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Multi-level policies and adaptive social networks – a conceptual modeling study for maintaining a polycentric governance system

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Abstract: Information and collaboration patterns embedded in social networks play key roles in multilevel and polycentric modes of governance. However, modeling the dynamics of such social networks in multilevel settings has been seldom addressed in the literature. Here we use an adaptive social network model to elaborate the interplay between a central and a local government in order to maintain a polycentric governance. More specifically, our analysis explores in what ways specific policy choices made by a central agent affect the features of an emerging social network composed of local organizations and local users. Using two types of stylized policies, adaptive co-management and adaptive one-level management, we focus on the benefits of multi-level adaptive cooperation for network management. Our analysis uses viability theory to explore and to quantify the ability of these policies to achieve specific network properties. Viability theory gives the family of policies that enables maintaining the polycentric governance unlike optimal control that gives a unique blueprint. We found that the viability of the policies can change dramatically depending on the goals and features of the social network. For some social networks, we also found a very large difference between the viability of the adaptive one-level management and adaptive co-management policies. However, results also show that adaptive co-management doesn't always provide benefits. Hence, we argue that applying viability theory to governance networks can help policy design by analyzing the trade-off between the costs of adaptive co-management and the benefits associated with its ability to maintain desirable social network properties in a polycentric governance framework.

Keywords: Adaptive co-management, adaptive social network, polycentric governance, viability framework

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1. Introduction

In what ways does the interplay between central and local governments affect the features of multilevel social networks? As we will elaborate below, this is one of the most crucial questions in current discussions about the benefits and drawbacks of polycentric governance (Giest and Howlett 2014; Schoon et al. 2015).

Ostrom et al. (1961) pioneered the theoretical concept of polycentric governance for addressing the issues of organizing co-operation among multiple levels of government. Polycentric systems are characterized by several governing authorities (rather than a monocentric unit), featuring multiple and overlapping jurisdictions at different scales (Ostrom 2010; Koontz et al. 2015; Schoon et al. 2015). It has been proposed that these types of systems are well-suited for the governance of dynamic natural resources due to their adaptability and capacities for self-organization and learning (Folke et al. 2005; Andersson and Ostrom 2008).

Despite advances in our understanding of the emergence and impacts of multilevel linkages in polycentric governance (Hooghe and Marks 2003; Cash et al. 2006), the role of social networks in these multilevel governance settings remain unclear. For example, it has been repeatedly been proposed that the policies implemented by a central agent (such as a national government) are likely to affect the evolution and the features of local organizations and networks (e.g. Ostrom 1990; Scharpf 1997). Some scholars have explored the issue based on case studies (e.g. Cash et al. 2006; Pahl-Wostl 2009; McGinnis 2011; Galaz et al. 2016).

The strength of formal modeling approaches such as the one used here, is that they can provide complementary and more precise theoretical insights (c.f. Morton 1999). More precisely, the current paper is dedicated to highlight conditions for which polycentric governance is maintained by addressing the following specific issues with our formal model:

- How to determine cases for which the social network dynamics can be influenced? We will identify the properties of the social network – i.e. the creation and removal rates of nodes and links – for which there exists (or does not exist) efficient policies for preserving the polycentricity of our governance system;

- How to determine when co-management is necessary? We seek to identify cases for which co-management is efficient when a single level of government fails as well as cases for which co-management is not necessary in order to maintain the polycentric governance system;
- How to quantify the importance of monitoring for successfully adapting the current policy to the state of the network? In our formal modeling, we will focus on the necessary time between monitoring the system and changing the policy according to the density of nodes and links of the network and the impact on the polycentric governance.

The aim is therefore to address these issues not only in a qualitative way (as done by many studies in the literature) but also in a quantitative way with our formal model by using a simple social network model.

For this purpose, we use the conceptual framework on decentralized resource governance from a polycentric view described by Andersson and Ostrom (2008) and Ostrom (2009) (see Figure 1). The framework focuses on the dynamics of the local social system including local resource users and local governments such as municipalities. Here local government organizations (say, water user associations) and local users (e.g. farmers) interact with each other, at times working towards a common goal such as preserving the water quality of adjacent rivers or lakes.

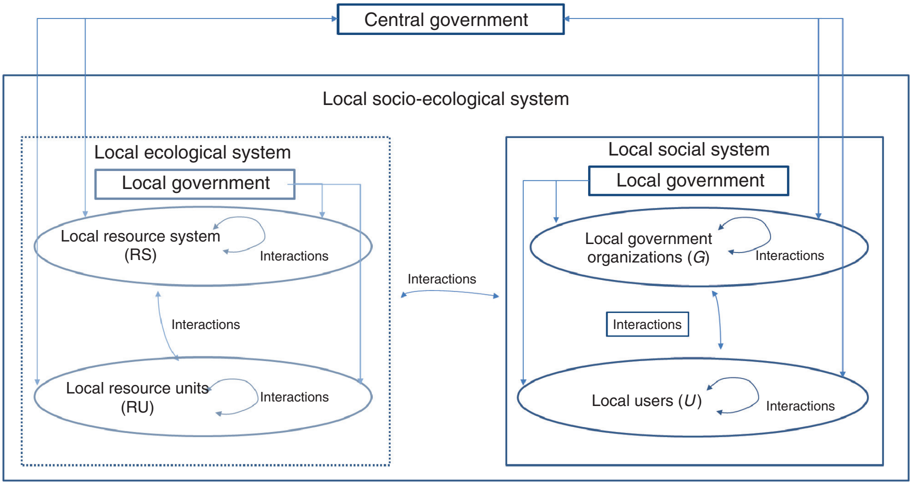

Figure 1: Conceptual framework for decentralized resource governance in a polycentric governance setting, based on (Andersson and Ostrom 2008) and (Ostrom 2009). Central and local governments as well as local government organizations and the local users interact. The current study only focuses on the social system of the SES (right side of this diagram).

Managing a network for preserving a polycentric governance can addressed in different ways. Managing a system to achieve an optimal state entails considerable risks, as shown by the literature on social-ecological systems (e.g. Gunderson 1999). While optimization might provide short-term benefits, it can also lead to loss of resilience and large-scale collapse of the system of interest (Carpenter et al. 2015). Hence rather than optimizing a given objective, managing SES within a range of acceptable outcomes might be preferable (Johnson 1999). In our context, we express the polycentricity of the governance system as acceptable boundaries represented by acceptable densities of nodes and links: we seek to manage our polycentric system within these acceptable boundaries instead of optimizing the polycentric properties of the governance system. For this purpose, we argue that viability theory (Aubin 1991; Rougé et al. 2013) is relevant to understand how stylized policies can result in "acceptable" ranges of social network properties rather than an "optimal" and vulnerable social network. Viability theory computes viable states of the network according to the different policy options: if a state of the network is considered as viable, it means there is at least a policy that maintains the desirable social network properties reflecting the polycentric features of the governance. On the other hand, if a state of the network is not viable, it means that there is no policy option for preserving the polycentric governance represented by the network properties.

More specifically, viability theory is used as a method to compare the strengths and weaknesses of two different stylized policy models. More specifically we explore in what ways central policies affect social network properties at the local level. The first model only has one adaptive administrative level. We call this model "adaptive one-level" (AOL) policy. The second stylized model is also adaptive, but adds one additional level of collaboration here called "adaptive co-management" (ACM) policy. These two models hence display two alternative policies – one where central policy-makers maintain a higher degree of decision-making power, and one where this power is decentralized. In addition, we underline that both policies are adaptive: decisions are taken according to the states of the system. We then explore the impacts of different social network parameters on the efficiency of the polycentric system. We use the model to ask: i) How does the evolving network affect the properties of the system from a polycentric perspective? and ii) Are there any qualitative differences in benefits between the two stylized policies from a social network perspective?

We present in the first section the theoretical framework used in this paper. This theoretical framework is based on both adaptive networks and viability theory. Then we present the results in the second section before discussing implications for network management for maintaining a polycentric governance in a last section.

2. Theoretical framework for maintaining polycentric governance

In this section, we introduce a network-based approach for conceptualizing governance systems and then for making explicit the problem of maintaining a polycentric governance as a viability problem. Network-based approaches have been broadly used in the literature for modeling the dynamics of social interactions, such as “small world” or “scale free” models (Watts and Strogatz 1998; Barabási and Albert 1999). The purpose here is to develop a suitable adaptive network model adapted to our polycentric governance problem.

2.1. Network structure of the local social system

We consider a resource being governed and exogenous of our model; this resource may be water as well as forest or a fishery. As a means to model the interactions between the users of this resource and organizations, we place our study in the general context of dynamical social networks (c.f. Ansell 2006; Janssen et al. 2006; Bodin and Crona 2009). In our case, the nodes consist of local government organizations and local actors linked through social links (see next section for more details). As a way to explore how these networks change and evolve, nodes and edges are not always active and governments may adapt their policies according to changing circumstances. For instance, an environmental disaster (such as an oil spill) will lead central agents to actively connect or create nodes and edges in social networks (through e.g. government subsidies, or policy changes) in order to increase the flow of information between social actors (as explained by crisis scholars such as Moynihan 2008). These processes are highly dynamic as these connections in turn influence how members of the network communicate, share management strategies, and shape the future evolution of the network. Inspired by Ostrom (2009), we use two types of social nodes (see Figure 2):

- local government organizations (denoted G): several local government organizations are implemented in a region. The number of local government organizations is denoted N_G;
- local users (denoted U): local users consume the natural resources. The number of the local users is denoted N_U.

In network theory, links in the adaptive network will represent the processes by which the nodes (i.e. users and organizations) interact through e.g. information sharing. In what follows, we focus only on the links between the local users and the local government organizations and their density D_{UG}. The emergence (and the dynamics) of such links is a key issue for polycentric governance, especially in multilevel settings (Olsson et al. 2004, 2006). In our model, links correspond to relationships and interactions through information sharing, interactions between actors, and flows of economic resources. As the literature shows, the creation of partnerships can help the emergence of new relationships and interactions (Schneider et al. 2003; Lubell 2015) between local users and local government organizations yielding substantial benefits for local “common-pool resource” problems (Ostrom 1990; Lubell et al. 2002). Such collaborative partnerships are successfully effective if actors are committed, and if they expect to extract benefits

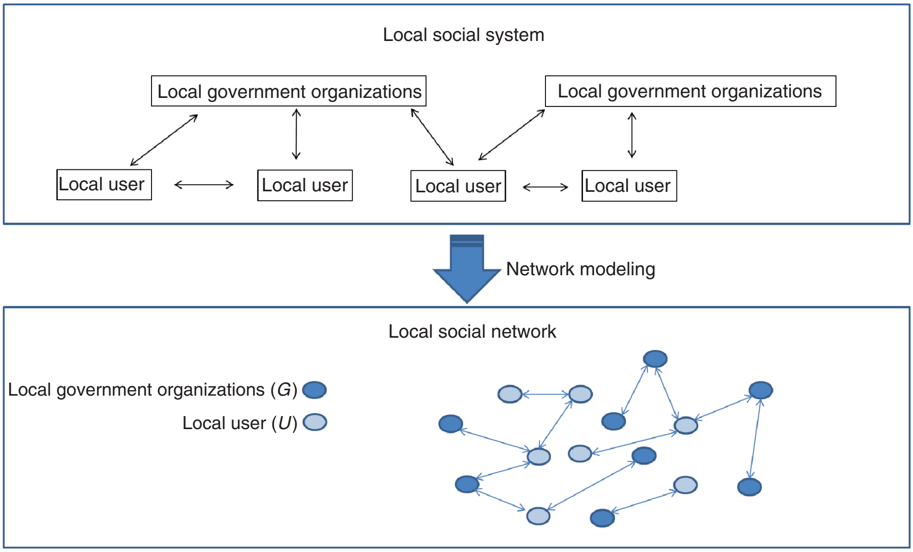

Figure 2: Definition of 2-level adaptive networks, inspired by (Ostrom et al. 2007). We assume that the local system can be modeled using a simple social network composed of local government organizations and local users.

from these collaborations (Klijn et al. 1995). The outcomes of the interactions in these networks are at best effective information sharing, deliberation processes that build trust, and/or lobbying activities (Ostrom 2009). These links have been proposed to increase the availability of information and the credibility of commitments of actors and finally favor policy agreements (Schneider et al. 2003).

Here, we assume that actions taken by the national and local governments change the structure of the network. In real terms, this can be done by financially supporting collaboration platforms thereby increasing information links, designing new policies which make collaborations more or less beneficial (e.g. through taxes), or by shifts in perceptions such as an increased sense of urgency (Koppenjan and Klijn 2004; Olsson et al. 2006).

Acting through social networks, such as partnerships and local associations, is a key aspect of modern governance. Central and local governments may foster or undermine the creation of links between local users and local government organizations, and may even if considered necessary contribute to increase the number of the local government organizations. An example of this is the adoption of the European Water Framework Directive that urges participating states to consider the work assumed by a diverse set of water user associations and organizations (Muxika et al. 2007).

We assume that such policies for promoting social interactions are associated with costs. The efforts of the central government for creating new nodes are denoted e_1^N and the efforts of the central government for creating new links are denoted e_1^L . For instance, these efforts may focus on the creation of new local organizations for preserving ecosystems (creation of nodes) and they may also promote the partnership between local users and these local organizations (creation of links). However, the efforts might be limited by economic reasons (such as limited subsidies) or by other reasons (such as limited information activities).

Moreover, local government also develops policies for fostering creation of new nodes and links. Therefore, we also consider the efforts of the local government for creating new nodes (denoted e_2^N) and the efforts of the local government for creating new links (denoted e_2^L). We also consider vertical connections between the central government and local government (e.g. Ruitenbeek and Cartier 2001; Folke et al. 2002; Olsson et al. 2004; Berkes 2009). These vertical connections are explored in detail in the next section.

A final assumption is that the local government and the central government are engaged in dynamical learning: they know the state of the system (through monitoring), and they know how the system responds according to different policy scenario (learning). However, we only consider a single loop between the outcomes and the governance as illustrated in Figure 3. All learning levels (from action level to governance level) are merged in the analysis for the sake of simplicity.

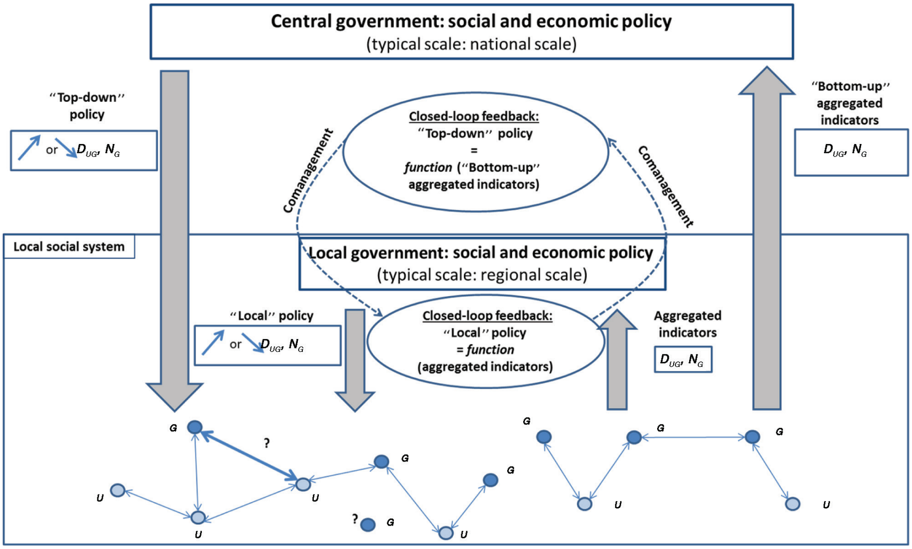

Figure 3: Polycentric governance system including a 2-scale adaptive network. We assume that the central and the local governments can foster or undermine the presence of nodes and links between the local users and the local government organizations according to aggregated indicators of the network (the node and link densities for instance).

2.2. Maintaining a polycentric governance: a viability problem

Government actors in our model have goals they want to achieve and therefore also have preferences about the evolving network structure in order to preserve polycentric governance. What constitutes "desirable" network properties is a normative question (Armitage et al. 2008), because it closely depends on the system studied. Here we define it as network properties that are able to preserve the polycentric character of the system. For maintaining the polycentricity of the system, we use the node and link densities as indicators and we define suitable ranges from which the node and link densities have to stay, under an associated budget. That is, government actors seek:

- to keep the density of local government organizations N_G within a specific range: the density of local government organizations N_G (with respect to the number of local users) influences their ability to interact and exchange information with local users. In the meantime, new local government organizations lead to new operating costs and maintenance costs. We therefore limit the number of local government organizations too;
- and to obtain a minimum density of links D_{UG} between local users and local government organizations. The density of links D_{UG} between the local users and the local government organizations enables them to interact for sharing information or developing activities;
- not to exceed a given budget: maintaining and developing the network structure involves costs. Their capacity to maintain and create nodes and links is limited by an overall budget.

Therefore, maintaining a polycentric governance system means here satisfying constraints defined by network metrics, which is a viability problem mathematically defined by the viability theory (e.g. Aubin 1991; Rougé et al. 2013; Brias et al. 2016; Mathias et al. 2017). This theory enables us to explore issues such as these as it allows an elaboration of network properties in a given polycentric system. Indeed, we aim at assessing all viable policies (for avoiding a unique blueprint) that satisfy polycentric constraints. In practice, the viable states of the network are the states for which there is at least a (local and central) policy such that the social network keeps the desirable properties. In these states, an adaptive multilevel polycentric system is maintained (e.g. Folke et al. 2005). These viable states are also associated with policies that adapt according to the state of the network. These enable governments to adapt their policies according to the information received from monitoring efforts. Our goal is to find these viable policies (not necessarily 'optimal' according to a certain criterion) that indefinitely will maintain the network in desirable states. It will give a family of viable options which give more flexibility to decision-makers for facing exogenous drivers.

This theory was used in previous works for tackling several environmental management issues for the fisheries management (Cury et al. 2005) or for managing uneven-aged forest (Mathias et al. 2015). Viability theory requires: 1) the definition of the properties of interest we want to preserve; 2) indicators or state variables that model these properties; 3) defining acceptable outcomes instead of defining optimal objectives. The outcomes are: 1) the viable policies that enable to preserve the properties of interest and 2) the viable states from which there exists at least one viable policy.

To assess these outcomes, the viability framework needs inputs that are closely related to the governance framework used such as the parameters of network dynamics or the monitoring-learning-responding time of central and local governments for instance (see Table 1). Figure 4 illustrates the different concepts used for defining these inputs and outcomes (Table 2). Mathematical details

Table 1: Description of the variables used in the current conceptual model.

Name	Type	Description	Value
N_G	State variable	Number of the local government organizations. We want to conserve this value between a minimum and a maximum value	[0.3;1]
D_{UG}	State variable	Link density between the local government organizations and the local users. We want to conserve a minimum value. Note that the value is limited to 1 by definition	[0.5;1]
e_1^N	Policy variable	Effort of the central government for promoting the creation of the local government organizations	[0;0.5]
e_1^L	Policy variable	Effort of the central government for promoting the creation of links between the local government organizations and the local users	[0;0.5]
c_1	Policy variable	Limit of the total efforts of the central government $(e_1^N + e_1^L < c_1)$	[0;0.5]
e_2^N	Policy variable	Effort of the local government for promoting the creation of the local government organizations	[0;0.5]
e_2^L	Policy variable	Effort of the local government for promoting the creation of links between the local government organizations and the local users	[0;0.5]
c_2	Policy variable	Limit of the total efforts of the local government $(e_2^N + e_2^L < c_2)$	[0;0.5]
c	Policy and state variable	Limit of the total efforts of the central and the local governments $(c_1 + c_2)$	[0;1]
u_c	Policy variable	Variation of the limit of the total efforts	[−0.1;0.1]
Δ_t	Policy variable	Monitoring-learning-responding time: time necessary to change the policy	1
γ_N	Model parameter	Probability to have a new node	0.2
α_N	Model parameter	Probability to remove a node	0.1
γ_L	Model parameter	Probability to have a new link	0.3
α_L	Model parameter	Probability to remove a link	0.1

A state variable is a variable which is monitored and used for defining the network properties of interest. A policy variable is defined by either the central government or the local government. The model parameters are the intrinsic variables of the network dynamics.

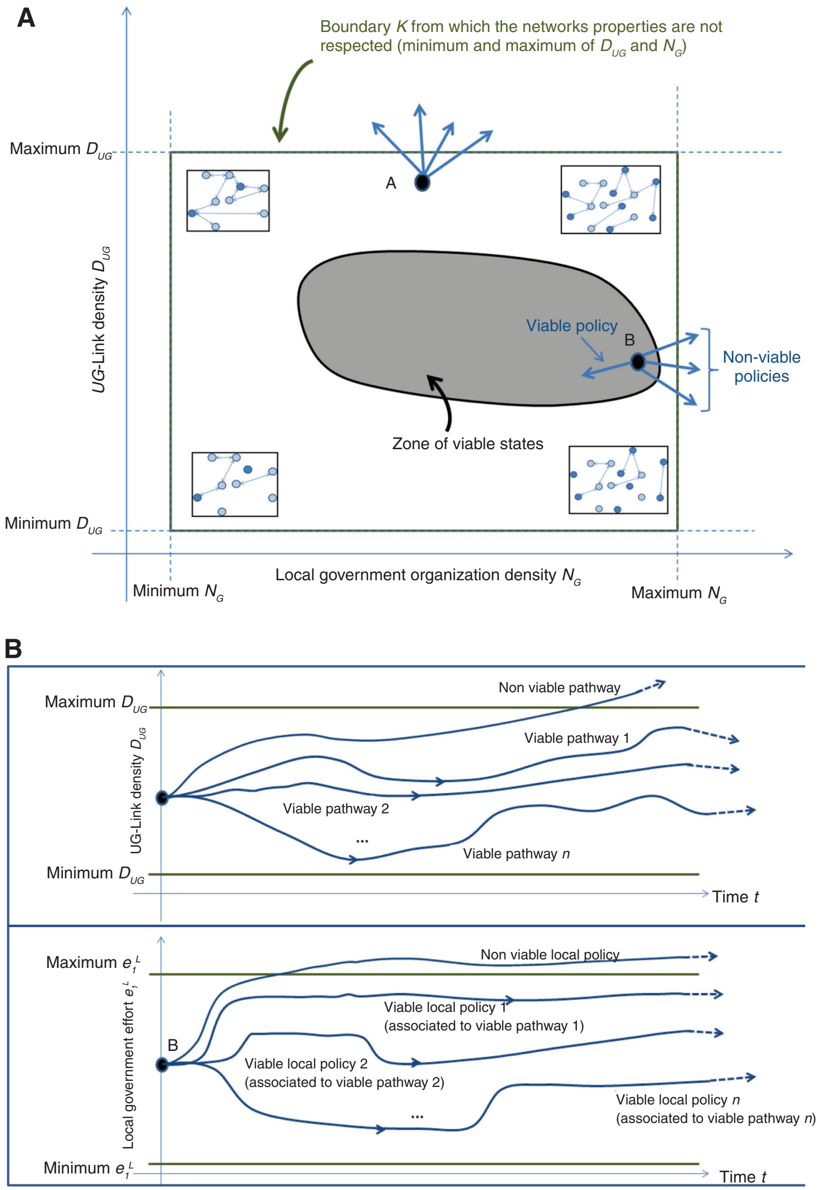

Figure 4: Calculation of the viable states. We delimit the properties of the network we want to keep (modeled by the boundary K). Four network examples are also represented for illustrating the properties of interest. The zone of the viable states (the gray zone) corresponds to the zone where there exists at least one policy for keeping the properties of the network. In point A, there is no policy that keeps the network properties. In point B, there is at least one policy that ensures to keep them. This policy is called viable policy. (A) Schematic representation of the viable states. (B) Example of viable dynamics of the link density and of the local policy.

Table 2: Description of the inputs and outcomes used in the viability approach, in the case of social network.

Inputs: governance issues	Outcomes: policy features
Desired properties of the network: maintaining link density and the number of local government organizations (green box in Figure 4A)	Viable states: Network states that enable keeping a polycentric system (gray zone in Figure 4A)
Dynamics of network: dynamics of links and nodes are described in Eq. (1) and (2)	Viable pathways: dynamics of the network for which the properties are preserved (Figure 4B).
Available policies (or policy options): Policies may depend on the state of the network (see blue arrows in Figure 4A).	Viable policies: government policies associated to the viable pathways (Figure 4B)

See also Figure 4 for more details.

about the calculation of the viable states and the viable policies are available in Appendix 1. Once the viable states have been calculated, we have gained access to all viable pathways of the network states. However, in order to use this mathematical theory, we need a dynamical controlled model of the network structure which is the purpose of the next section.

2.3. Changing adaptive network structure

To investigate the dynamics of the resulting governance network, we constructed a simple model of how the network structure might change over time. The approach here consists in using an aggregated model of the social network. Aggregated models capture the dynamics of a random network subjected to the processes detailed in previous section (creation of nodes/links etc…). The interest of having such aggregated model is that 1) it captures the results of an ABM [i.e. we will have the same results with an ABM, see for instance (Bonté et al. 2012)] and 2) it clearly highlights the dynamical parameters in the aggregated equation; 3) there is no stochasticity because it represents a mean field approximation of an ABM (it is not necessary to carry out a high number of replicates). Another issue is that we can apply mathematical tools based on differential equations (such as viability theory) for defining management strategy, which is not possible (or more tricky) with ABM. All variables used in the following are summarized in Table 1. Equations are written in dimensionless units for the sake of simplicity and the dimensions have been normalized in order to keep the values between 0 and 1. We seek to model two key features of the network: the number of local government organizations N_G and the density of links D_{UG} between resource users and local government organizations. We choose a constant number of local users $N_U = 1$ corresponding to a reference density.

Local government organizations, in the adaptive network framework, can change in number over time. As explained above, the efforts of central and local governments (e_1^N and e_2^N) can create new nodes. We consider γ_N the rate per unit effort of local government for creating new local organizations. The nodes vanish at rate α_N: some local organizations are removed every year due to high operating costs or reassignment of spending for example. This leads to the following dynamics for the node density N_G:

$$\frac{dN_G}{dt} = (e_1^N + e_2^N)\gamma_N - \alpha_N N_G \tag{1}$$

Similarly, local and central governments create links between resource users and local governments through efforts e_1^L and e_2^L respectively. These efforts lead to link creation between users and local government at a rate γ_L per unit of effort. In our model, we do not identify which actors these new links involve, but rather model the total density of links. Links are also removed at a rate α_L: links between resource users and local organizations can vanish because of for example changes in farmland ownership or in local organizations (reassignment of agents). Writing in terms of the density of links D_{UG} yields:

$$\frac{dD_{UG}}{dt} = -\alpha_L D_{UG} + (e_1^L + e_2^L)\gamma_L(1 - D_{UG}) - \frac{D_{UG}}{N_G}(e_1^N + e_2^N)\gamma_N \tag{2}$$

The link density D_{UG} is 0 when there are no links between users and organizations, and is equal to 1 when all users are connected with all organizations. We see that the creation of nodes decreases the mean density of links (see last term of Equation 2) if no efforts are made for the creation of links in the same time (second right-term of this equation). It highlights the necessity to balance between node creation and link creation of existing nodes.

2.4. The cost of network management

Developing and maintaining networks is constrained by costs. Federalism (such as in the USA) is a typical example for which costs are significant because of the creation of vertical links between levels of the federal system and horizontal links between local organization (Schneider et al. 2003). The key-issue relies in a trade-off between the transaction costs (for developing and maintaining networks) and the benefits of the partnerships (Lubell et al. 2002). In what follows, we consider that the local and central governments are constrained in achieving these goals by their budgets, b_1 and b_2, respectively. Their total expenditures cannot exceed these budgets: $e_1^N + e_1^L < b_1$ and $e_2^N + e_2^L < b_2$. It means that, in the network dynamics, we include all costs (transaction costs as well as creation of new organizations) in the efforts $(e_1^N, e_1^L, e_2^N, e_2^L)$, limited by b_1 and b_2. Although we acknowledge that creating and maintaining networks involve a lot of social processes (such as beliefs, values, trusts etc…), we limit our study to these costs in this first attempt of formalization.

Central and local governments are limited to the same total budgets at each point in time $[b_1(t) = b_2(t)]$. The total available budget (denoted b) represents the

Table 3: Description of reference policy scenarios.

Scenario name	Description	Parameter values
No adaptive policy	Central and local policies are constant over time	$e_2^N = e_2^L$ = constant values $e_1^N = e_1^L$ = constant values
Adaptive one-level (AOL) policy	Efforts by central government are adaptive. Those of the local government are constant over time	$e_2^N = e_2^L$ = constant values e_1^N, e_1^L = variable values
Adaptive co-management (ACM) policy	The efforts of the central and the local governments are adaptive in an interactive way. They are conjointly managed	$e_1^N + e_2^N$ = variable values $e_1^L + e_2^L$ = variable values

sum of the budgets of the central and the local governments $(b = b_1 + b_2)$. Finally, we assume that the budgets of the central and local governments evolve in the same way $\left(\frac{db_1}{dt} = \frac{db_2}{dt}\right)$ yielding the evolution of the total budget $b(t)$ as follows:

$$\frac{db(t)}{dt} = u_b \tag{3}$$

with a minimum and a maximum value of u_b: the local and central governments have a limited capacity to change their budget allocated to their "social network" policy.

Governments can act on the social network by choosing a Δ_t-year strategy regarding their levels of expenditure. These can be adapted every Δ_t years. Δ_t corresponds to the time that governments have available for monitoring (yielding knowledge on the state of the network), learning (knowledge on the effect of the different policy options) and responding (decision to apply a new adequate policy). It consists of choosing a strategy the first year and then 'waiting' for the next Δ_t years in order to decide whether or not to change the policy (i.e. through monitoring and learning). This timeframe corresponds to a "monitoring-learning-responding" time.

2.5. Modeling stylized policies

We define the following reference scenarios (see Table 3) to explore the differences between the stylized policies benefits from a social network perspective:

- no adaptive policy scenario: central and the local governments policies do not evolve in time: they kept the same policy independently from the network state;

- adaptive one-level (AOL) policy scenario: central government efforts are adaptive depending on changes in network states. Local efforts are constant and not adaptive.[1]
- adaptive co-management (ACM) policy scenario: the efforts of the local and the central governments are adaptive in an interactive way: central and local governments are connected across levels and scales. It is important to note that central and local governments don't necessarily follow the same strategy especially when there is no benefits to cooperate yielding independent (and multiple) strategies.

The states of the network for which there are, at least, a central and a local policy (called viable policies) that preserve these properties are called 'viable states' in what follows. The higher the number of viable states is, the higher the viability of the governance system is.

3. Results

3.1. What are the initial states from which the polycentric governance can be achieved and maintained?

Using the parameters described in the previous section, we calculated the viable states of the network associated to each scenario defined above (see Appendix 1 for mathematical details). These viable states are represented in Figure 5 (blue points).

We recall that a viable state means that there is at least a strategy that enables to preserve the polycentric system. The number of viable states is also an important indicator: for a given policy, it means how this policy is flexible for maintaining our objectives. The number of viable states is simply represented by the kernel size. For the sake of clarity, the viable states are represented according to the density of local governments organizations (N_G), the density of 'local users – local government organization' link (D_{UG}) and the total budget b. In the case of the "no adaptive policy scenario" (Figure 5A), there are no viable states. That is, no strategy has been found that enables governments to maintain the network properties. This is due to the fact that chosen parameters yield a social network that does not comply with the properties of interest. However, in the case of the adaptive policy scenarios (AOL and ACM, Figure 5B and C), our results show viable states.

In the latter two cases, the number of viable states increases according to the total available budget. The higher the available budget is, the higher the viability of the network is. In addition, the network exhibits 71% of viable states for the AOL strategy against 86% for the ACM strategy. A part of the budget is fixed in

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[1] Note that considering the opposite case (constant central efforts and adaptive local efforts) will give similar results in our case due to the same limited capacity of acting of the governments;

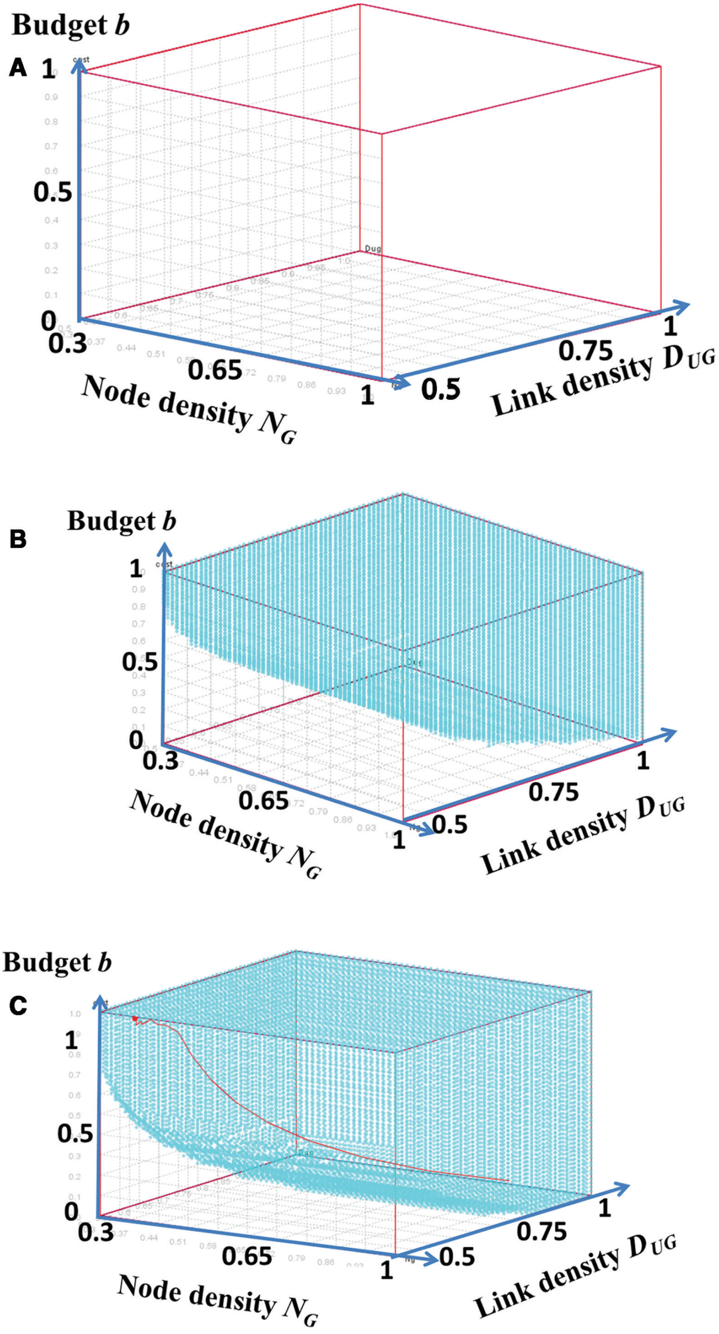

Figure 5: Viable states (blue points) of the network according to the reference scenarios. (A) No adaptive policy scenario (no viable states), (B) AOL scenario (71% of the network states are viable), and (C) ACM scenario (86% of the network states are viable).

the case of the AOL policy, which decreases the capacity of the governments to adapt their policies to changing circumstances (through monitoring and policy learning). In the ACM policy scenario, the local and the central governments are able to pool together their efforts for maintaining the network properties. This parallels wider insights in the governance literature about the complementary potential of multiple levels in network governance (e.g. Koppenjan and Klijn 2004; Duit and Galaz 2008).

To better understand these results, an example of the evolution of the network is represented in Figures 5C and 6. The initial network exhibits a high node density ($N_G = 0.9$) and a high link density ($D_{UG} = 0.9$) but presents few resources ($b = 0.1$). The challenge from the perspective of central policy makers is to maintain a polycentric network structure despite few available resources. In this case, a viable policy is possible in the case of the ACM scenario, but not in AOL scenario.

Why the ACM case (unlike the AOL case) yields a viable policy, can also be represented in Figure 5C. The evolution of the network follows the boundary of viable states, and then converges to a network with low values of node and link densities and a high value of the total budget. In this case, governments need high funds to maintain the network properties: the entire available budget is consumed. Note that away from the boundary of the viable states, not all the budget is necessarily consumed. The dynamics are more detailed in Figure 6. Here, the local and central governments jointly increase their budgets in order to reach this network state. Figure 7 shows the associated viable policy for explaining difference between the AOL and ACM scenarios. Initially for the ACM case, the local and the central governments don't put their efforts on node creation (i.e. the total node effort equals 0) in order to focus all efforts on creating links. This is not possible in the AOL scenario because parts of local government efforts are used for node creation initially. We recall that policies represented in Figures 6 and 7 are only ones among a family of policies. Here, for instance, node efforts oscillate around an equilibrium (policies may oscillate in the case of variable annual subventions for instance) as well as they can be constant.

3.2. How do network parameters affect the viability of the policies?

In what follows, the influences of the creation and removal rates of nodes and links ($\gamma_L, \gamma_N, \alpha_L, \alpha_N$) on the preservation of the polycentric properties are studied. Extreme values of these parameters are not expected to lead to significant differences between the ACM and AOL scenarios because whatever the type of policy cooperation, local and central governments will have a weak influence on the network evolution due to its own dynamics. If the node creation rate is high, no cooperation is necessary as well as the case of very low creation rate for which cooperation will be not sufficient for maintaining the polycentric properties of the network. However, we also expect the existence of cases where central and local governments are forced to adopt an ACM policy to preserve the desired network properties. Figure 8 presents the percentage of viable states for different parameter values for both policy scenarios.

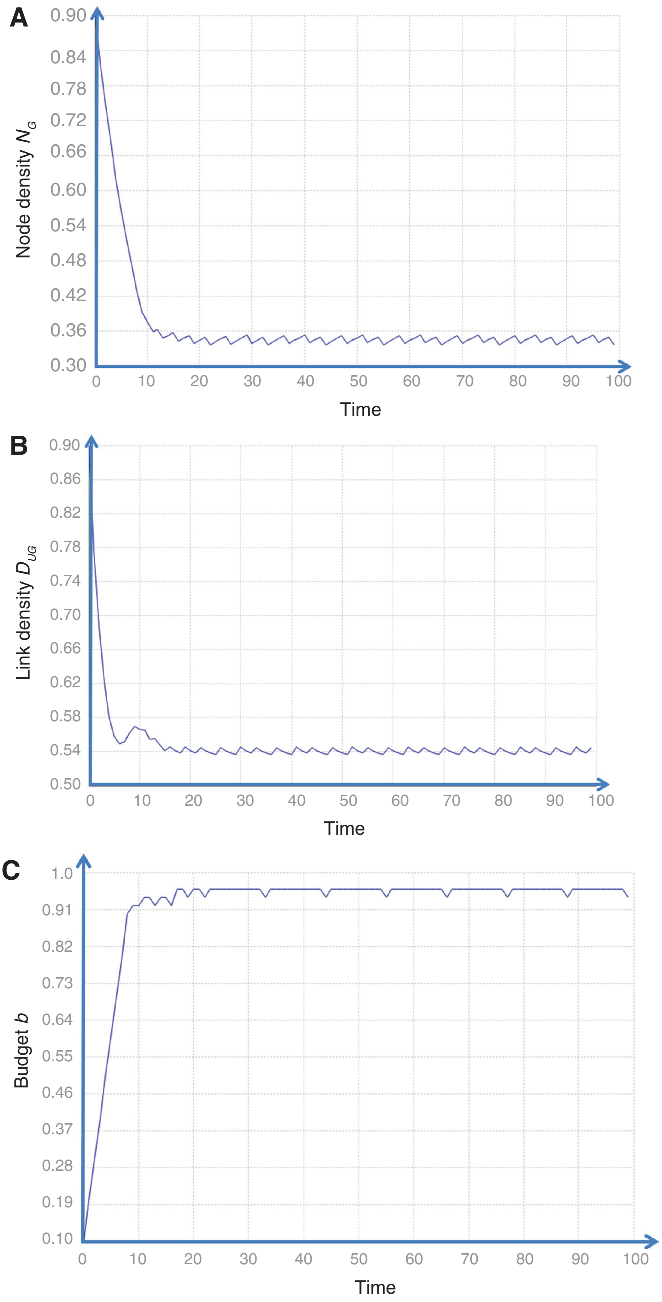

Figure 6: Example of viable dynamics of the network states using an ACM policy. Initial states are a node density equal to 0.9, a link density equal to 0.9 and a total available budget equal to 0.1. In this case, all available budgets are consumed. (A) Node dynamics, (B) link dynamics, and (C) budget dynamics.

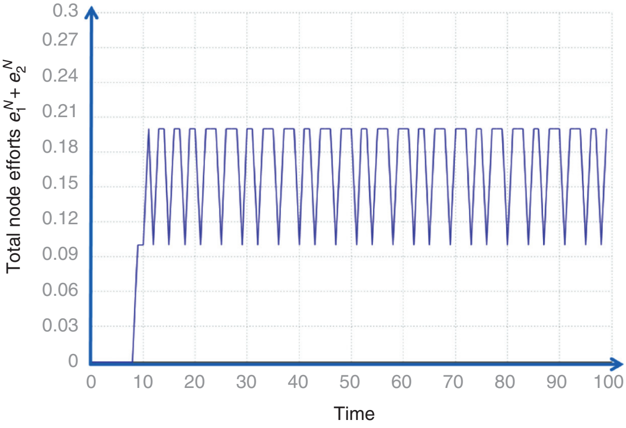

Figure 7: Viable policy: evolution of the total "node" effort $e_1^N + e_2^N$*. The total effort focus on the link creation at the beginning. Then, the total efforts oscillate around an equilibrium.*

The differences between both policies are significant when link creation and link removal rates are changed (γ_L and α_L). Indeed, the parameters of the link dynamics are such that they have a significant influence on the difference between both policies. This difference is most extreme when the link creation rate γ_L is 0.25 for which there is no viable state for the AOL case, whilst there are 77% of viable states for the ACM scenario. Even with when high levels of resources are available, local and the central governments are unable to pool together their resources in the AOL scenario thereby creating inefficient policies. On the other hand, when the tension largely decreases (the network tends naturally to preserve its properties), the difference between the AOL and ACM policies decreases: the cooperation between the local and central governments gives similar results than non-cooperative strategy in this case. The ACM scenario is less sensitive to link creation and removal (γ_L and α_L) because the two governments can compensate lack of investment of the other government on link creation (see Appendix 2 for more details).

However, the value of the node creation rate γ_N does not have a significant influence on both the ACM and AOL policies. The node efforts of the local and central governments may (partially) compensate a too low node creation: they are of the same order of magnitude. The value of the node removal rate α_N shows a higher influence but the difference between the ACM and the AOL policies reaches 15% of viable states unlike 77% in the case of the γ_L-influence.

3.3. How does the monitoring-learning-responding timeframe affect the viability of the policies?

The influence of the monitoring-learning-responding time Δ_t to change policy (see Figure 9) is explored below. As explained before, it corresponds to the time necessary for the local and central governments to monitor, learn and react. Actors may adapt their policies every Δ_t years. The number of viable states decreases in the same way for both the AOL and ACM scenarios. There is a loss of 25% of viable states between $\Delta_t = 1$ and $\Delta_t = 5$. Indeed, adapting policies to the perceived state of the network through monitoring and learning enables the governments to preserve desired network properties. This capacity to adapt may contribute to balance the lack of multilevel collaboration.

4. Implications for network management

4.1. Adaptive co-management is not always necessary

Determining situations for which cooperation between governments leads to substantial benefits constitutes a challenging issue for decision makers. Our nested

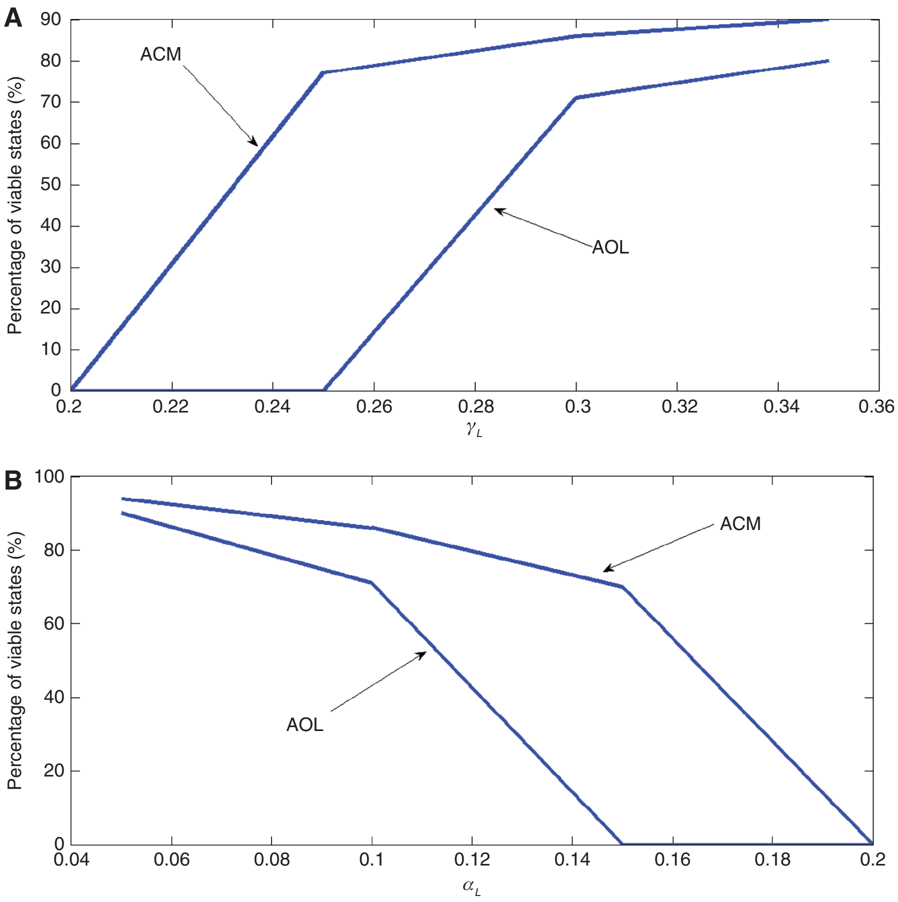

Figure 8: (continued)

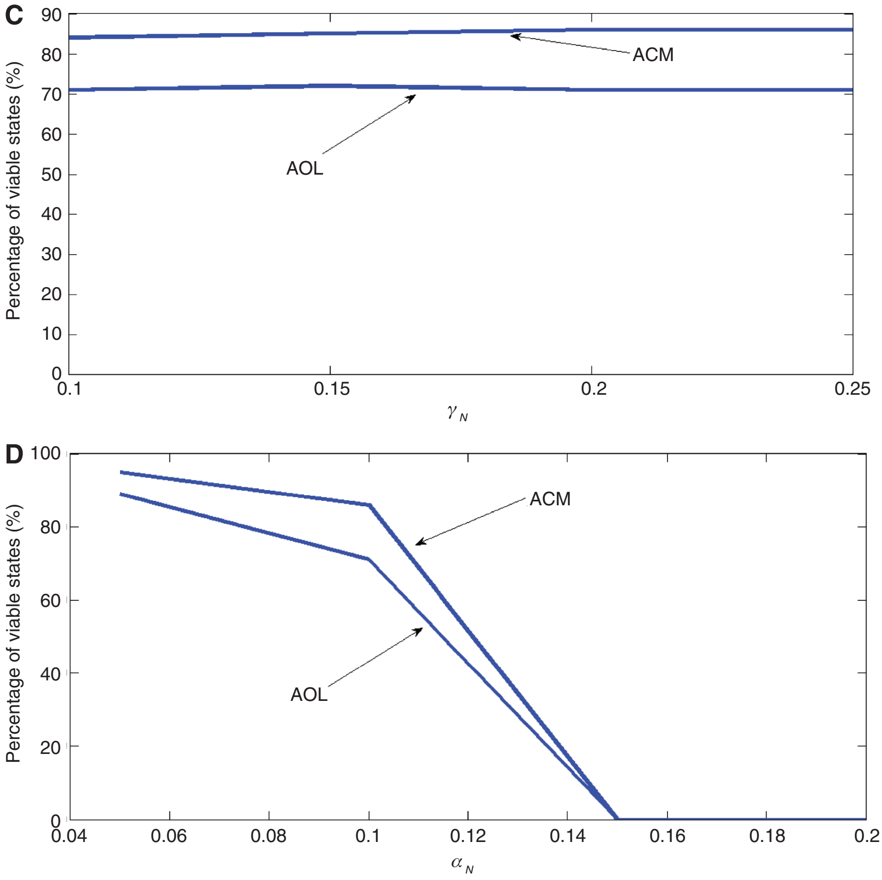

Figure 8: Percentage of states within the desired region that are viable according to scenarios and parameter values. AOL, adaptive one-level policy. ACM, adaptive co-management policy. (A) Influence of the link creation rate γ_L, (B) Influence of the link removal rate α_L, (C) Influence of the node creation rate γ_N, and (D) Influence of the node removal rate α_N.

conceptual model allows us to compare two stylized policies where central governments either maintain or decentralize decision-making power. Both strategies yield different results due to the level of cooperation. In some cases, local and central governments can maintain the desired network properties only with an ACM approach: for instance, our results show that ACM is required in the case of low creation of link ($\gamma_L = 0.25$). This clearly indicates that cooperation between central and local governments may yield to substantial benefits in order to preserve the polycentric properties of the system in this case. However, cooperation benefits clearly depend on both the acting capacity of the governments and on evolving network properties: if the acting capacity of governments has a limited influence

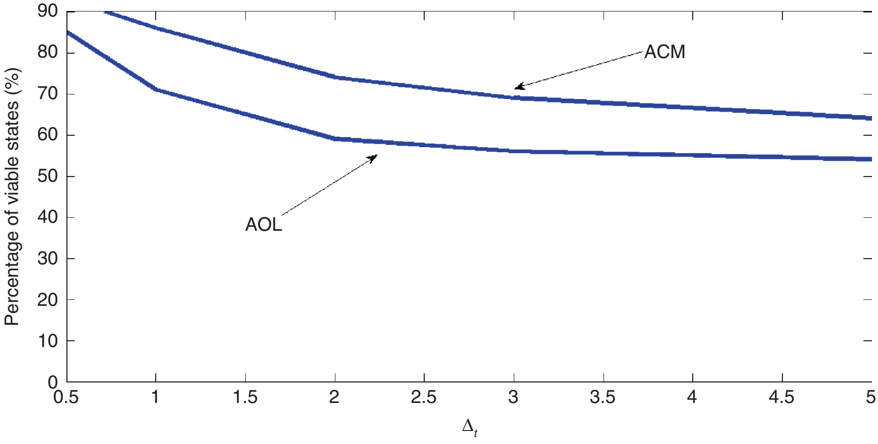

Figure 9: Percentage of viable states according to the monitoring-learning-responding time Δ_t *to change policy. AOL, adaptive one-level policy; ACM, adaptive co-management policy.*

on the network dynamics, cooperation between governments has a limited effect. For instance, in our case study, such cases correspond to social networks with a high node removal rate. In this case, cooperation between governments cannot counterbalance the node removal. On the other hand, there are many situations for which ACM does not gain benefits: both AOL and ACM policies are viable because there is no tension in terms of maintaining the polycentric governance. Identifying such cases constitutes a great challenge for both scholars and policy-makers in order to decide when it is useful to implement ACM policies. In addition, ACM and social networks completely interact: social networks constitute the most influential factor that contributes to success of ACM (Plummer et al. 2012) and social networks may favor ACM. The first approach we propose may help better understand these interactions between ACM and social networks.

4.2. Investing in network monitoring for reactive decision-making

Our conceptual approach also shows the need to integrate the network dynamics in the decision-making process in order to create social links "*at the right time, around the right issues*" and keep together modes of multilevel governance (Westley 2002; Olsson et al. 2004). Integrating the network dynamics requires monitoring and learning processes that constitute other key issues in polycentric governance. Monitoring and learning may help governments to take the right decision at the right time (Pahl-Wostl 2009) as they constitute one of the basis of adaptive co-management (Ruitenbeek and Cartier 2001; Folke et al. 2002; Olsson et al. 2004; Berkes 2009) and require interaction across levels (Armitage et al. 2008). Although we only considered learning from two indicators monitored (link and node densities), our results show that the efficiency of these monitoring and learning on the policy impacts clearly depends on the time necessary for governments to adapt their policy: the lower the value of this time is, the higher the viability of the governance system is. For instance, the model highlights that if we postpone the creation of links or nodes (we double the monitoring-learning-responding time for instance, see Figure 9), we lose 10% of viable states. In these cases, we can maintain the properties of the social network only with short-term responses showing the necessity to create the link (or the node) at the right time before the system evolves (dynamical system). However, monitoring could be difficult in practice, yielding to no policy adaptation. It may lead to a lack of learning and therefore may decrease the adaptive capacity of governments as it is the case in our example when the monitoring-learning-responding time is large. Here again, it is necessary to identify the trade-off between monitoring and its impact on the viability policies. For instance, the gain (in terms of viability) is more significant when we decrease small values of monitoring time Dt (see Figure 9).

4.3. Getting flexibility for mitigating exogenous drivers

Once cooperation is well established, the policies decided by governments may not be viable due to hazards and surprises (Gunderson 1999). In order to cope with such hazards, we argue that governments must have different policy options instead of a unique policy optimized according a given criterion to, such as an economic objective for instance. The viability approach used in this paper may tackle this issue by offering not only the viable states but also all the viable policies associated to these viable states. Having access to all viable policies (and not only one) may contribute to increase adaptive capacity and flexibility of governments and enable them to face to exogenous stresses (Mathias et al. 2015). In the viability set, there are several options for decision-makers yielding this flexibility: there is not a unique blueprint like optimal decision but a diversity of solutions (such as Figure 7 that shows an example of viable policy among all available viable policies). In case of exogenous stresses, if the system stays within the viability set, we know that we have different options in order to preserve polycentric properties. However, if stresses push the system outside of the viability set, there is no strategy that guarantees to keep polycentric properties. Finally, we argue that this first attempt of mathematical formalization is a first step towards integrating node-link models of institutions in the design of efficient multi-level policies for the management of socio-ecological systems.

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Appendix 1 Mathematical basis of the viability approach: the viability theory

The viability theory aims to preserve some qualities of a dynamical system that evolves in a set of desired states symbolized by K (Aubin 1991). In the viability framework, an important innovation is to introduce controls to explicitly account for the possibility to act on the system: controls are not fixed beforehand. Indeed, the purpose is to find suitable strategies that will maintain indefinitely the properties of our social network within K (see Figure 4). In discrete time, this means that at each time step, there is a set of possible controls that one must choose from. Noting in general $x_t \in X$ the state of the system at date t and $u_t \in U$ its controls, a typical controlled discrete-time dynamical system can be written as:

$$x_{t+1} = g(x_t, u_t)$$

u_t is a vector that may contain several control variables. One objective of the viability theory is to determine which are the desirable states of the social network for which the dynamics can keep the network properties indefinitively. This objective to keep relevant network properties is achieved through control strategies u_t. A strategy can be represented by a function which associates a control u_t to any date t and to any state x. These controls are, in our case, based on the efforts of governments for creating nodes and links. The set of all the states for which there is, at least, a control strategy such that the system can be maintained indefinitively inside the set of desirable states is called the ‘viability set’ or the ‘viability kernel’ *Viab*(K). The viability kernel *Viab*(K) is composed of all initial states of the network for which there is at least a sequence of action policies u_t which influences the evolution of x_t at time t and allows the system to stay within this same viability kernel. In discrete time, it can be formally defined as the set of initial states for which there exists a trajectory that does not leave K:

$$Viab(K) = \left\{ x_0 \in K \mid \forall t > 0,\ \exists f,\ \forall t \geq 0,\ x_t = g_f(t, x_0) \in K \right\}$$

Within the viability kernel, the system is maintained in a desirable for so long as it is not disturbed: it is the set of all the viable states. The computation of a viability kernel also yields the set of controls which maintain the system, which are called the viable controls. Thus, it incorporates the impacts of management policies, and implicitly optimizes them. For the calculation, the Saint-Pierre’s algorithm has been used (Saint-Pierre 1994).

Appendix 2 Influence of the link creation rate γ_L

The lower the value is, the higher the tension becomes. Indeed, when this value decreases governments have to report their efforts of the link creation in order

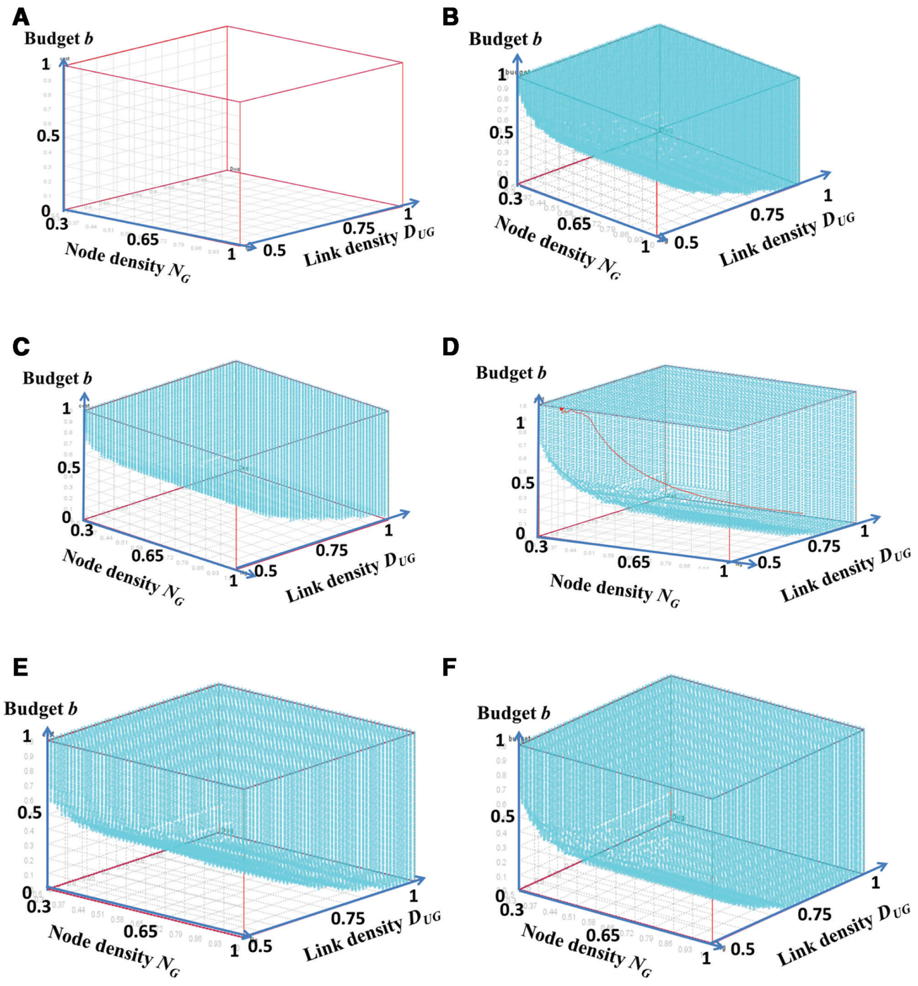

Figure 10: Viable states according to scenarii and γ_L. AOL, adaptive one-level policy; ACM, adaptive co-management policy. (A) AOL (0% of viable states), $\gamma_L = 0.25$, (B) ACM (77% of viable states), $\gamma_L = 0.25$, (C) AOL (71% of viable states), $\gamma_L = 0.3$, (D) ACM (86% of viable states), $\gamma_L = 0.3$, (E) AOL (80% of viable states), $\gamma_L = 0.35$, and (F) ACM (90% of viable states), $\gamma_L = 0.35$.

to preserve the network properties (in terms of link density). Figure 10 presents viability kernels for different values of γ_L and for both types of management.

For $\gamma_L = 0.25$, there is no strategy for preserving the link density in the case of AOL policy scenario. Indeed, in this case, the tension is too important even in the case of high budget for the AOL strategy: only an ACM strategy enables to maintain the properties of the network. Then, when the tension decreases, the difference between the AOL and the ACM policies decreases too in terms of number of viable states.