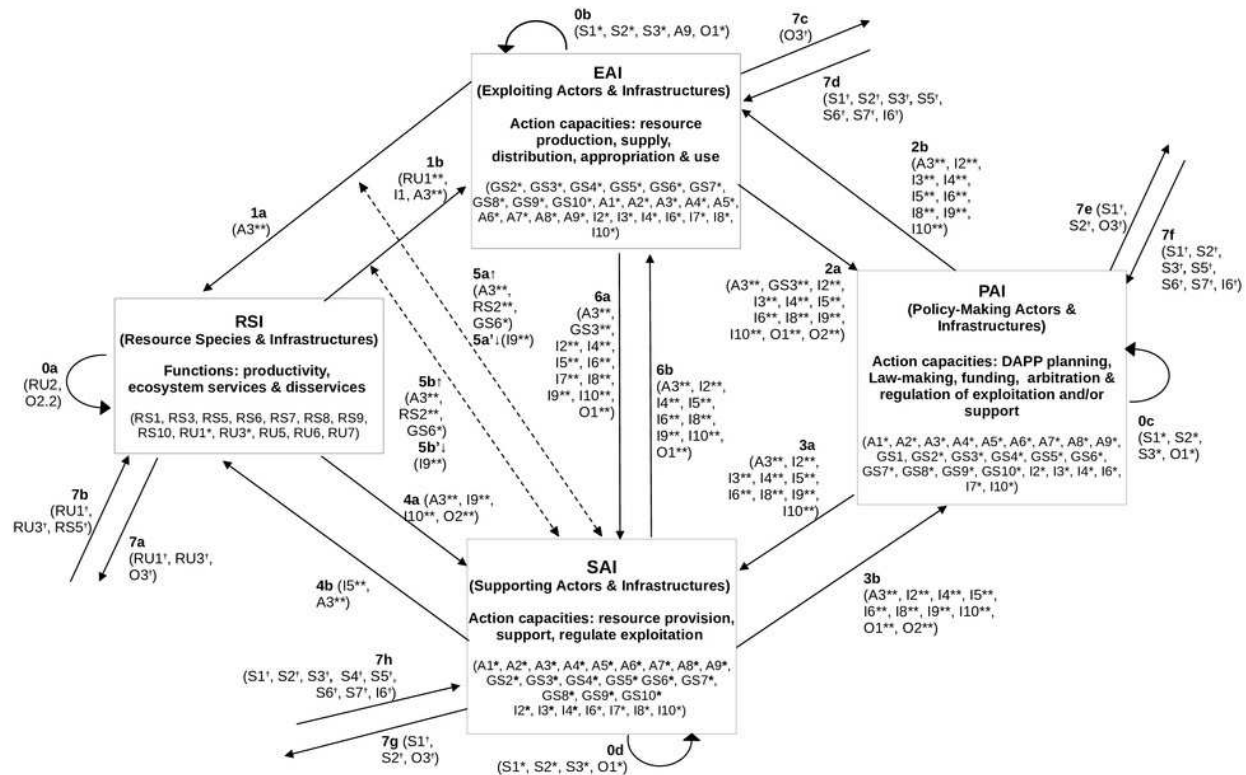


Figure 2

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).

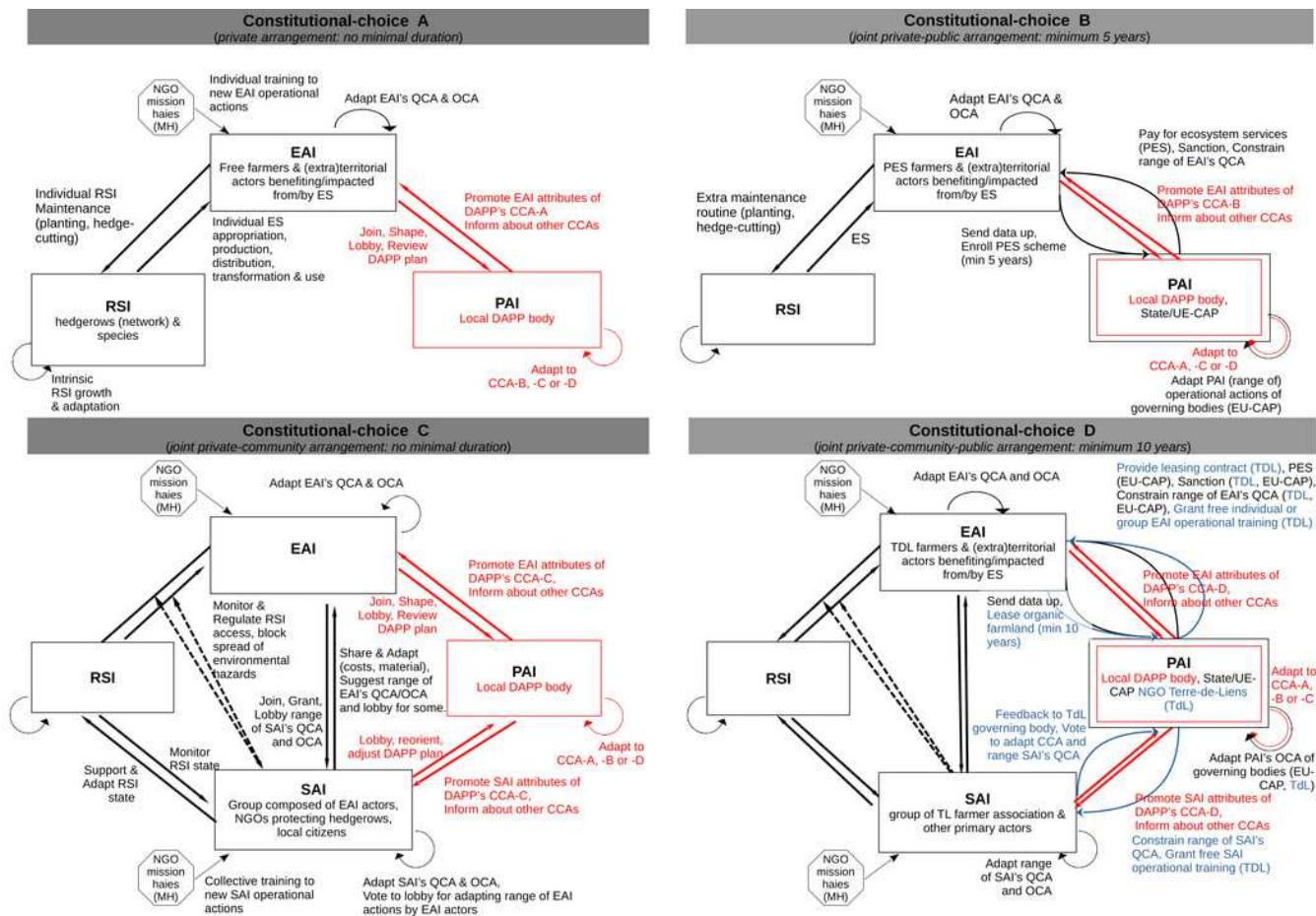


Figure 3

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.

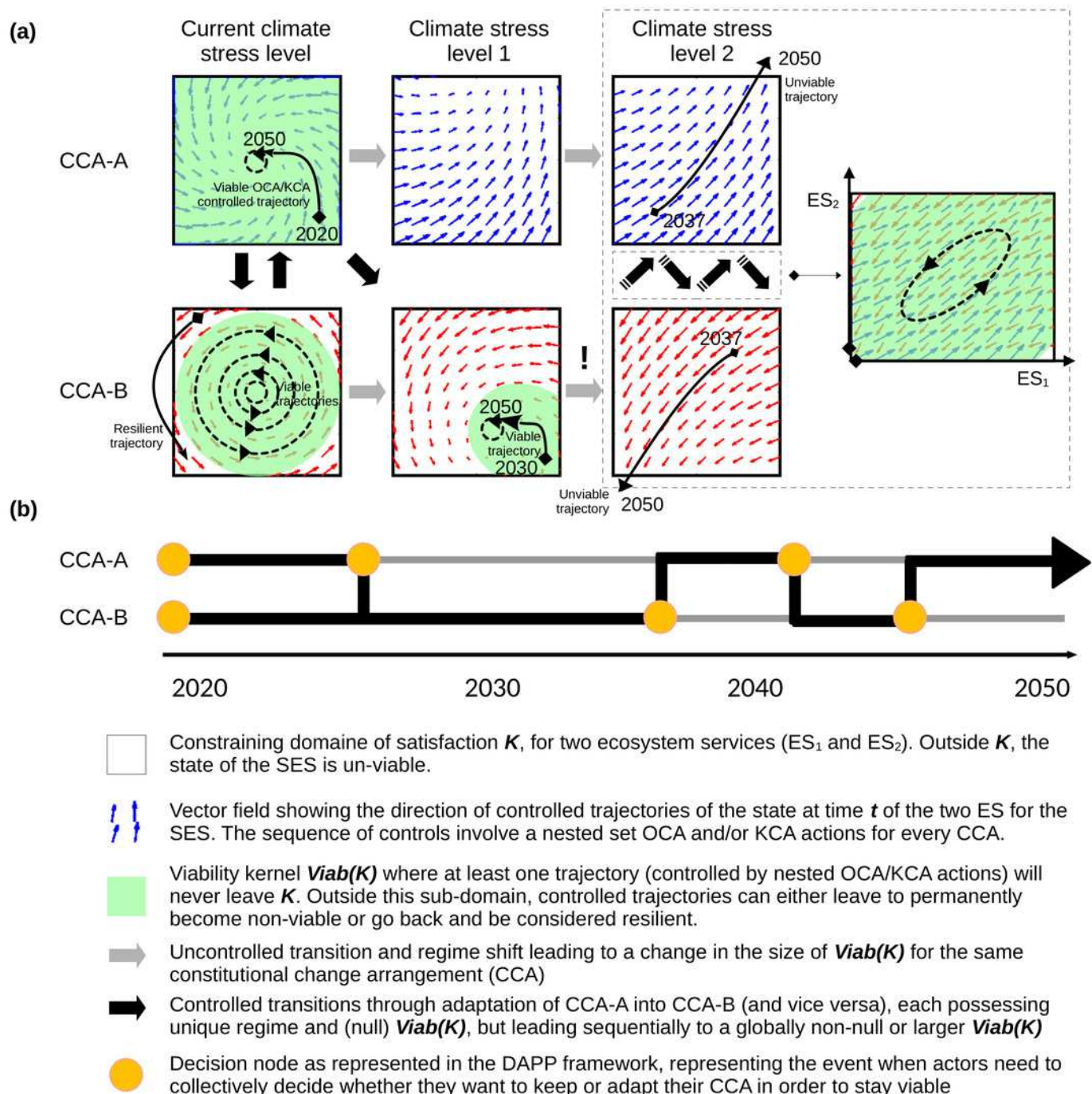


Figure 4

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.

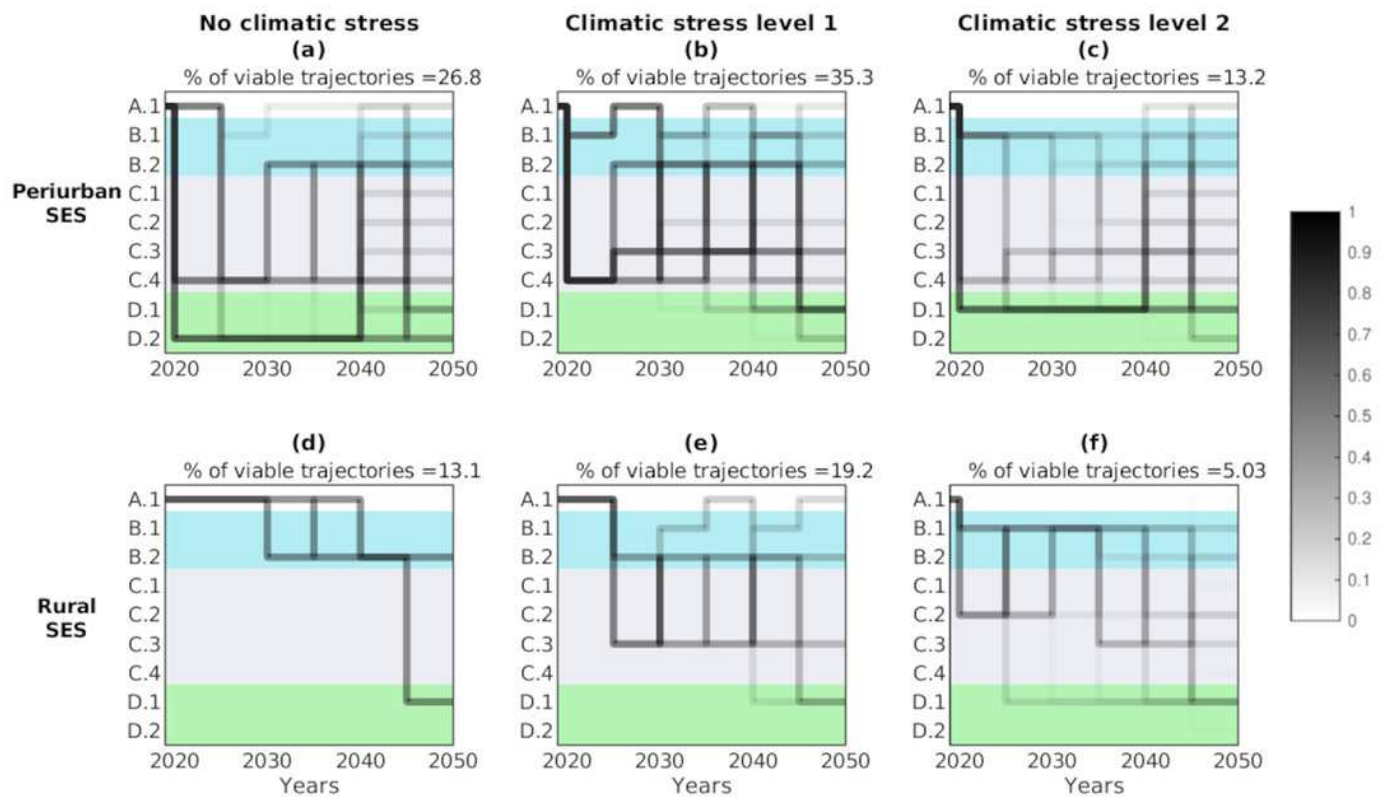
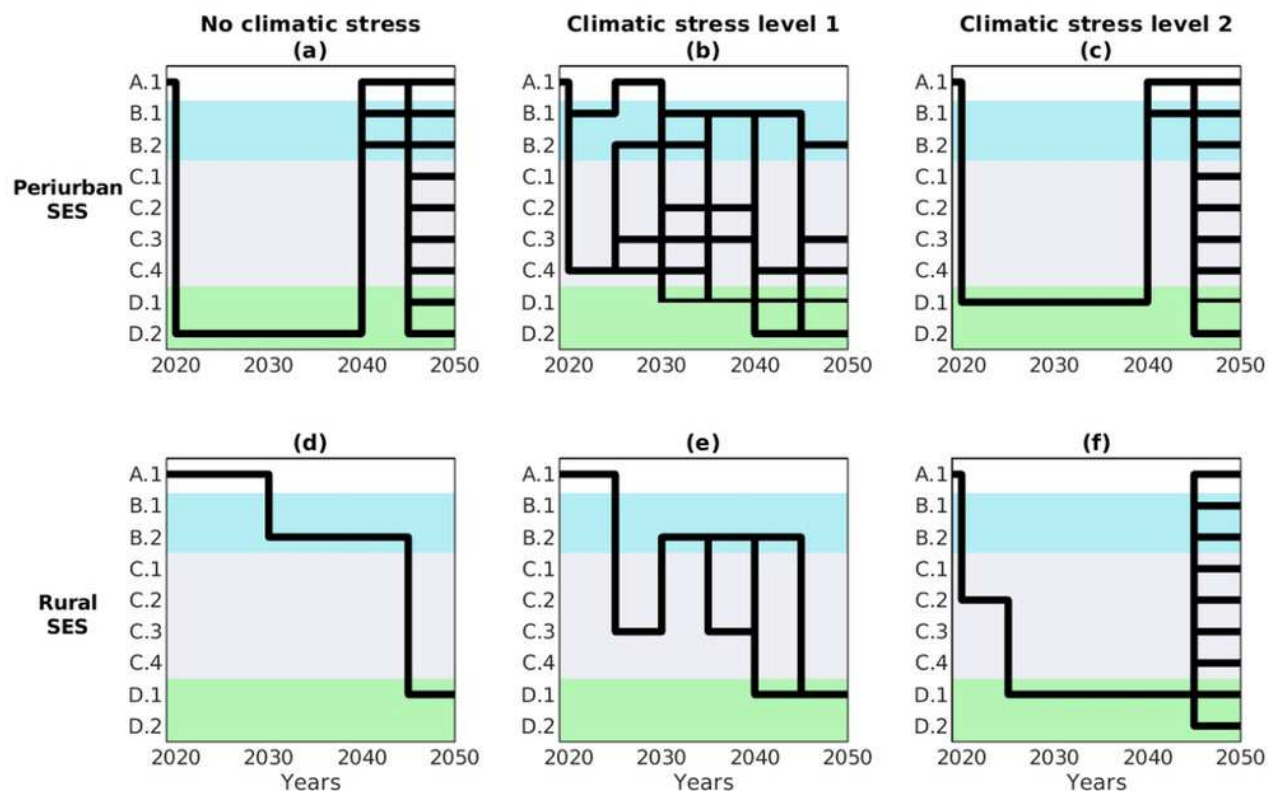


Figure 5

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).



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.

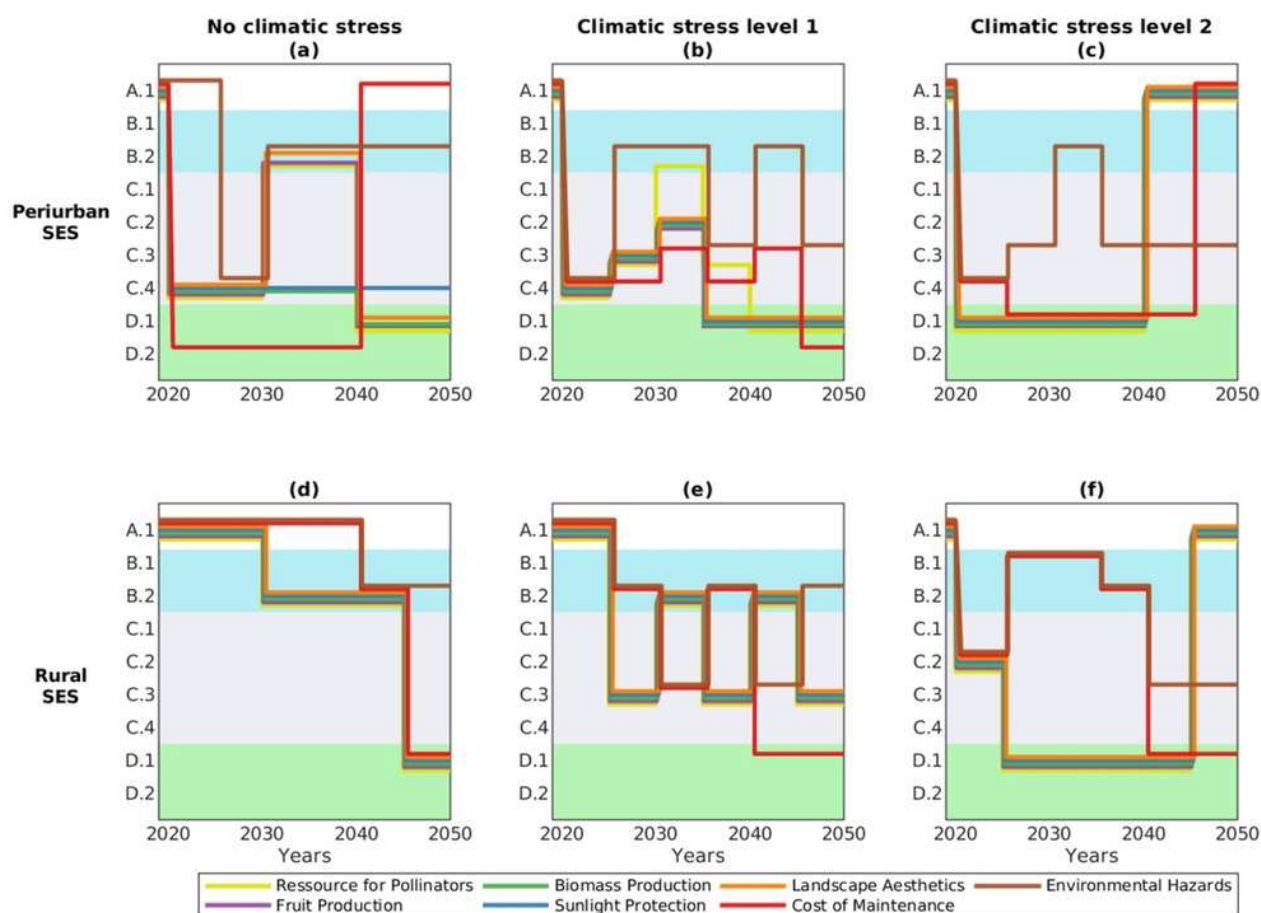


Figure 7

Temporal dynamics of all seven studied ecosystem (dis)services

Predicted temporal dynamics of all seven studied ecosystem services ES^+ and disservices (ES^-) when selecting the most optimal adaptation pathway aiming to either maximizing ES^+ or minimizing ES^- , as listed in the labels. For instance, panel (a) reads as the maximized ES^+ is resource for pollinators (prominent trend line) and the other ES^+/ES^- 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).

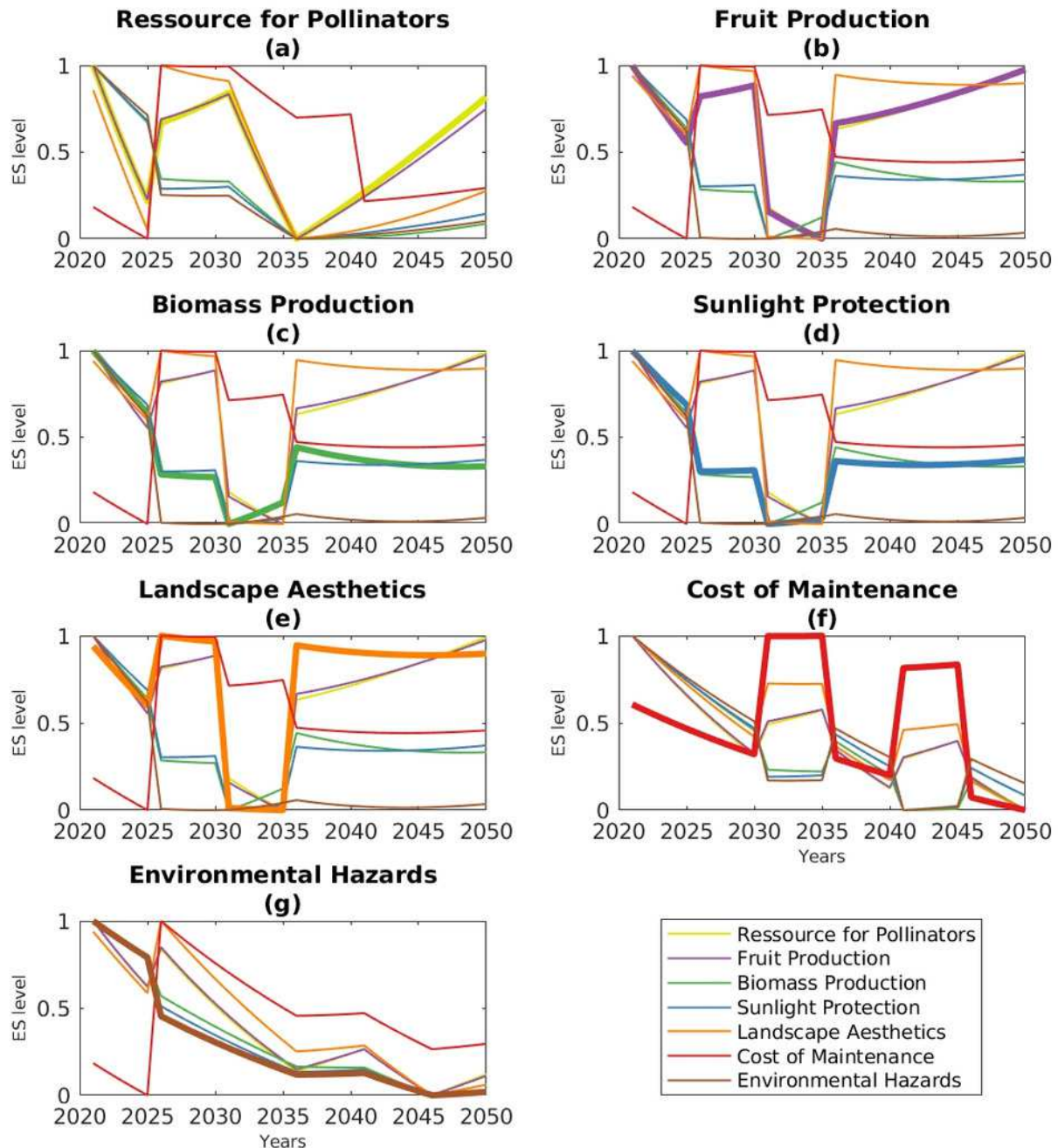


Figure 8

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.

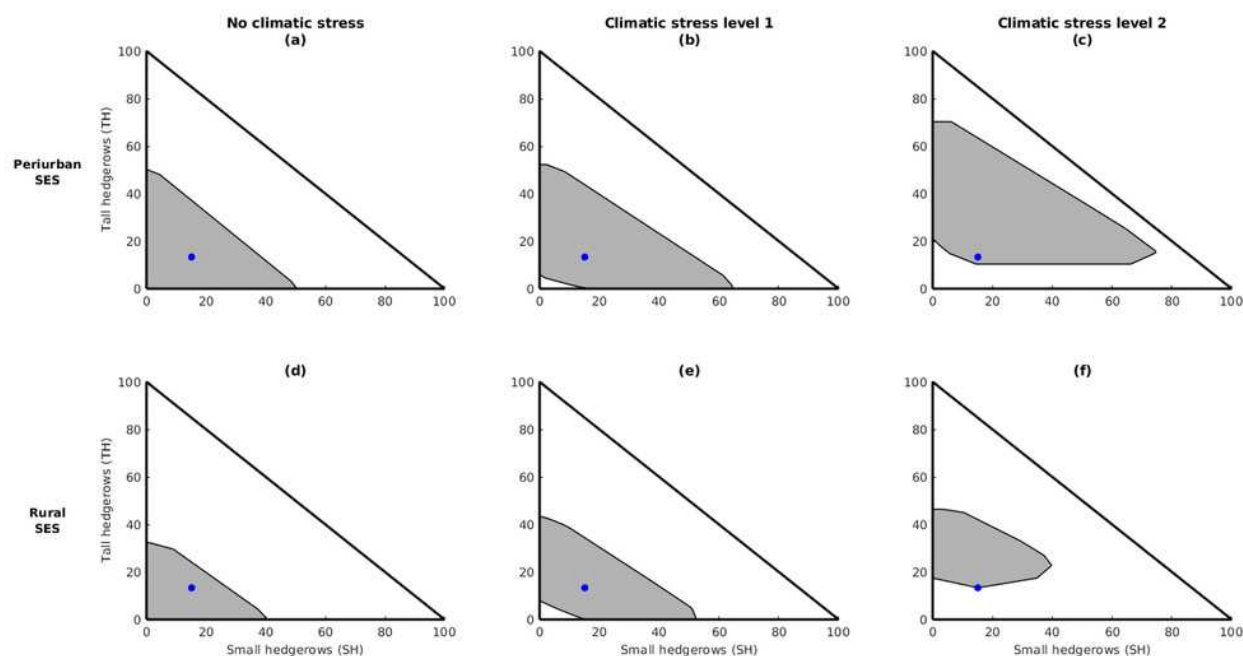


Figure 9

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

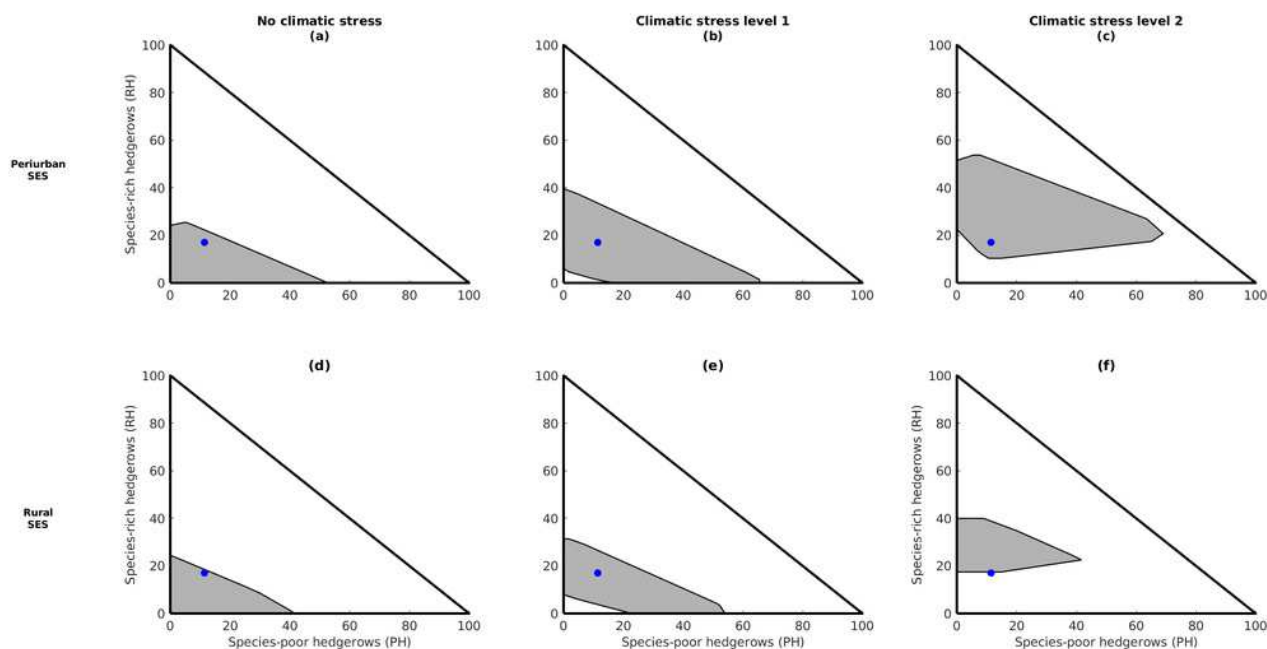


Figure 10

Security gains ΔES_{TH-SH} relative to the limits of the ES satisfactory domain

Security gains ΔES_{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, $\Delta ES_{TH-SH} > 0$ 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 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.

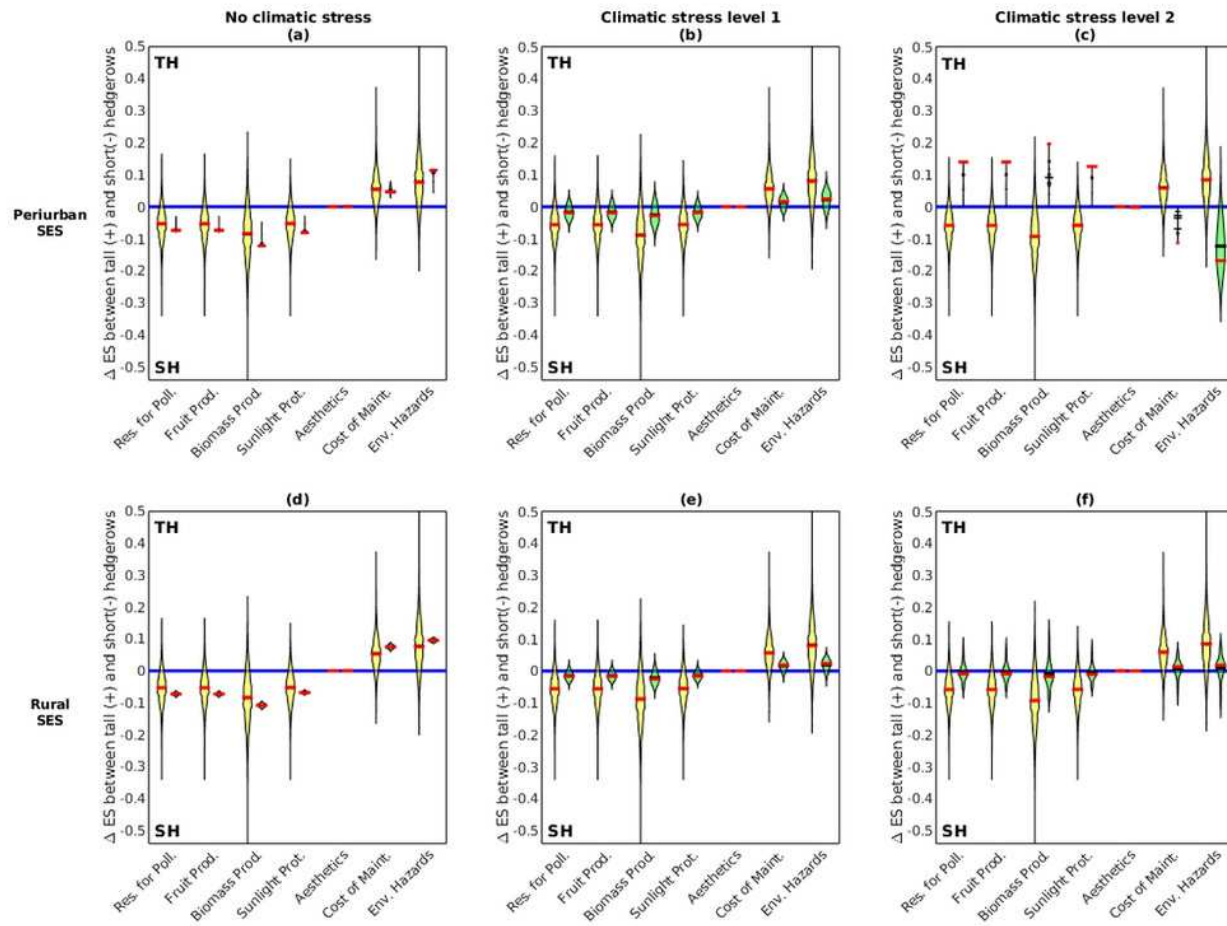
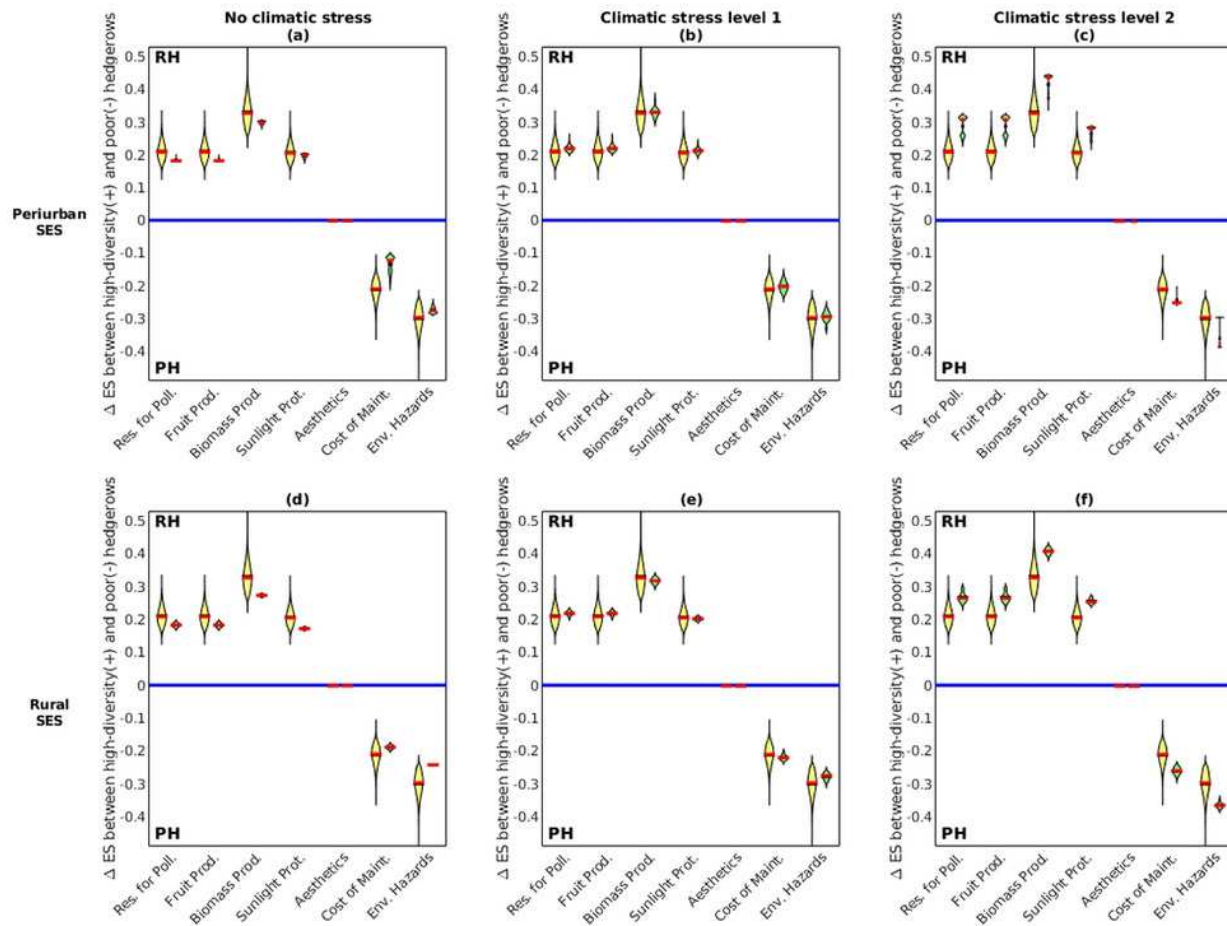





Figure 11


Security gains ΔES_{RH-PH} relative to the limits of the ES satisfactory domain


Security gains ΔES_{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 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 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.




PeerJ



Jean-Baptiste Pichancourt

New submission

Submissions

Status: **Awaiting resubmission**

Type: **Research Article**

Journal: **PeerJ**

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

Overview

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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

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

[illegible]

SECTION

Environmental Science

SUBJECTS

BiodiversityEcologyMathematical BiologyCoupled Natural and Human
SystemsNatural Resource Management

KEYWORDS

Social-Ecological System
(SES) Agroecosystem Hedgerows Biodiversity Ecosystem Services SES
Analysis Robustness Framework Complex Dynamical System Viability
Theory Adaptation 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 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.

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

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Last 36 months (excludes rejected/withdrawn):

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Antoine Brias

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Table.1.PEERJ.odt

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[TABLE \(169KB\)](#)

2nd 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 2nd tier attributes are decomposed into three 3rd 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 3rd tier attributes are extended to account for the directional influences of one 3rd tier attribute on the other, or also the resource system (RS). † indicates the decomposition of the 3rd tier attributes the following 4th tier attributes: Operational-choice arrangement (OCA), Collective-choice arrangement (KCA), Constitutional-choice arrangements (CCA). The 3rd and 4th-tier analyses of the study area are presented in Supplementary S1.

Table.2.PEERJ.odt

8578c048eb2b02a213acbcfb18a5b867d97e0ecb

[TABLE \(115KB\)](#)

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, constraints, 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 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.

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 → d). Arrows labeled with bold numbers (1a → b to 6a → 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 → 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^+ and disservices (ES^-) when selecting the most optimal adaptation pathway aiming to either maximizing ES^+ or minimizing ES^- , as listed in the labels. For instance, panel (a) reads as the maximized ES^+ is resource for pollinators (prominent trend line) and the other ES^+/ES^- 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).

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 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

Figure.10.pdf

7ee5a5a9809ead34972840173f1aba67bf7b96d5

[FIGURE \(333KB\)](#)

Security gains ΔES_{TH-SH} relative to the limits of the ES satisfactory domain

Security gains ΔES_{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, $\Delta ES_{TH-SH} > 0$ 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 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.

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[FIGURE \(286KB\)](#)

Security gains ΔES_{RH-PH} relative to the limits of the ES satisfactory domain

Security gains ΔES_{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 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 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.

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