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

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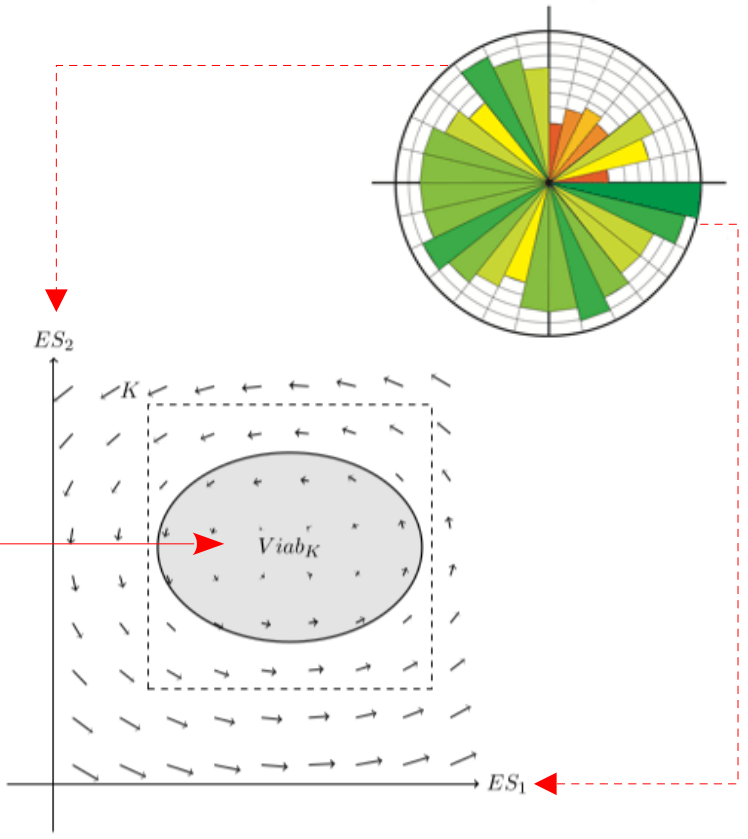
Viability of a dynamical system in SES

Axiological definition (value theory)

System's value, its robustness, durability, resilience, f(utilitarian, ethic, aesthetic values)

Viability (robustness):

$$\mathrm{Viab}_f(K) = \{\mathbf{x}(0) \in K \mid \exists u(.) \in U \text{such that} \forall t \geq 0, \mathbf{x}(u(.)) \in K\}$$



Difference between

viability or adaptation

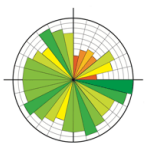
Adaptation of a dynamical system in SES

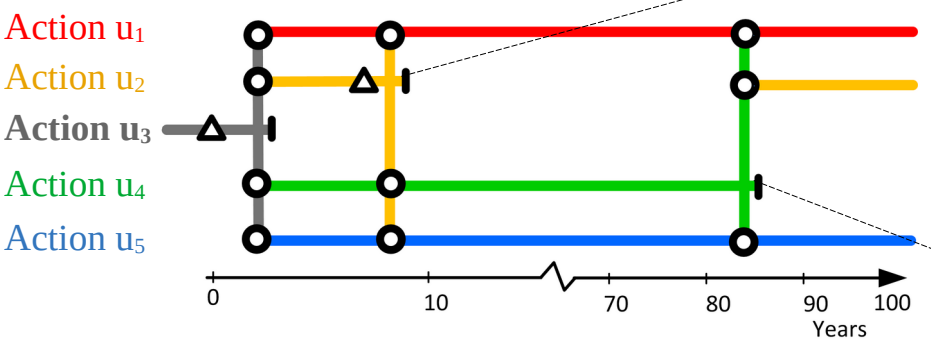
Praxeological definition (theory of action)

Planning actions & decisions, nodes, transitions, collective vs indiv., effectiveness, etc ...

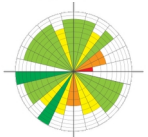
Set of actions:

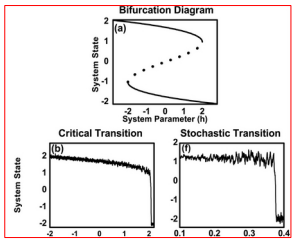
$$\mathbf{U} = \{u_1, u_2, u_3, u_4, u_5\}$$



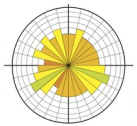


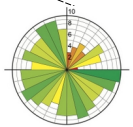
$x(u_2(t_7)) \in K$

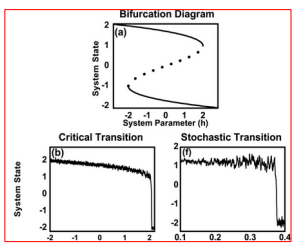




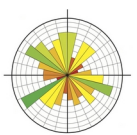
$x(u_2(t_8)) \notin K$







$x(u_4(t_84)) \in K$



$x(u_4(t_85)) \notin K$

Haasnoot, Marjolijn, et al. 2013.Dynamic adaptive policy pathways (DAPP). Global environmental change 23.2. 485-498

What is a DAPP map?

Definition independent from viability

Conditions (actions, time):

- Set of actions: $\mathbf{U} = \{u_1, u_2, \ldots, u_i, \ldots, u_m\}$,
- Time sequence: $T = \{t_0, t_1, \ldots, t_j, \ldots, t_n\}$,

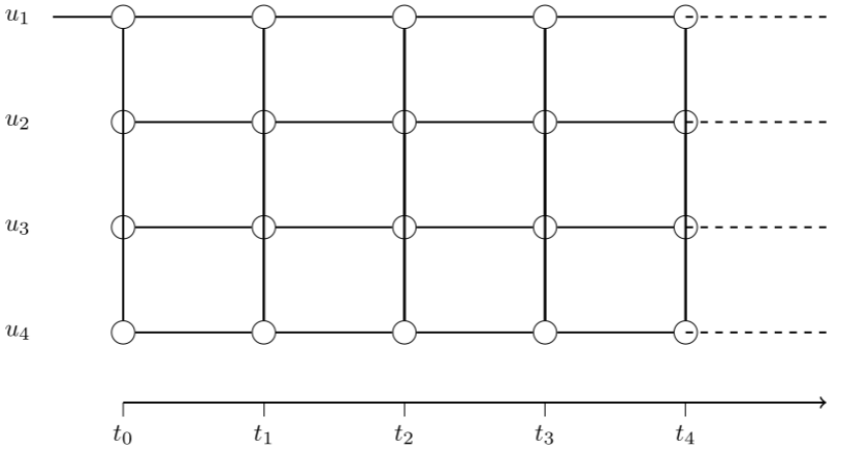
A policy pathway (i.e. DAPP) $u(.)$:

$$u(.) = u(t_0), u(t_1), \ldots, u(t_j), \ldots, u(t_n) \quad \text{such that} \quad u(t_j) \in \mathbf{U} \tag{32}$$

DAPP map (graph)

DAPP Graph: $\mathcal{G} = V \times E$ with $dim(\mathcal{G}) = U^T$

- Vertex V $\rightarrow U \times T$ representing decision nodes at time $t_0, t_1, ..., t_n$ for every possible action u, such that $V = \bigcup_{t=0}^{T} U(x(t))$
- Edges $E \rightarrow U^T$ possible transition pathways under control $u(t)$ between decision nodes V.



$\mathcal{G}: V(u_1, t_0) = \{u_1, u_2, u_3, u_4\}$ $\mathcal{G}: V(u_1, t_1) = \{u_1, u_2, u_3, u_4\}$ $\mathcal{G}: V(u_1, t_2) = \{u_1, u_2, u_3, u_4\}$

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Formal definition of a DAPP map

Definition that integrates viability

Conditions (actions, time, states):

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- Time sequence: $T = \{t_0, t_1, \ldots, t_j, \ldots, t_n\}$,
- Set of states: $X = \{x_1, x_2, \ldots, x_l\}$

A viable policy pathway (i.e. viable DAPP):

$$u_K(.) = u(t_0), u(t_1), \ldots, u(t_j), \ldots, u(t_n) \quad \text{such that} \quad u(t_j) \in (\mathbf{U}_K(t_j)\ \forall j) \in \mathbf{U} \tag{33}$$

Regulatory Map (Aubin et al., 2011)[Definition 2.9.4 p.73]:

$$\mathcal{R}(x) = \{u \in U(x) \mid x \in K, f(x, u(x)) \in Viab_K\} \tag{34}$$

Viable DAPP map (graph):

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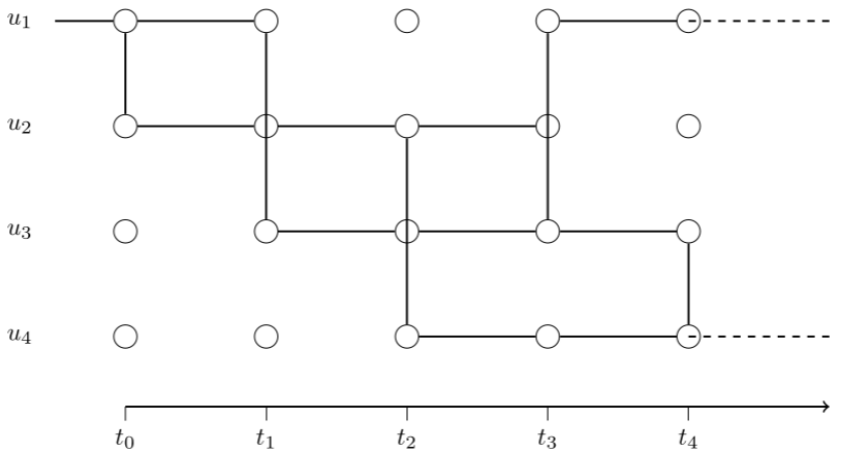

$\Gamma(u_1, t_0) = \{u_1, u_2\}$ $\quad$ $\Gamma(u_1, t_1) = \varnothing$ $\quad$ $\Gamma(u_1, t_2) = \varnothing$

$\Gamma(u_2, t_0) = \{u_1\}$ $\quad$ $\Gamma(u_2, t_1) = \{u_1, u_2, u_3\}$ $\quad$ $\Gamma(u_2, t_2) = \{u_2, u_3, u_4\}$

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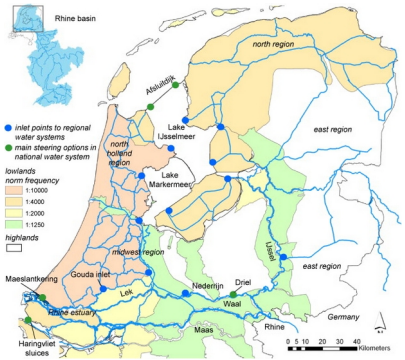
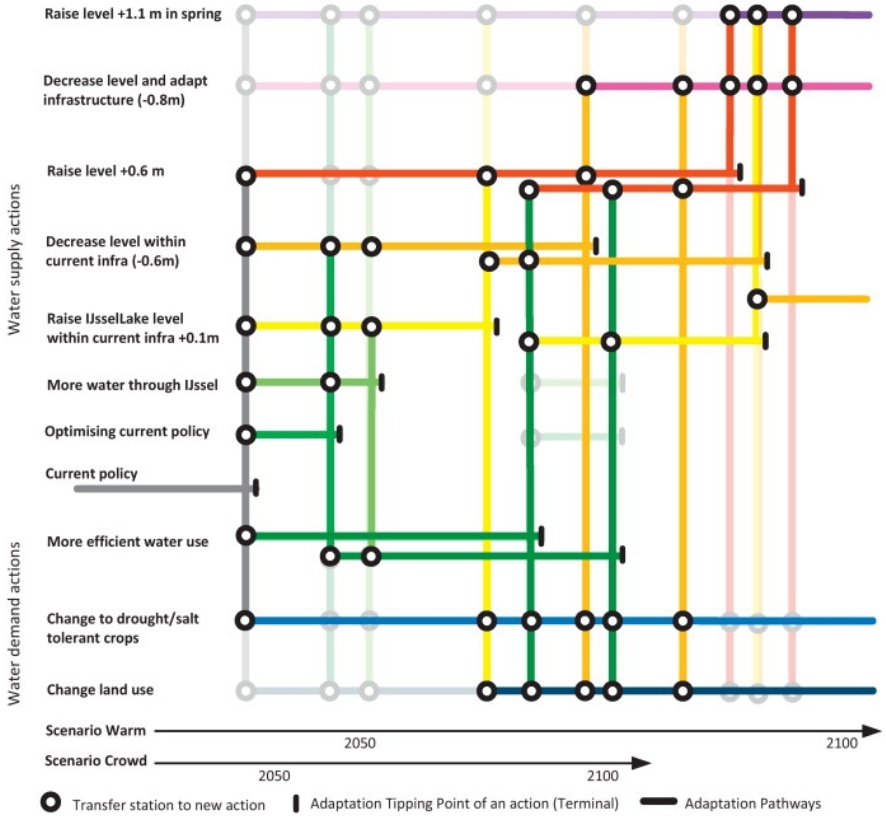
Adaptive policy of few infrastructures for fresh water supply vs safety



$dim(U) = 10$



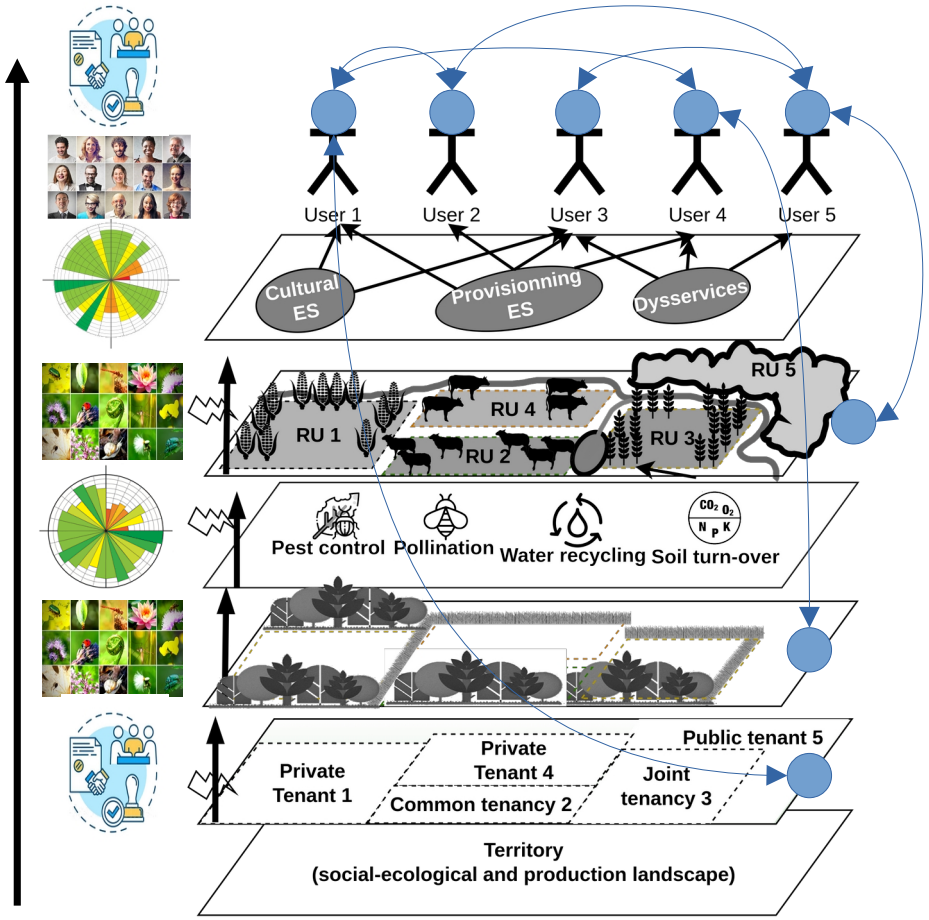
$dim(\mathcal{G}_K) \leq 10^{11}$ viable policy pathways

$dim(T) = 11$

Haasnoot, M., Kwakkel, J.H., Walker, W.E. and Ter Maat, J., 2013. Dynamic adaptive policy pathways: A method for crafting robust decisions for a deeply uncertain world. Global environmental change, 23(2), pp.485-498.

Problem

How to operationalize this method for hyper diverse social-ecological systems?



Social rules (operational, collective, constitutional)?

Resource actors (exploite, use, conserve, govern)?

Final ecosystem services (Private, common, Public, Club)?

Infrastructures, e.g. field, forest, river (private, communal, public, club)?

Supporting & regulating ecosystem services (common, private, public, club)?

Hedgerow network (~private)?

Cadastral rules (private, public, common, club) ?

Territorial geography

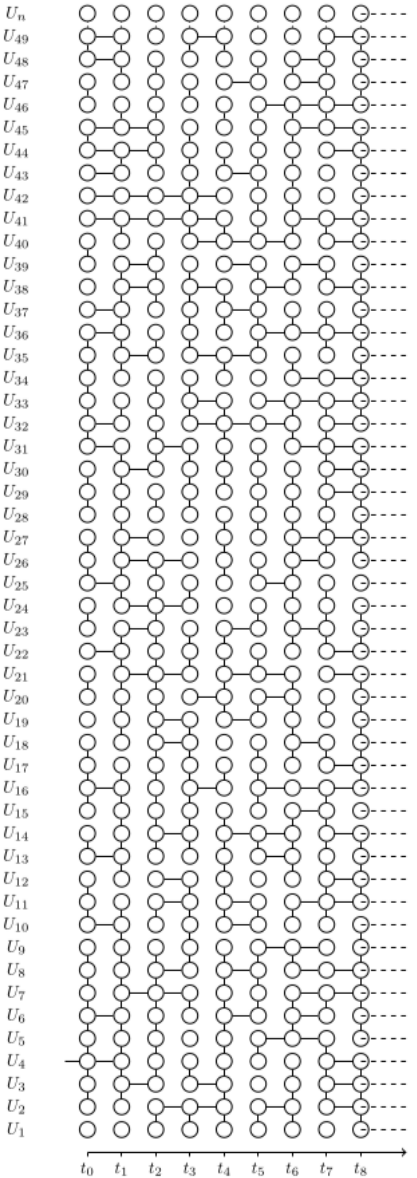
Challenge!

Define U, Viab_K and $\mathcal{G}(u(x), x(t))$ for these hyper-diverse SES

Modelling, structural & visual explosion

$dim(U) = n$

$dim(\mathcal{G}_K) \leq n^m$ viable policy pathways



Hypothetical DAPP map with *n* actions

Challenge!

Define U, Viab$_K$, $\mathcal{G}(u(x), x(t))$

Modelling, structural & visual explosion

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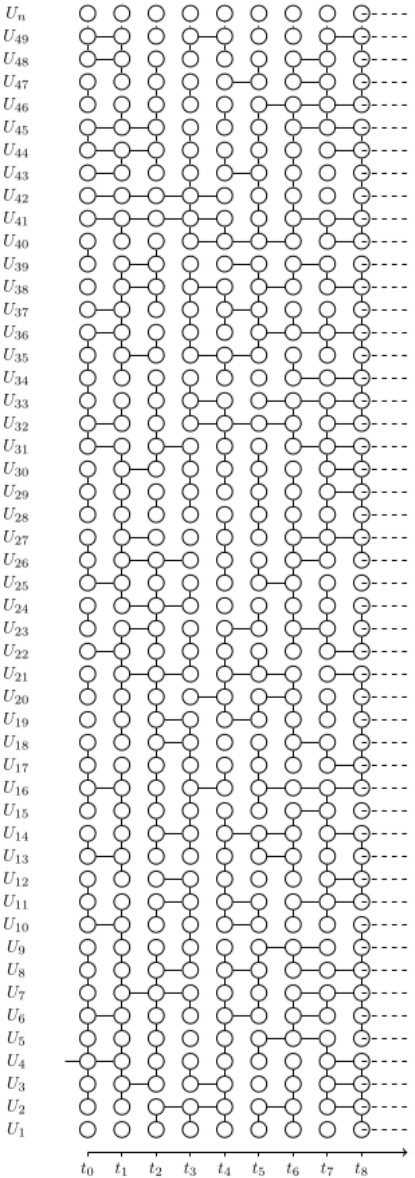

Hypothetical DAPP map with *n* actions

We need guidelines for their design

Focus

Organizing principles

~~Algorithm to match dimensional problem (combinatorial problem)~~

Possible guidelines

Ostrom's theory on the governance of common pool resources

Conditions (actions, time, states):

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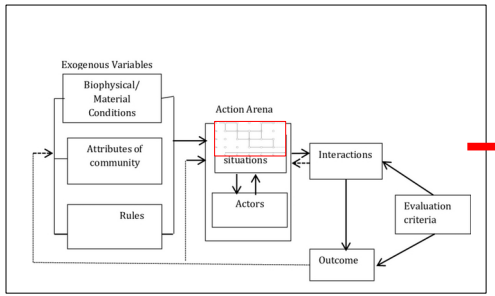
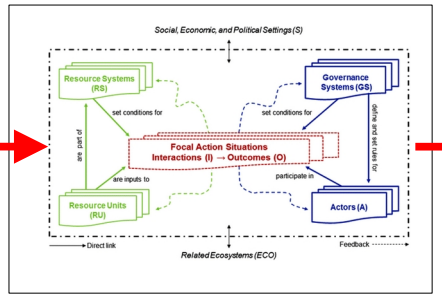
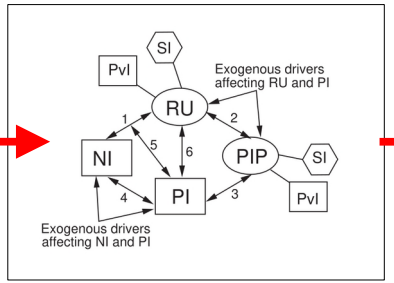


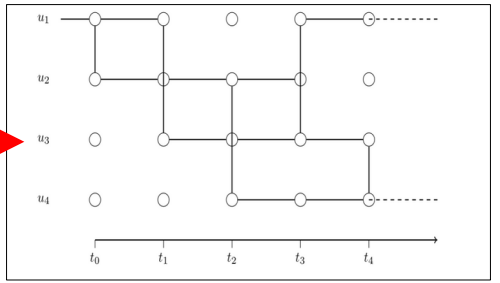
IAD framework



SES framework

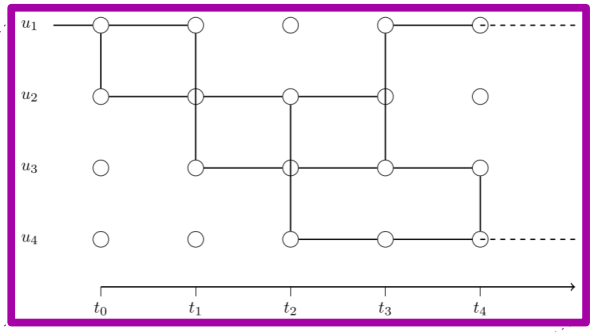


CIS framework

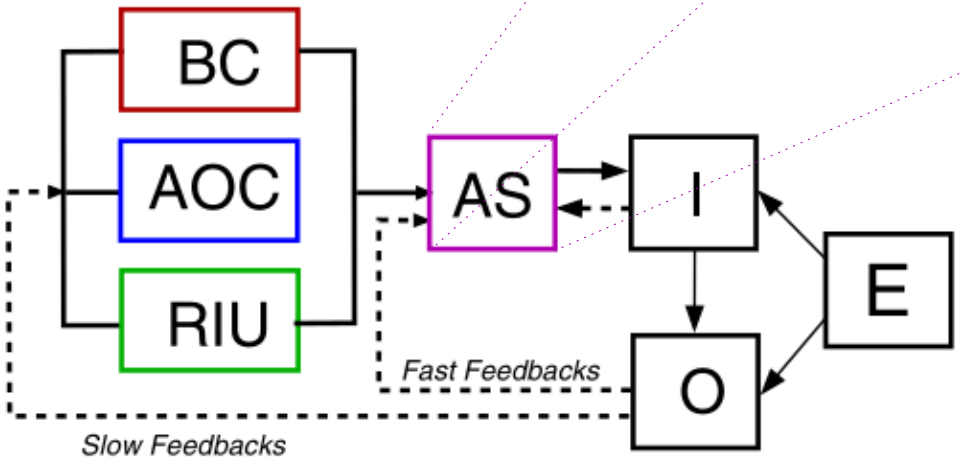


DAPP framework

IAD framework

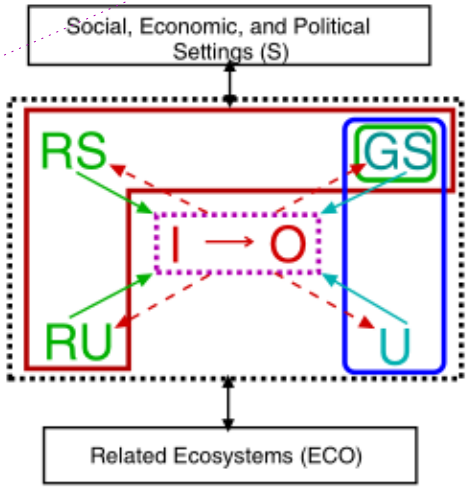


DAPP = “action situation”



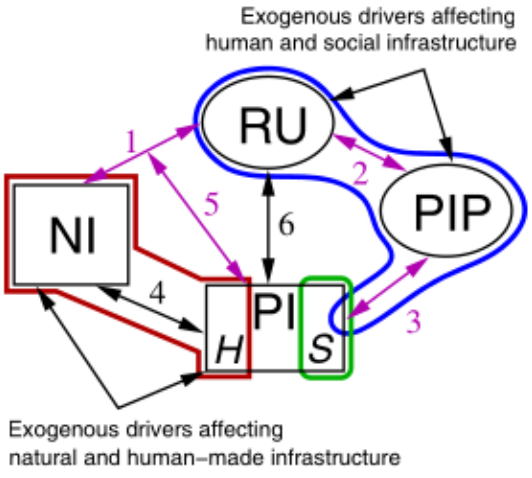
IAD Framework

a



Diagnostic/SES Framework

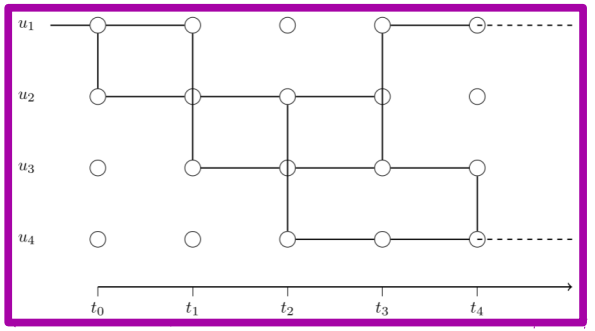
b



Robustness Framework

c

SES framework



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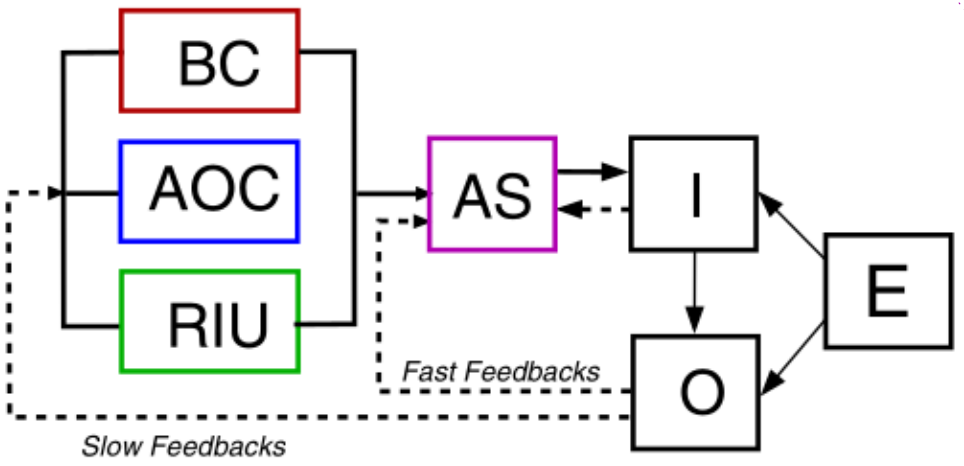
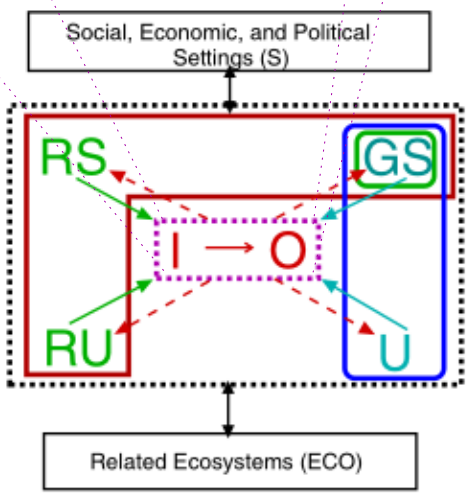


IAD Framework

a



Diagnostic/SES Framework

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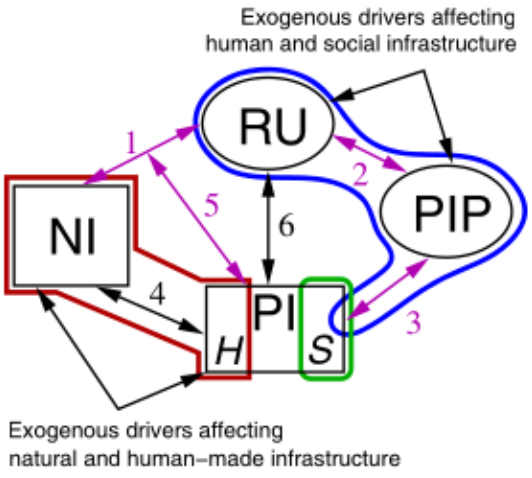
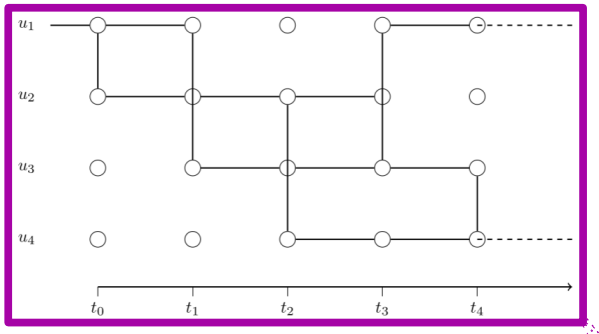


Robustness Framework

c

CIS & Robustness framework



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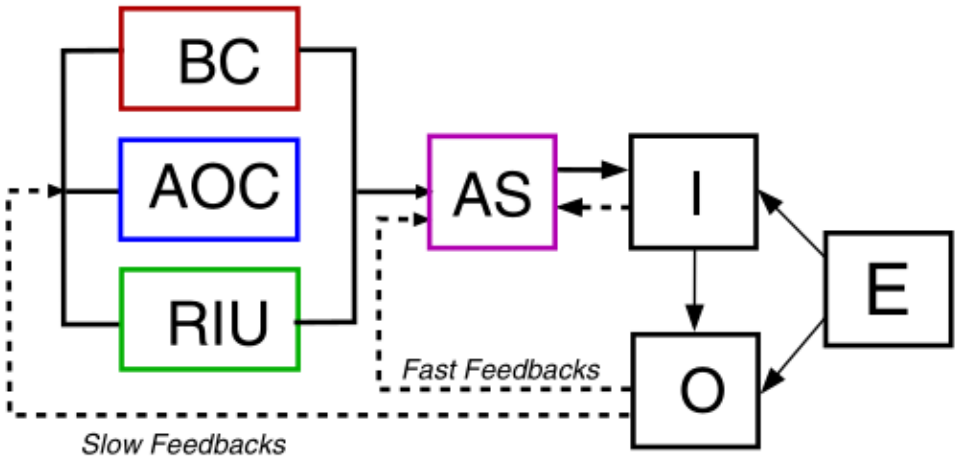

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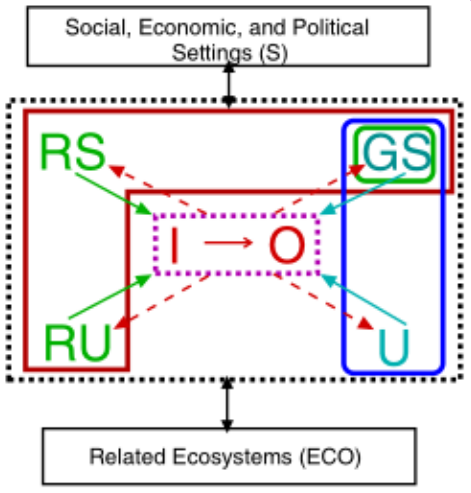

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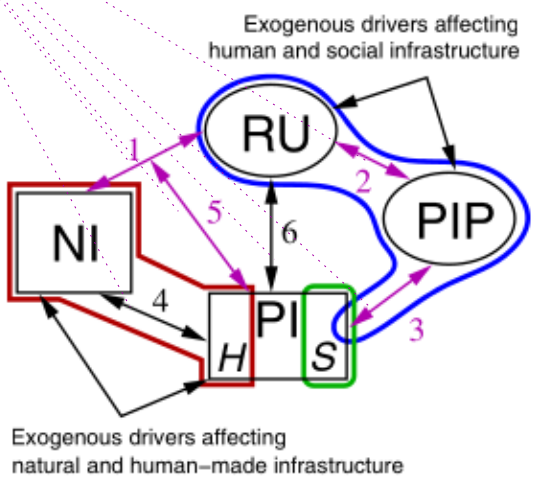
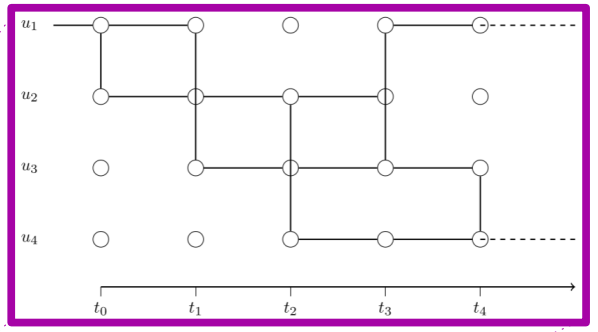


Robustness Framework

c

IAD framework



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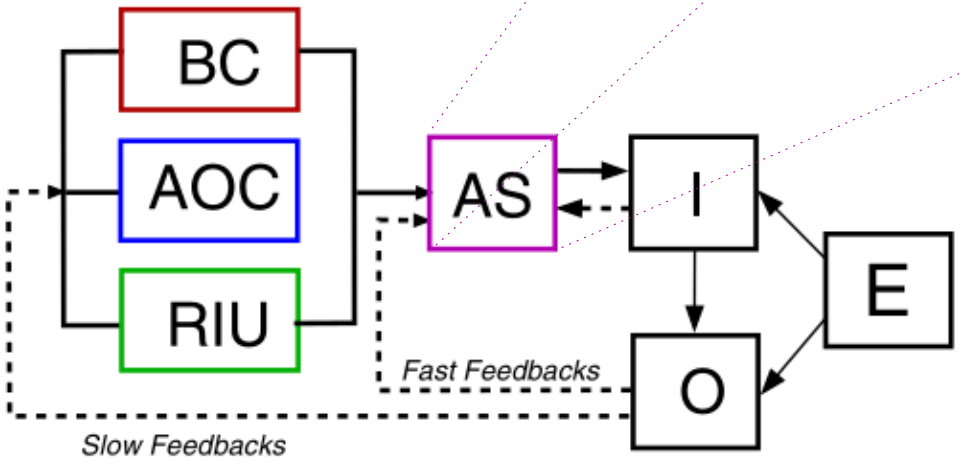

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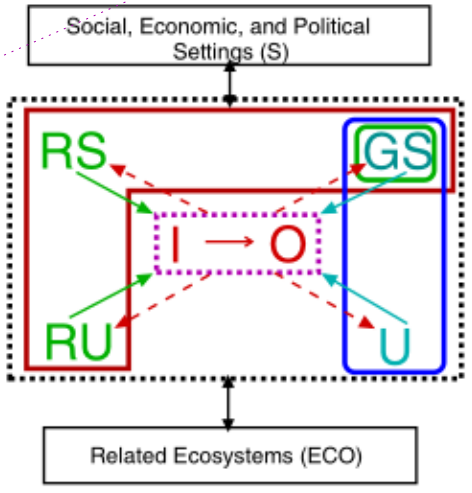

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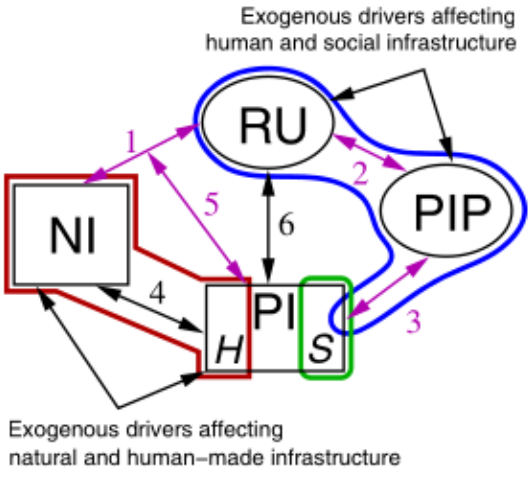
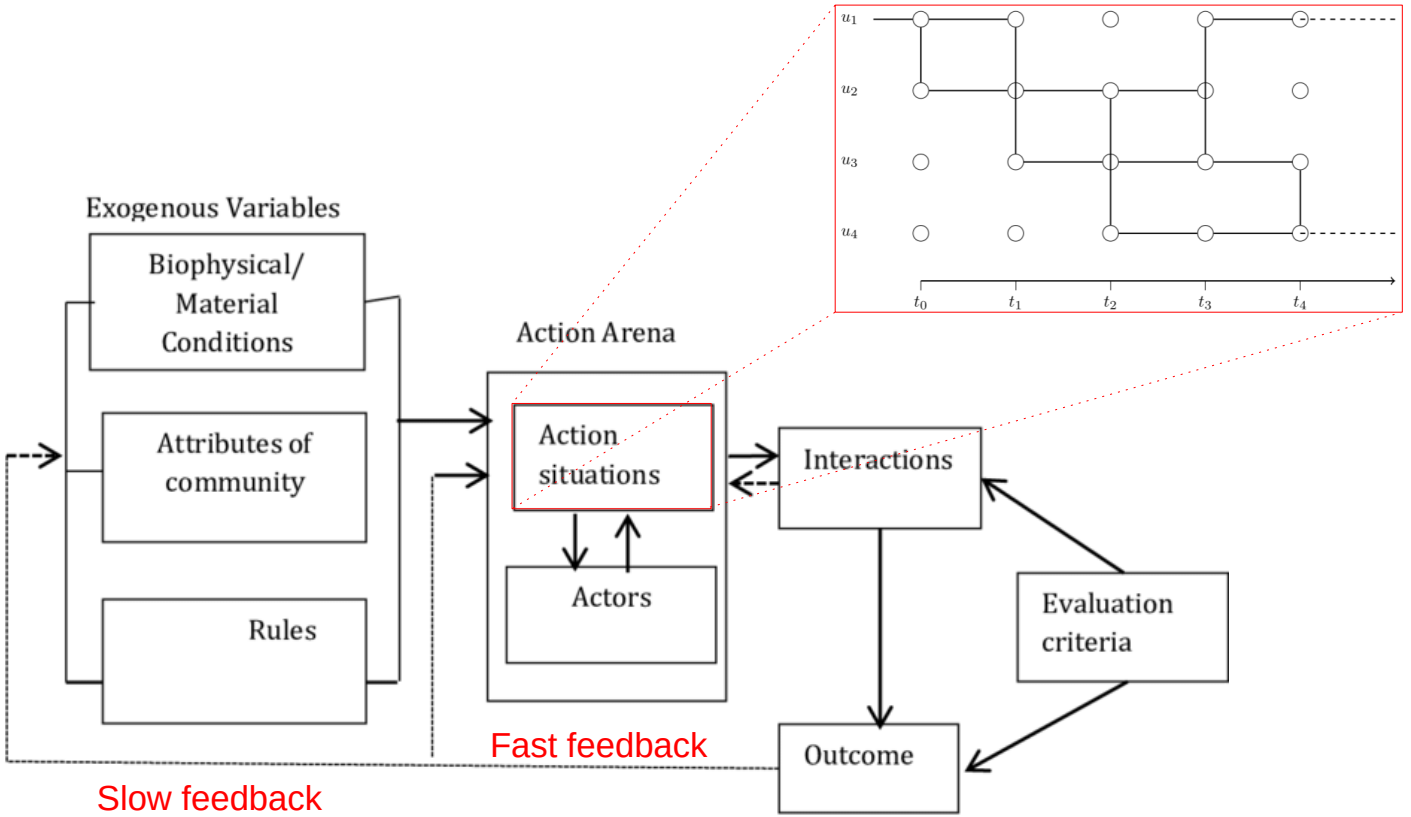


Robustness Framework

c

What are DAPP maps inside IAD framework?

DAPP = “action situation”



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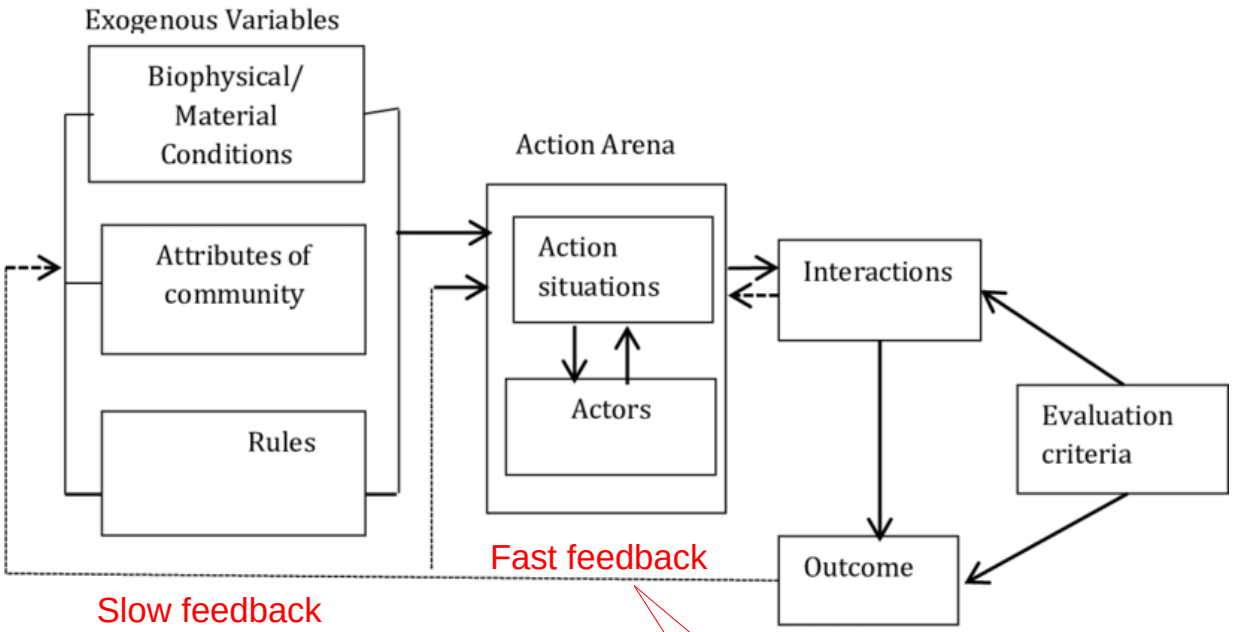
DAPP Graph: $\mathcal{G} = V \times E$ with $dim(\mathcal{G}) = U^T$

- Vertex $V \to U \times T$ representing decision nodes at time $t_0, t_1, ..., t_T$ for every possible action u, such that $V = \bigcup_{t=0}^{T} U(x(t))$
- Edges $E = e_{ij} \subseteq V \times V$ representing possible viable transition pathways between decision nodes, which correspond to viable state transitions under control $u(t)$, such that: $E = \{u(t), u(t+1) \mid u(t) \in \mathcal{R}(x(t), u(t)), u(t+1) \in \mathcal{R}(x(t+1), u(t+1))\}$

Ostrom, E. (1990). Governing the commons: The evolution of institutions for collective action. Cambridge University Press.

Feedback (slow / fast) = adaptation at different levels

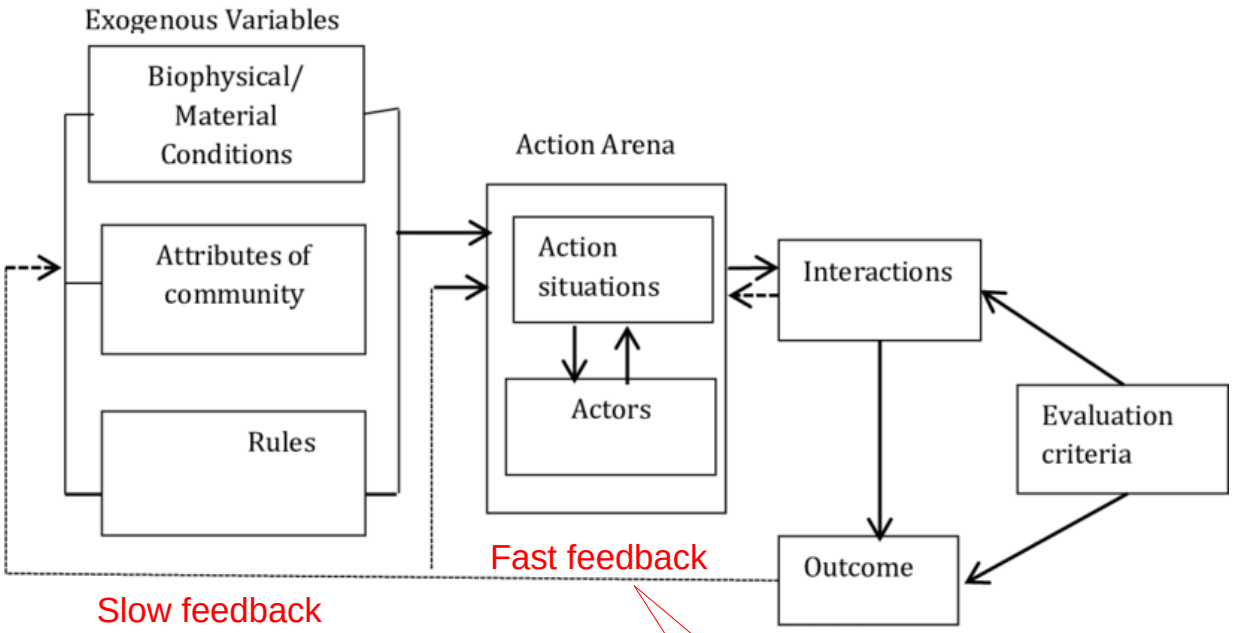


Operational-choice level (U^{OCA}) How much ?

Collective-choice level (U^{KCA}) How to organize?

Constitutional-choice level (U^{CCA}) Who is eligible?

Nested (slow / fast) DAPP maps



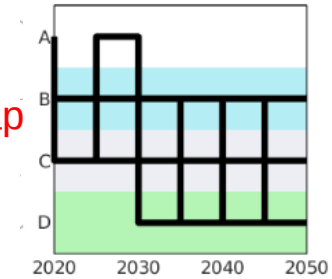
Operational (U^{OCA})

Collective (U^{KCA})

Constitutional (U^{CCA})

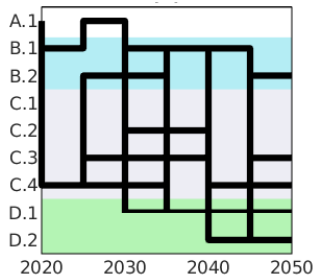
Constitutional DAPP map

Who ? What ? Eligible



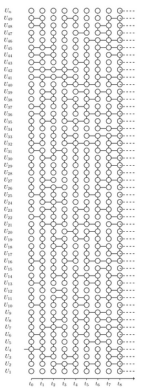
Collective DAPP map

How to organize?

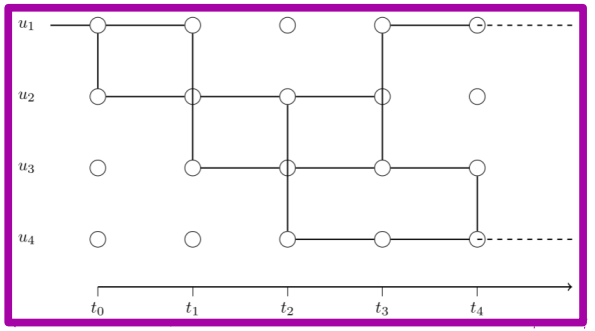


Operational DAPP map

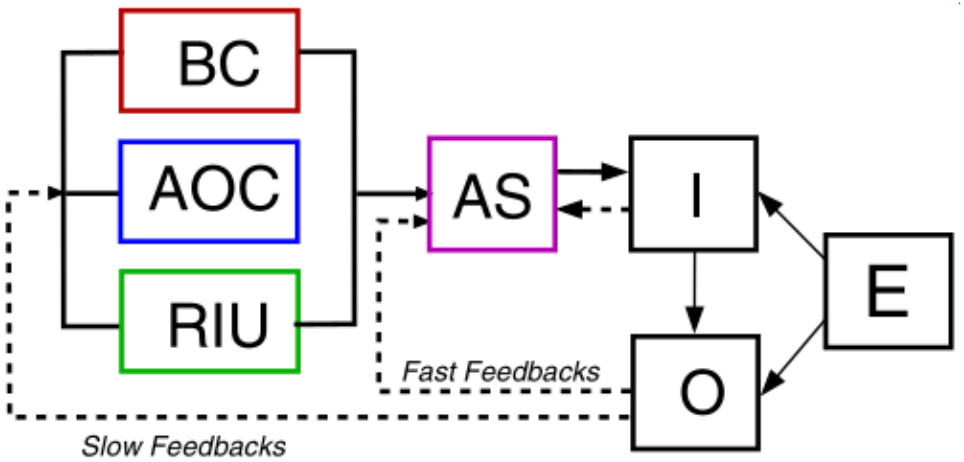
How much ?



SES framework
(targets of adaptation)

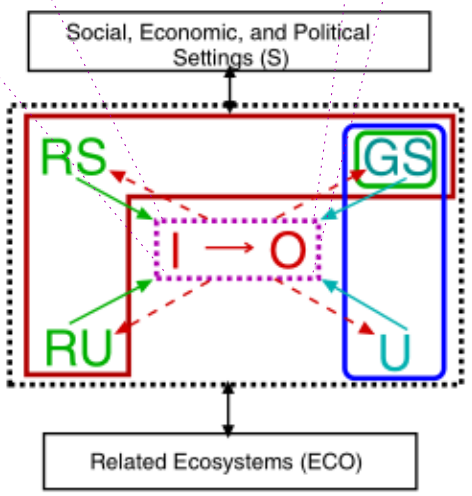


DAPP = “action situation”



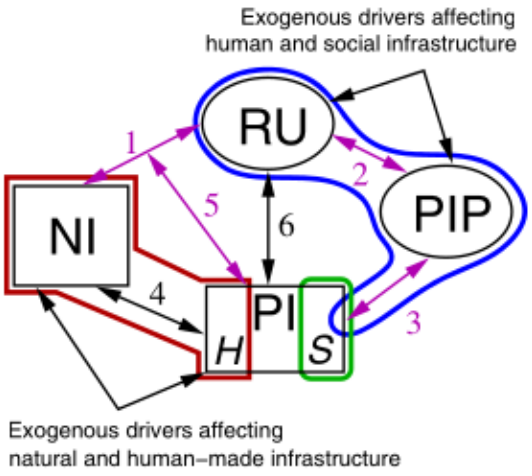
IAD Framework

a



Diagnostic/SES Framework

b



Robustness Framework

c

SES framework

Goal: describe SES attributes using a multi-tier framework

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 *, **		

SES framework

Constant improvement of the framework, match different ways of describing SES

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 *, **		

Ostrom, E. (2007). A diagnostic approach for going beyond panaceas. Proceedings of the National Academy of Sciences of the United States of America, 104(39), 15181-15187.

Iteration 1

Ostrom, E. (2009). A general framework for analyzing sustainability of social-ecological systems. Science, 325, 419-422

Iteration 2

McGinnis, M. D., and **Ostrom**, E. (2014). Social-ecological system framework: initial changes and continuing challenges. Ecology and Society, 19

Iteration 3

Vogt, J., Epstein, G., Mincey, S.K., Fischer, B.C., and McCord, P.F. (2015). Putting the "E" in SES: unpacking the ecology in the Ostrom social-ecological system framework. Ecology and Society, 20.

Iteration 4

Filtre 1 : SES framework

Define adaptation actions according to targeted SES attributes

$U = \{u_1, u_2, u_3, \ldots u_n\}$

SES framework

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 *, **		

Attributs : Tier 1

$U = \{U_S, U_{RS}, U_{RU}, U_{GS}, U_A, U_I, U_O\}$

Tier 2

$U_S = \{u_{S1}, u_{S2}, \ldots, u_{S7}\}$

$U_{RS} = \{u_{RS1}, u_{RS2}, \ldots, u_{RS10}\}$

$U_{RU} = \{u_{RU1}, u_{RU2}, \ldots, u_{RS7}\}$

$U_{GS} = \{u_{GS1}, u_{GS2}, \ldots, u_{GS10}\}$

$U_A = \{u_{A1}, u_{A2}, \ldots, u_{A9}\}$

$U_I = \{u_{I1}, u_{I2}, \ldots, u_{I10}\}$

$U_O = \{u_{O1}, u_{O2}, u_{O3}\}$

Tier 3

...

Construction the set U of 2nd tier actions based on a version of Ostrom's social-ecological system framework (SESF)

Set of actions related to the social, economic & political Settings (U_S)

U_{S1} Economic development *, †
U_{S2} Demographic trends *, †
U_{S3} Political stability (rate of political change) *, †
U_{S4} Other governance systems †
U_{S5} Markets †
U_{S6} Media organizations †
U_{S7} Technology †

Set of actions related to the Resource Systems (U_{RS})

U_{RS1} Sector
U_{RS2} Clarity of system boundaries
U_{RS3} Size of resource system
U_{RS4} Human constructed facilities *
U_{RS5} Productivity of the system
U_{RS6} Equilibrium properties
U_{RS7} Predictability of system dynamics
U_{RS8} Storage characteristics
U_{RS9} Location
U_{RS10} Ecosystem history

Set of actions related to the Resource Units (U_{RU})

U_{RU1} Resource unit mobility *, **, †
U_{RU2} Growth or replacement rate of resource units
U_{RU3} Interactions among resource units *, †
U_{RU4} Economic value
U_{RU5} Number of units
U_{RU6} Distinctive characteristics
U_{RU7} Spatial & temporal distribution

Set of actions related to the Governance Systems (U_{GS})

U_{GS1} Policy area
U_{GS2} Geographic scale of governance system *
U_{GS3} Proportion of participating population **
U_{GS4} Regime type (demo/auto-cratic, mono/poly-centric) *
U_{GS5} Rule-making organizations *
U_{GS6} Rules-in-Use *
U_{GS7} Property rights systems (relations among people in relation to resource units and infrastructures) *
U_{GS8} Repertoire of cultural knowledge, beliefs, norms, practices (strategies) with no rules and sanctions *
U_{GS9} Network structure (connections among the rule-making organizations and the population subject to these rules) *, **
U_{GS10} Historical continuity of the governance system (recent vs long-lasting, open vs close to internal adaptation) *

Set of actions related to the Actors (U_A)

U_{A1} Number of relevant actors *
U_{A2} Socio-economic attributes *
U_{A3} History of past experience *, **
U_{A4} Location *
U_{A5} Leadership / entrepreneurship *
U_{A6} Norms /(trust-reciprocity) / social capital *
U_{A7} Knowledge of SES / mental models / beliefs *
U_{A8} Proportion of resource dependent actors *
U_{A9} Technologies available *

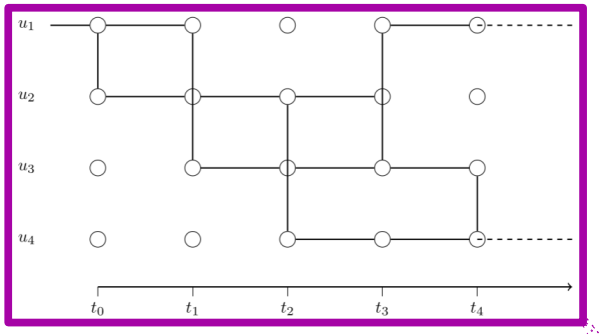
Set of actions related to the Interactions (U_I)

U_{I1} Harvesting / using resource units by divers users
U_{I2} Information sharing among actors *, **
U_{I3} Deliberation process *, **
U_{I4} Conflicts among actors *, **
U_{I5} Investment activities *, **
U_{I6} Lobbying activities *, **, †
U_{I7} Self-organizing activities *, **
U_{I8} Networking activities *, **
U_{I9} Monitoring activities *, **
U_{I10} Evaluative activities *, **

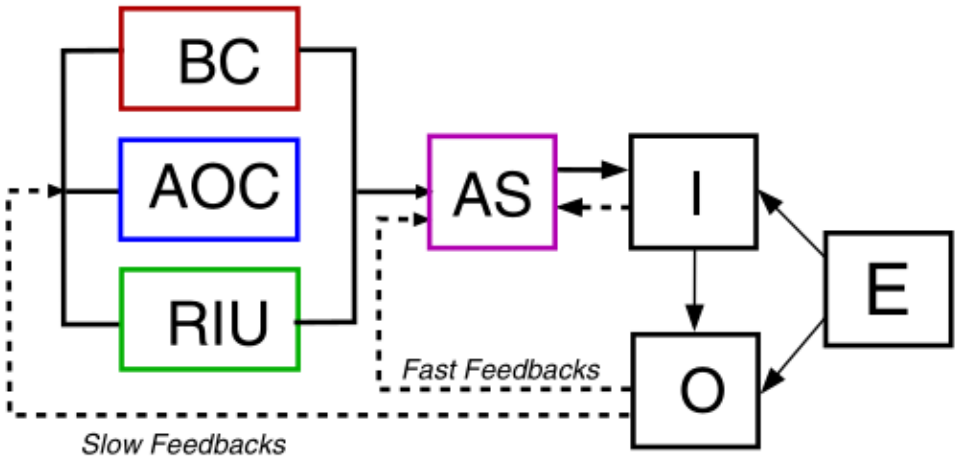
Set of actions related to the Outcomes (U_O)

U_{O1} Social performance measures (e.g. efficiency, equity, accountability, sustainability) *, **
U_{O2} Ecological performance measures (e.g. overharvested, resilience, robustness, biodiversity) **
U_{O3} Externalities to other SES †

CIS & Robustness framework
(triggering of actions)

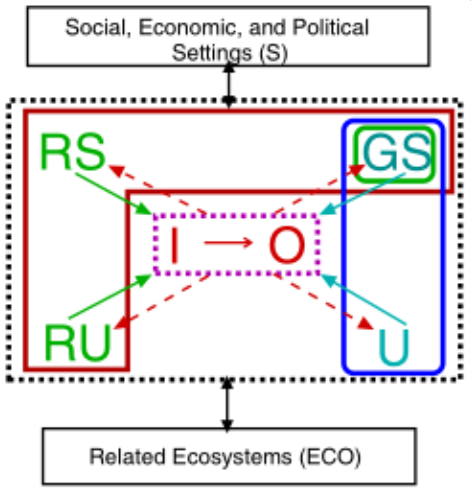


DAPP = “action situation”



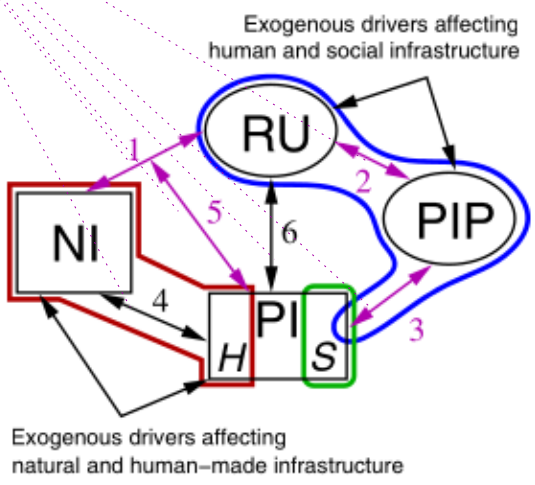
IAD Framework

a



Diagnostic/SES Framework

b



Robustness Framework

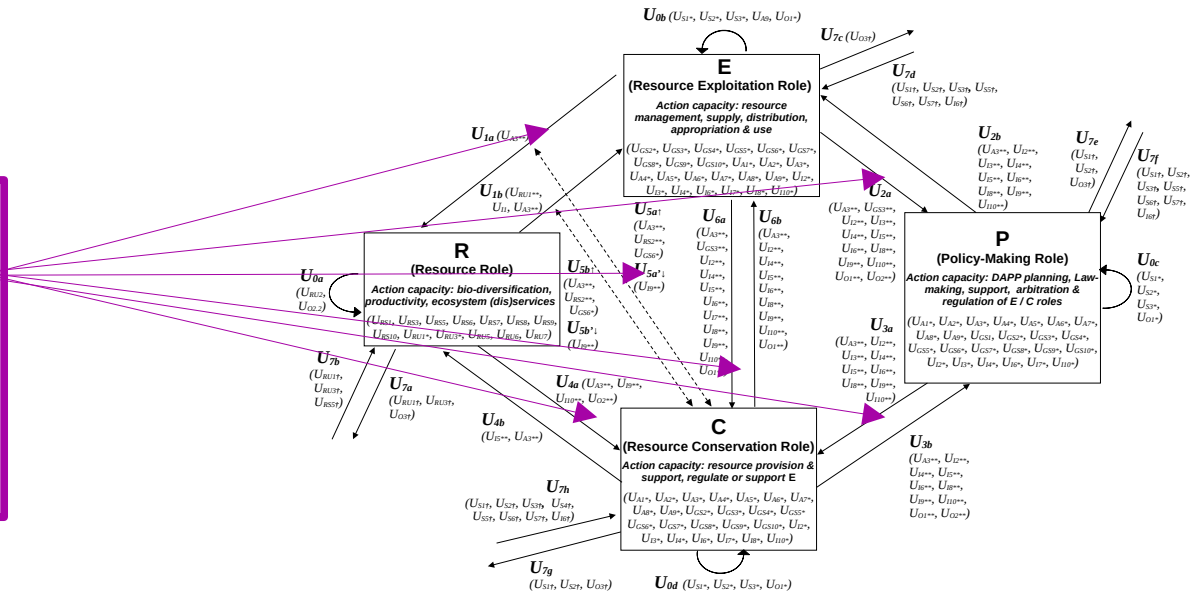
c

SES + CIS

targets of action → Roles that trigger & receive actions

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 (democratic-cratic, monopoly-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 * **		



$$U = \{U_S, U_{RS}, U_{RU}, U_{GS}, U_A, U_I, U_O\}$$

Filtre 2 : CIS framework

Spread adaptation action by roles' actors & infrastructures

Principle 8-A: Polycentricity

Tier 1

$U = \{U_S, U_{RS}, U_{RU}, U_{GS}, U_A, U_I, U_O\}$

Tier 2

$U_S = \{u_{S1}, u_{S2}, \ldots, u_{S7}\}$

$U_{RS} = \{u_{RS1}, u_{RS2}, \ldots, u_{RS10}\}$

$U_{RU} = \{u_{RU1}, u_{RU2}, \ldots, u_{RS7}\}$

$U_{GS} = \{u_{GS1}, u_{GS2}, \ldots, u_{GS10}\}$

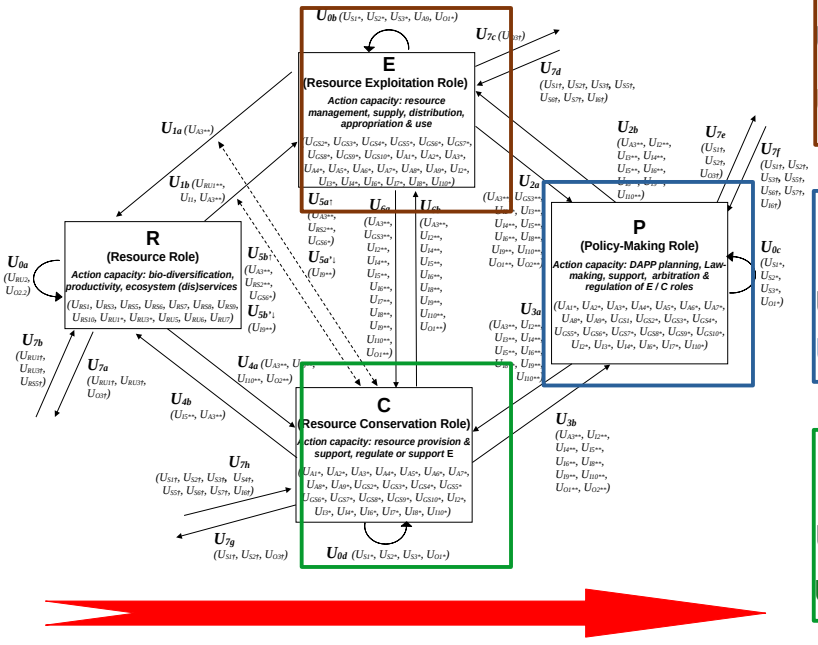
$U_A = \{u_{A1}, u_{A2}, \ldots, u_{A9}\}$

$U_I = \{u_{I1}, u_{I2}, \ldots, u_{I10}\}$

$U_O = \{u_{O1}, u_{O2}, u_{O3}\}$

Tier 3

...



Anderies, J. M., Janssen, M. A., and **Ostrom, E.** (2004). A framework to analyze the robustness of social-ecological systems from an institutional perspective. Ecology and society, 9(1).

Exploitation (E)

$U_E = \{U_{E:S}, U_{E:RS}, U_{E:RU}, U_{E:GS}, U_{E:A}, U_{E:I}, U_{E:O}\}$

$U^E = \{u_{E:0b}, u_{E:1a}, u_{E:1b}, u_{E:2a}, u_{E:6a}, u_{E:7c}, u_{E:7d}\}$

Arbitration (P)

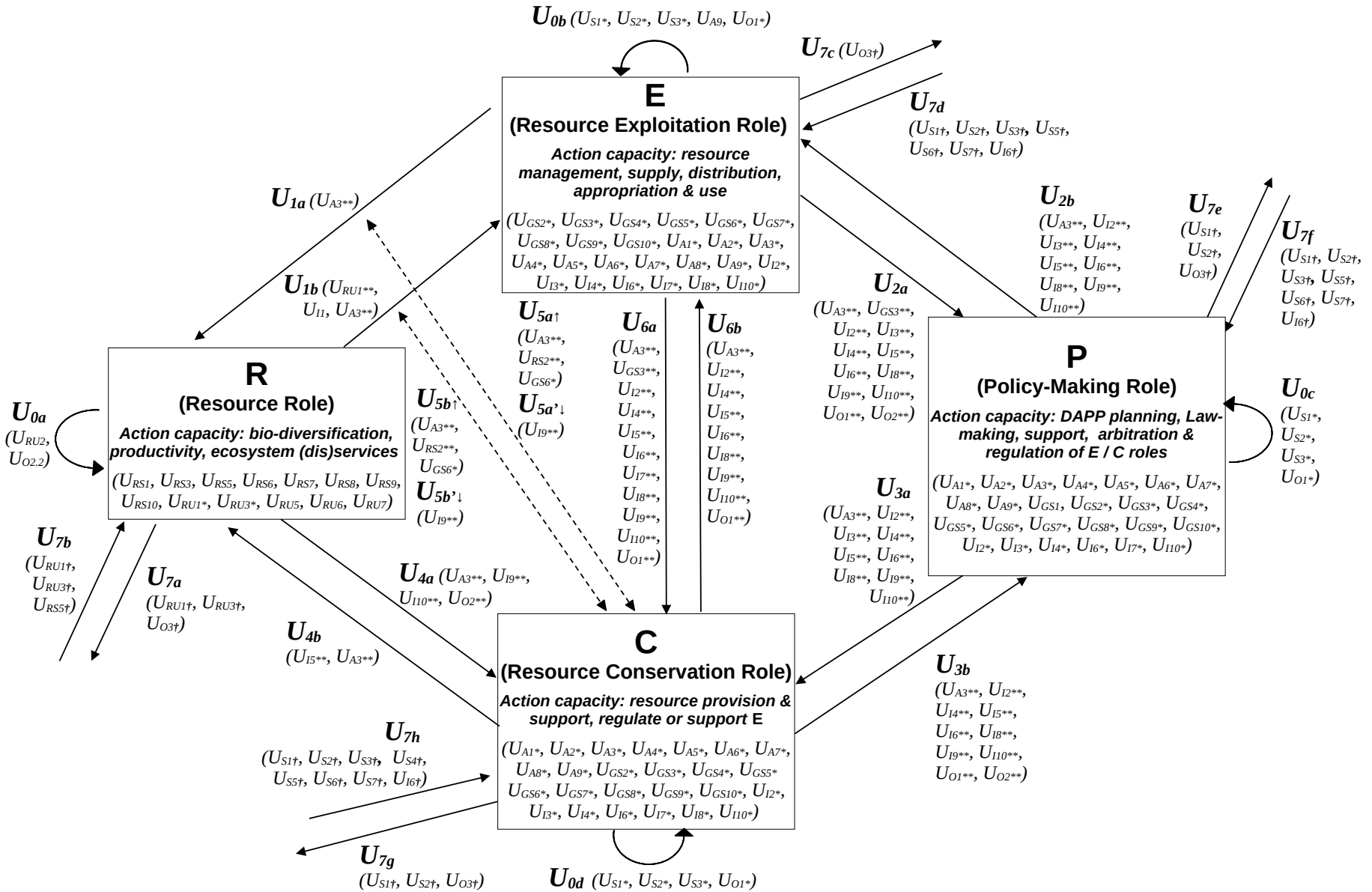
$U_P = \{U_{P:S}, U_{P:RS}, U_{P:RU}, U_{P:GS}, U_{P:A}, U_{P:I}, U_{P:O}\}$

$U_P = \{u_{P:0c}, u_{P:2b}, u_{P:3a}, u_{P:7e}, u_{P:7f}\}$

Conservation (C)

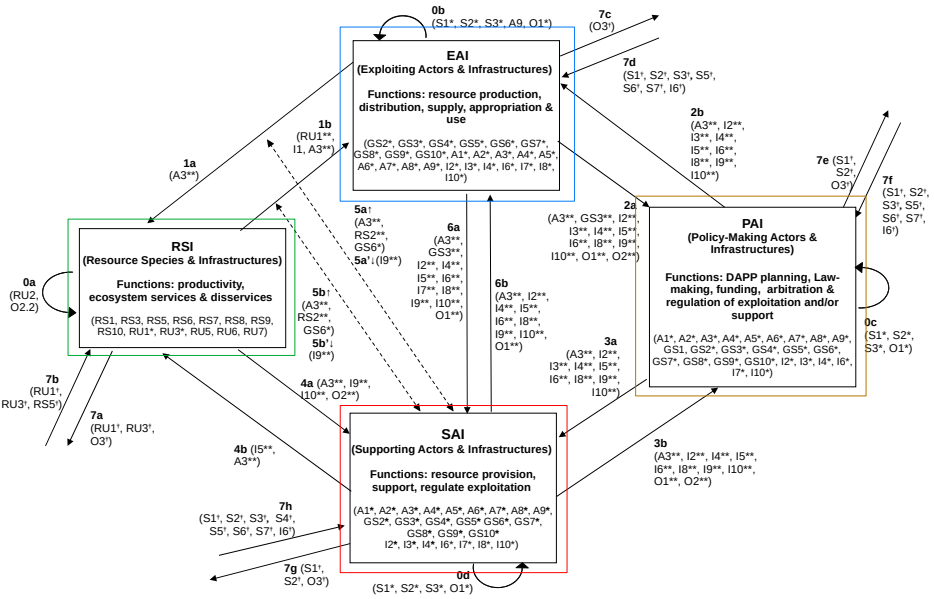
$U_C = \{U_{C:S}, U_{C:RS}, U_{C:RS}, U_{C:GS}, U_{C:A}, U_{C:I}, U_{C:O}\}$

$U_C = \{u_{C:0d}, u_{C:4a}, u_{C:4b}, u_{C:5a}, u_{C:5b}, u_{C:6b}, u_{C:7g}, u_{C:7h}\}$


U_{0b} (U_{S1*}, U_{S2*}, U_{S3*}, U_{A9}, U_{O1*})
E
(Resource Exploitation Role)
Action capacity: resource management, supply, distribution, appropriation & use
(U_{GS2*}, U_{GS3*}, U_{GS4*}, U_{GS5*}, U_{GS6*}, U_{GS7*}, U_{GS8*}, U_{GS9*}, U_{GS10*}, U_{A1*}, U_{A2*}, U_{A3*}, U_{A4*}, U_{A5*}, U_{A6*}, U_{A7*}, U_{A8*}, U_{A9*}, U_{I2*}, U_{I3*}, U_{I4*}, U_{I6*}, U_{I7*}, U_{I8*}, U_{I10*})
U_{7c} ($U_{O3\dagger}$)
U_{7d} ($U_{S1\dagger}$, $U_{S2\dagger}$, $U_{S3\dagger}$, $U_{S5\dagger}$, $U_{S6\dagger}$, $U_{S7\dagger}$, $U_{I6\dagger}$)
U_{1a} (U_{A3**})
U_{1b} (U_{RU1**}, U_{I1}, U_{A3**})
R
(Resource Role)
Action capacity: bio-diversification, productivity, ecosystem (dis)services
(U_{RS1}, U_{RS3}, U_{RS5}, U_{RS6}, U_{RS7}, U_{RS8}, U_{RS9}, U_{RS10}, U_{RU1*}, U_{RU3*}, U_{RU5}, U_{RU6}, U_{RU7})
U_{0a} (U_{RU2}, $U_{O2.2}$)
$U_{5a}\uparrow$ (U_{A3**}, U_{RS2**}, U_{GS6*})
$U_{5a'}\downarrow$ (U_{I9**})
$U_{5b}\uparrow$ (U_{A3**}, U_{RS2**}, U_{GS6*})
$U_{5b'}\downarrow$ (U_{I9**})
U_{6a} (U_{A3**}, U_{GS3**}, U_{I2**}, U_{I4**}, U_{I5**}, U_{I6**}, U_{I7**}, U_{I8**}, U_{I9**}, U_{I10**}, U_{O1**})
U_{6b} (U_{A3**}, U_{I2**}, U_{I4**}, U_{I5**}, U_{I6**}, U_{I8**}, U_{I9**}, U_{I10**}, U_{O1**})
U_{2b} (U_{A3**}, U_{I2**}, U_{I3**}, U_{I4**}, U_{I5**}, U_{I6**}, U_{I8**}, U_{I9**}, U_{I10**})
U_{7e} ($U_{S1\dagger}$, $U_{S2\dagger}$, $U_{O3\dagger}$)
U_{7f} ($U_{S1\dagger}$, $U_{S2\dagger}$, $U_{S3\dagger}$, $U_{S5\dagger}$, $U_{S6\dagger}$, $U_{S7\dagger}$, $U_{I6\dagger}$)
U_{2a} (U_{A3**}, U_{GS3**}, U_{I2**}, U_{I3**}, U_{I4**}, U_{I5**}, U_{I6**}, U_{I8**}, U_{I9**}, U_{I10**}, U_{O1**}, U_{O2**})
P
(Policy-Making Role)
Action capacity: DAPP planning, Law-making, support, arbitration & regulation of E / C roles
(U_{A1*}, U_{A2*}, U_{A3*}, U_{A4*}, U_{A5*}, U_{A6*}, U_{A7*}, U_{A8*}, U_{A9*}, U_{GS1}, U_{GS2*}, U_{GS3*}, U_{GS4*}, U_{GS5*}, U_{GS6*}, U_{GS7*}, U_{GS8*}, U_{GS9*}, U_{GS10*}, U_{I2*}, U_{I3*}, U_{I4*}, U_{I6*}, U_{I7*}, U_{I10*})
U_{0c} (U_{S1*}, U_{S2*}, U_{S3*}, U_{O1*})
U_{3a} (U_{A3**}, U_{I2**}, U_{I3**}, U_{I4**}, U_{I5**}, U_{I6**}, U_{I8**}, U_{I9**}, U_{I10**})
U_{7b} ($U_{RU1\dagger}$, $U_{RU3\dagger}$, $U_{RS5\dagger}$)
U_{7a} ($U_{RU1\dagger}$, $U_{RU3\dagger}$, $U_{O3\dagger}$)
U_{4a} (U_{A3**}, U_{I9**}, U_{I10**}, U_{O2**})
U_{4b} (U_{I5**}, U_{A3**})
C
(Resource Conservation Role)
Action capacity: resource provision & support, regulate or support E
(U_{A1*}, U_{A2*}, U_{A3*}, U_{A4*}, U_{A5*}, U_{A6*}, U_{A7*}, U_{A8*}, U_{A9*}, U_{GS2*}, U_{GS3*}, U_{GS4*}, U_{GS5*} U_{GS6*}, U_{GS7*}, U_{GS8*}, U_{GS9*}, U_{GS10*}, U_{I2*}, U_{I3*}, U_{I4*}, U_{I6*}, U_{I7*}, U_{I8*}, U_{I10*})
U_{3b} (U_{A3**}, U_{I2**}, U_{I4**}, U_{I5**}, U_{I6**}, U_{I8**}, U_{I9**}, U_{I10**}, U_{O1**}, U_{O2**})
U_{7h} ($U_{S1\dagger}$, $U_{S2\dagger}$, $U_{S3\dagger}$, $U_{S4\dagger}$, $U_{S5\dagger}$, $U_{S6\dagger}$, $U_{S7\dagger}$, $U_{I6\dagger}$)
U_{7g} ($U_{S1\dagger}$, $U_{S2\dagger}$, $U_{O3\dagger}$)
U_{0d} (U_{S1*}, U_{S2*}, U_{S3*}, U_{O1*})

Transform the CIS into a system of equations

Consequences of adaptation actions on SES dynamics & viability



$$
\begin{cases}
\dfrac{dR}{dt} = \overbrace{U_{0a}.R}^{\text{Natural ES Growth}} \pm \overbrace{U_{7b}.R}^{\text{Impact of SES Settings}} - \overbrace{U_{7a}.R}^{\text{ES Externalities}} \\
\quad + \overbrace{U_{4a}.R.C}^{\text{R Support by C}} - \overbrace{U_{1b}.R.E}^{\text{ES Access \& Flow}} . \overbrace{U_{5b}.C}^{\text{Regulation}} + \overbrace{U_{1a}.E.R}^{\text{Access \& Management}} . \overbrace{U_{5a}.C}^{\text{Regulation}} & (1a) \\
\dfrac{dE}{dt} = \pm \overbrace{U_{0b}.E}^{\text{Natural Growth/Decay}} \pm \overbrace{7d.E}^{\text{Impact of SES Settings}} - \overbrace{U_{7c}.E}^{\text{Externalities}} & (1b) \\
\quad + \overbrace{U_{1b}.R.E}^{\text{Access R \& ES Flow}} . \overbrace{U_{5b}.C}^{\text{Regulation}} \pm \overbrace{U_{6b'}.E.C}^{\text{C Support \& Regulation}} \pm \overbrace{U_{2b}.E.P}^{\text{P Support \& Sanctions}} \\
\dfrac{dC}{dt} = \pm \overbrace{U_{0d}.C}^{\text{Natural Growth/Decay}} \pm \overbrace{U_{7h}.C}^{\text{Impact of SES Settings}} - \overbrace{U_{7g}.C}^{\text{Externalities}} & (1c) \\
\quad + \overbrace{U_{1b}.R.E}^{\text{Access \& ES Flow}} . \overbrace{U_{5b'}.C}^{\text{Monitoring}} + \overbrace{U_{1a}.R.E}^{\text{Access \& Management}} . \overbrace{U_{5a'}.C}^{\text{Monitoring}} \\
\quad + \overbrace{(U_{6a} - U_{6b}).E.C}^{\text{E Joining/leaving}} \pm \overbrace{U_{3a}.P.C}^{\text{P Support/Sanction}} \\
\dfrac{dP}{dt} = \pm \overbrace{U_{0c}.P}^{\text{Natural Growth/Decay}} \pm \overbrace{U_{7f}.C}^{\text{Impact of SES Settings}} - \overbrace{U_{7e}.C}^{\text{Externalities}} & (1d) \\
\quad \pm \overbrace{U_{2a}.E.P}^{\text{Join/Support/Sanction}} \pm \overbrace{U_{3b}.C.P}^{\text{Join/Support/Sanction}}
\end{cases}
$$

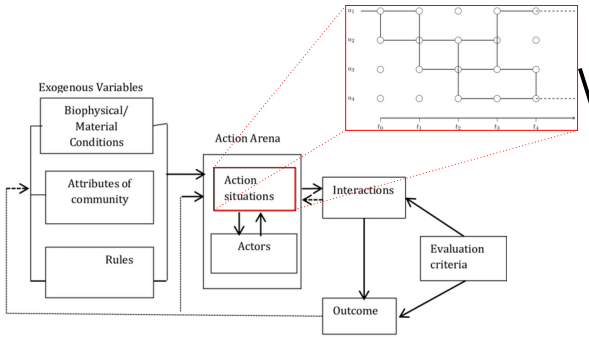
Muneepeerakul, R., & Anderies, J. M. (2020). The emergence and resilience of self-organized governance in coupled infrastructure systems. Proceedings of the National Academy of Sciences, 117(9), 4617-4622.

Houbbalah M., Mathias J.-D. and T. Cordonnier. (2021). An infrastructure perspective for enhancing multi-functionality of forests: A conceptual modeling approach. Earth's Future.

Viability (robustness):

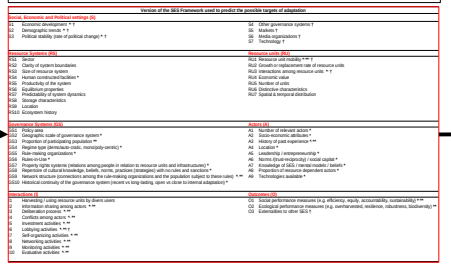
$$\mathrm{Viab}_f(K) = \{\mathbf{x}(0) \in K \mid \exists u(.) \in U \text{such that} \forall t \geq 0, \mathbf{x}(u(.)) \in K\}$$

Step (1) : SES targets



$U = \{u_1, u_2, u_3, \ldots u_n\}$

SES Framework



Attributs : Tier 1

$U = \{U_S, U_{RS}, U_{RU}, U_{GS}, U_A, U_I, U_O\}$

Tier 2

$U_S = \{u_{S1}, u_{S2}, \ldots, u_{S7}\}$

$U_{RS} = \{u_{RS1}, u_{RS2}, \ldots, u_{RS10}\}$

$U_{RU} = \{u_{RU1}, u_{RU2}, \ldots, u_{RS7}\}$

$U_{GS} = \{u_{GS1}, u_{GS2}, \ldots, u_{GS10}\}$

$U_A = \{u_{A1}, u_{A2}, \ldots, u_{A9}\}$

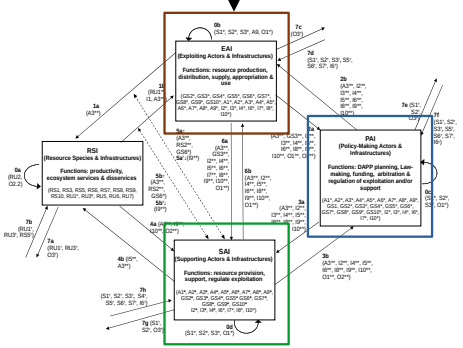
$U_I = \{u_{I1}, u_{I2}, \ldots, u_{I10}\}$

$U_O = \{u_{O1}, u_{O2}, u_{O3}\}$

Tier 3

...

Step (2) Triggering Roles



Exploitation (E)

$U^E = \{U^E_S, U^E_{RS}, U^E_{RU}, U^E_{GS}, U^E_A, U^E_I, U^E_O\}$

$U^E = \{u^E_{0b}, u^E_{1a}, u^E_{1b}, u^E_{2a}, u^E_{6a}, u^E_{7c}, u^E_{7d}\}$

Arbitrage politique (P)

$U^P = \{U^P_S, U^P_{RS}, U^P_{RU}, U^P_{GS}, U^P_A, U^P_I, U^P_O\}$

$U^P = \{u^P_{0c}, u^P_{2b}, u^P_{3a}, u^P_{7e}, u^P_{7f}\}$

Conservation (C)

$U^C = \{U^C_S, U^C_{RS}, U^C_{RS}, U^C_{GS}, U^C_A, U^C_i, U^C_O\}$

$U^C = \{u^C_{0d}, u^C_{4a}, u^C_{4b}, u^C_{5a}, u^C_{5b}, u^C_{6b}, u^C_{7g}, u^C_{7h}\}$

Step (3) Nested governance

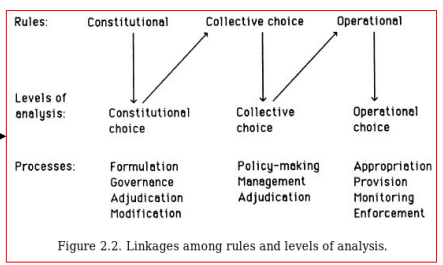
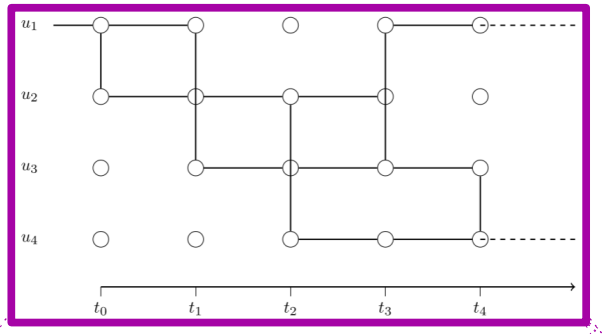
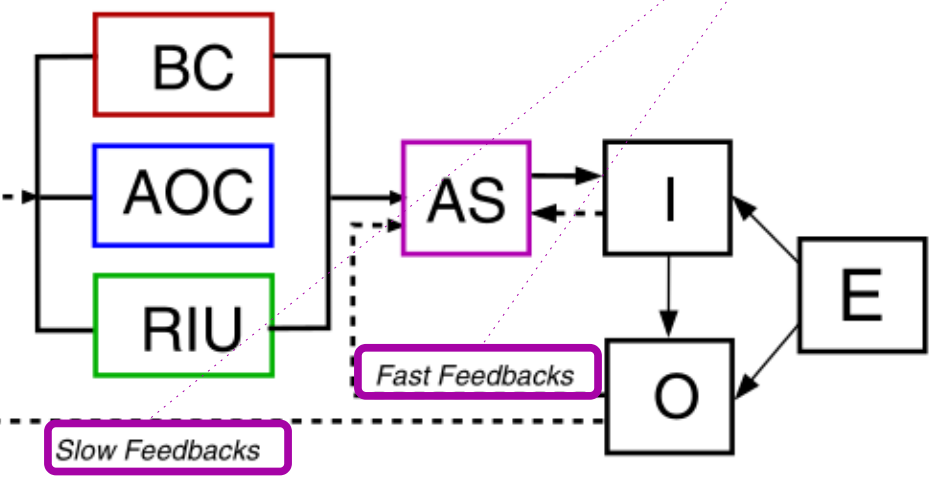


Figure 2.2. Linkages among rules and levels of analysis.

CIS & Robustness framework
Nested governance

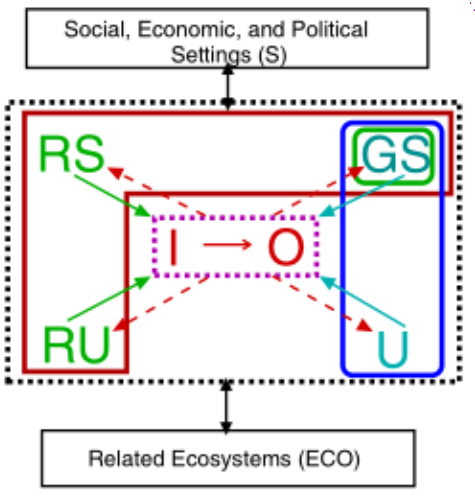


DAPP = “action situation”



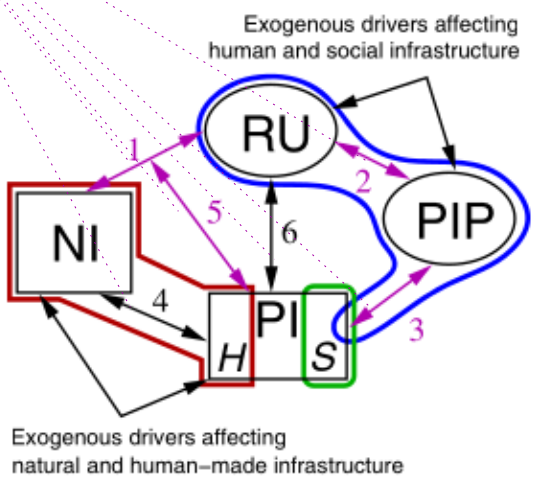
IAD Framework

a



Diagnostic/SES Framework

b



Robustness Framework

c

Filtre 3 : Nested levels of gouvernance

Spread actors per nested levels of governance for adaptation actions

Principe 8-B : "*Nested governance*"

Exploitation (E)

$U_E = \{U_{E:S}, U_{E:RS}, U_{E:RU}, U_{E:GS}, U_{E:A}, U_{E:I}, U_{E:O}\}$

$U^E = \{u_{E:0b}, u_{E:1a}, u_{E:1b}, u_{E:2a}, u_{E:6a}, u_{E:7c}, u_{E:7d}\}$

Arbitration (P)

$U_P = \{U_{P:S}, U_{P:RS}, U_{P:RU}, U_{P:GS}, U_{P:A}, U_{P:I}, U_{P:O}\}$

$U_P = \{u_{P:0c}, u_{P:2b}, u_{P:3a}, u_{P:7e}, u_{P:7f}\}$

Conservation (C)

$U_C = \{U_{C:S}, U_{C:RS}, U_{C:RS}, U_{C:GS}, U_{C:A}, U_{C:I}, U_{C:O}\}$

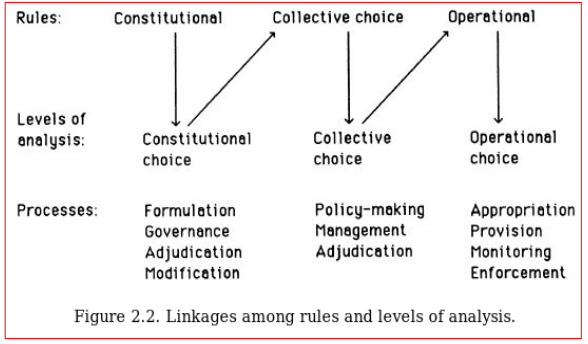


Figure 2.2. Linkages among rules and levels of analysis.

Ostrom, E. (1990). Governing the commons: The evolution of institutions for collective action. Cambridge University Press.

Constitutional (CCA)

$U^E = \{u_{E:0b}, u_{E:1a}, u_{E:1b}, u_{E:2a}, u_{E:6a}, u_{E:7c}, u_{E:7d}\}$?

$U_P = \{u_{P:0c}, u_{P:2b}, u_{P:3a}, u_{P:7e}, u_{P:7f}\}$?

$U_C = \{u_{C:0d}, u_{C:4a}, u_{C:4b}, u_{C:5a}, u_{C:5b}, u_{C:6b}, u_{C:7g}, u_{C:7h}\}$?

Who ? What ?

Collective (KCA)

Composition de rôles & d'actions (chaînes)

$U^{KCA-1} = u_{E:1a}(x) \circ (u_{C:6b} + u_{C:5a})$?

$U^{KCA-2} = u_{E:1a}(x) + u_{C:4b}$?

$U^{KCA-3} = u_{E:1a}(x) \circ (u_{C:6b} + u_{C:5a}) + u_{C:4b}$? ...

How ?

Operational (OCA)

$u_{E:1a}(x) = [0.1 – 0.5]$?, $= [0.5 – 0.9]$?

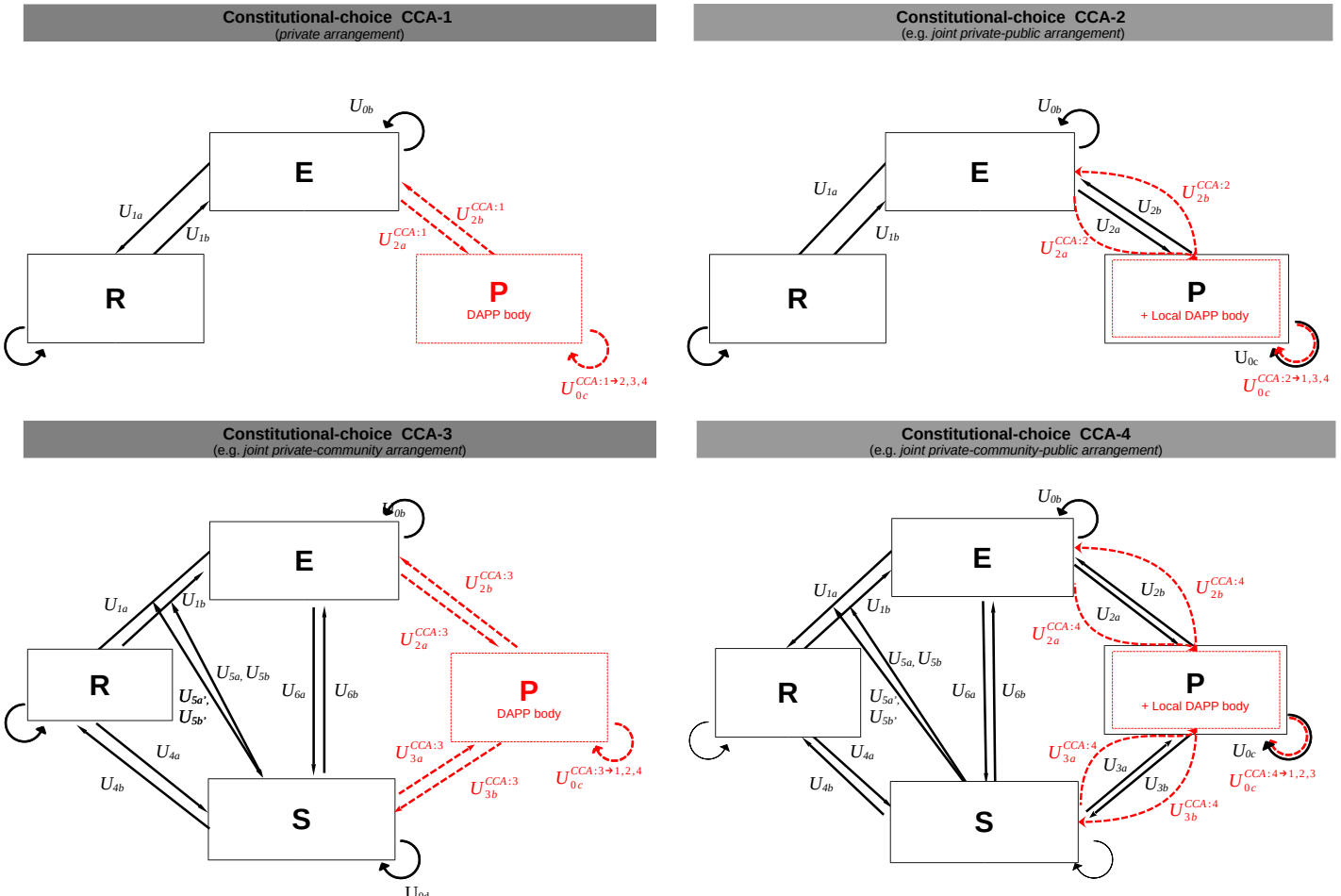
$u_{C:4b}(x) = [0.2 – 0.3]$?, $= [0.7 – 0.8]$?

...

How much ?

What constitutional choice or who can join ?

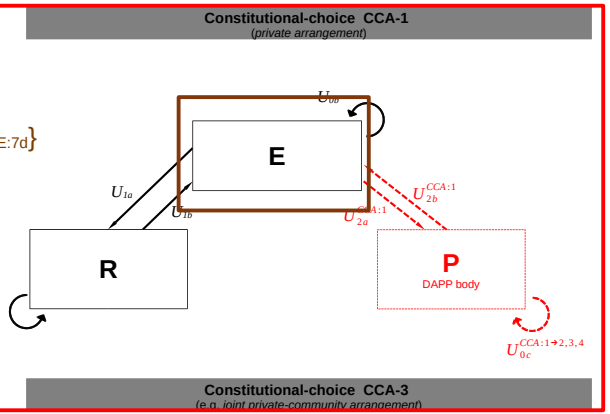
Adapt roles of actors & infra. that belong to *U* = {…}

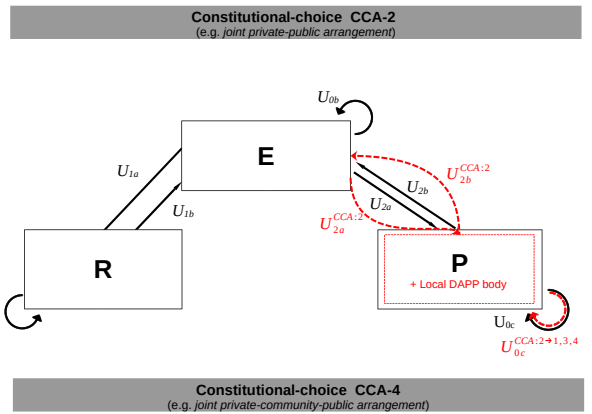


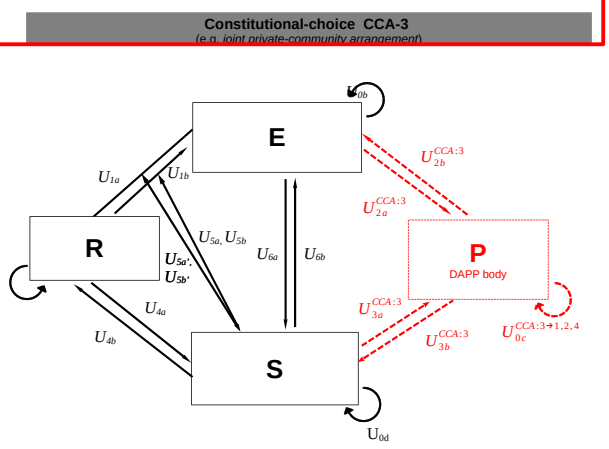
What constitutional choice or who can join ?

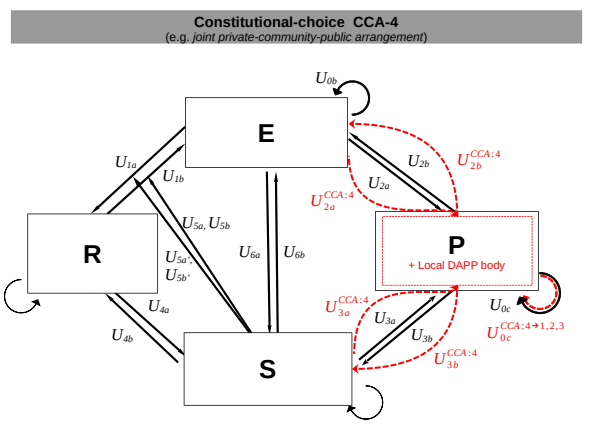
Private arrangement around the resource

$U^E = \{u_{E:0b}, u_{E:1a}, u_{E:1b}, u_{E:2a}, u_{E:6a}, u_{E:7c}, u_{E:7d}\}$



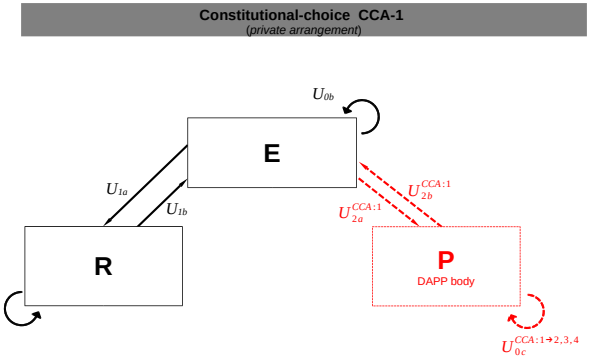


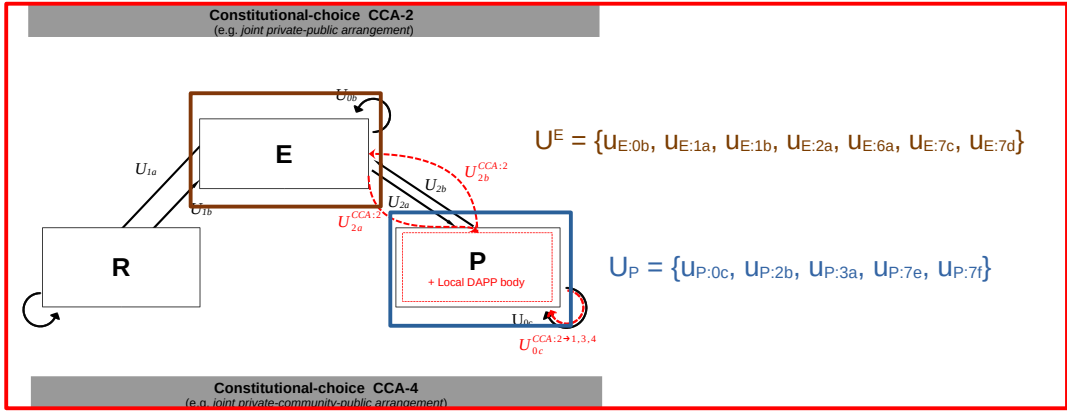


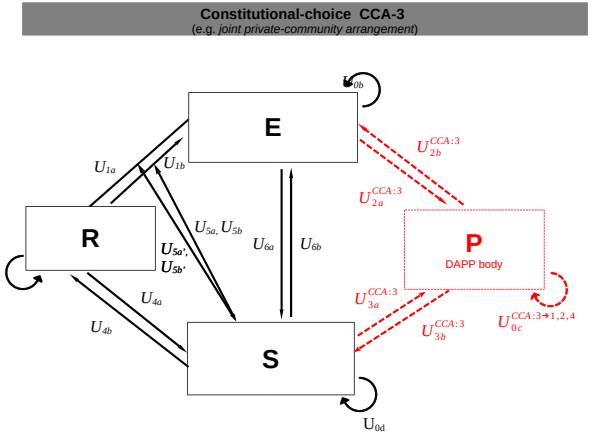


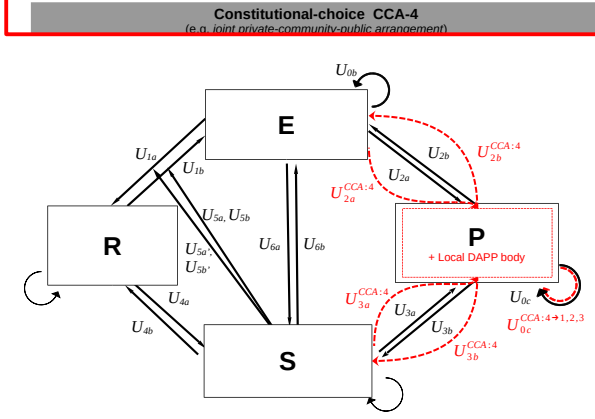
What constitutional choice or who can join ?

Private-Public arrangement





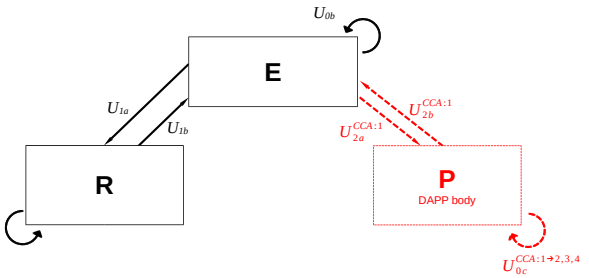




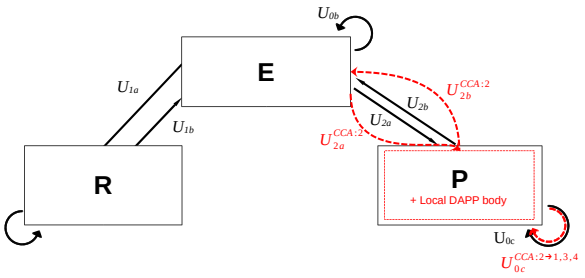
What constitutional choice or who can join ?

Private-Community Arrangement

Constitutional-choice CCA-1
(*private arrangement*)

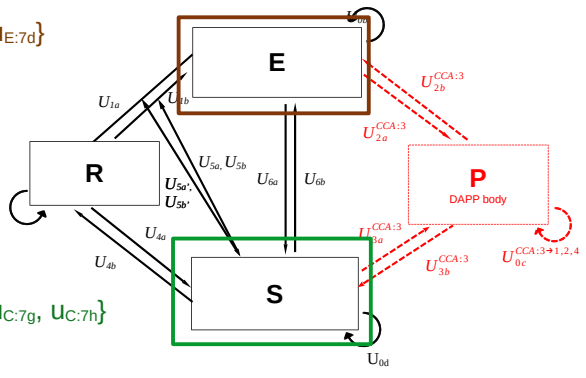


Constitutional-choice CCA-2
(e.g. *joint private-public arrangement*)



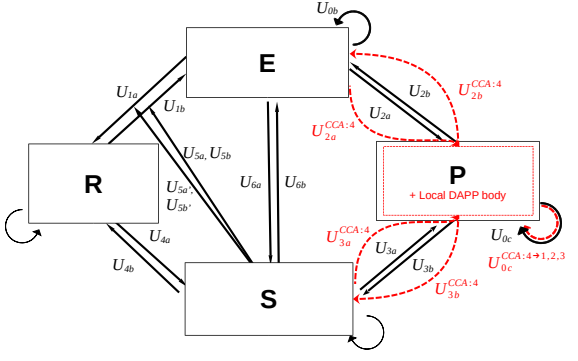
Constitutional-choice CCA-3
(e.g. *joint private-community arrangement*)

$U^E = \{u_{E:0b}, u_{E:1a}, u_{E:1b}, u_{E:2a}, u_{E:6a}, u_{E:7c}, u_{E:7d}\}$



$U_C = \{u_{C:0d}, u_{C:4a}, u_{C:4b}, u_{C:5a}, u_{C:5b}, u_{C:6b}, u_{C:7g}, u_{C:7h}\}$

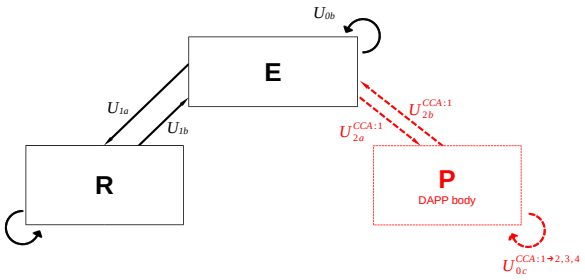
Constitutional-choice CCA-4
(e.g. *joint private-community-public arrangement*)



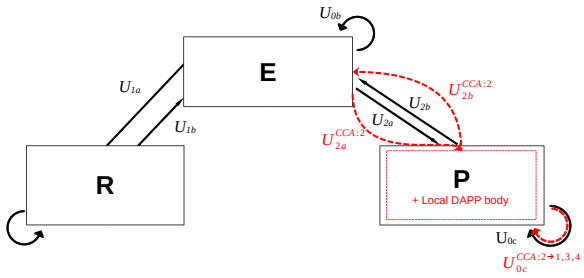
What constitutional choice or who can join ?

Private-Public-Community arrangement

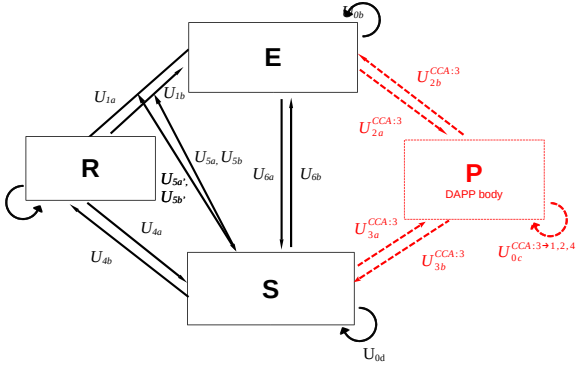
Constitutional-choice CCA-1
(*private arrangement*)



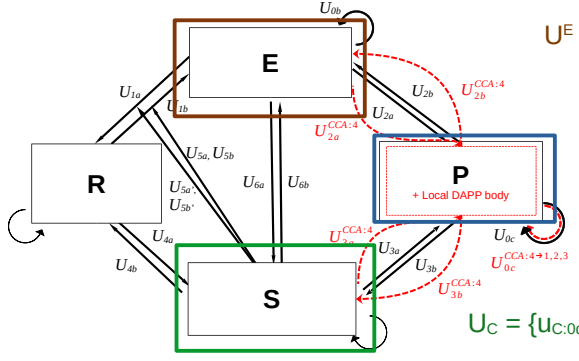
Constitutional-choice CCA-2
(e.g. *joint private-public arrangement*)



Constitutional-choice CCA-3
(e.g. *joint private-community arrangement*)



Constitutional-choice CCA-4
(e.g. *joint private-community-public arrangement*)



$U^{E} = \{u_{E:0b}, u_{E:1a}, u_{E:1b}, u_{E:2a}, u_{E:6a}, u_{E:7c}, u_{E:7d}\}$

$U_{P} = \{u_{P:0c}, u_{P:2b}, u_{P:3a}, u_{P:7e}, u_{P:7f}\}$

$U_{C} = \{u_{C:0d}, u_{C:4a}, u_{C:4b}, u_{C:5a}, u_{C:5b}, u_{C:6b}, u_{C:7g}, u_{C:7h}\}$

What constitutional choice or who can join ?

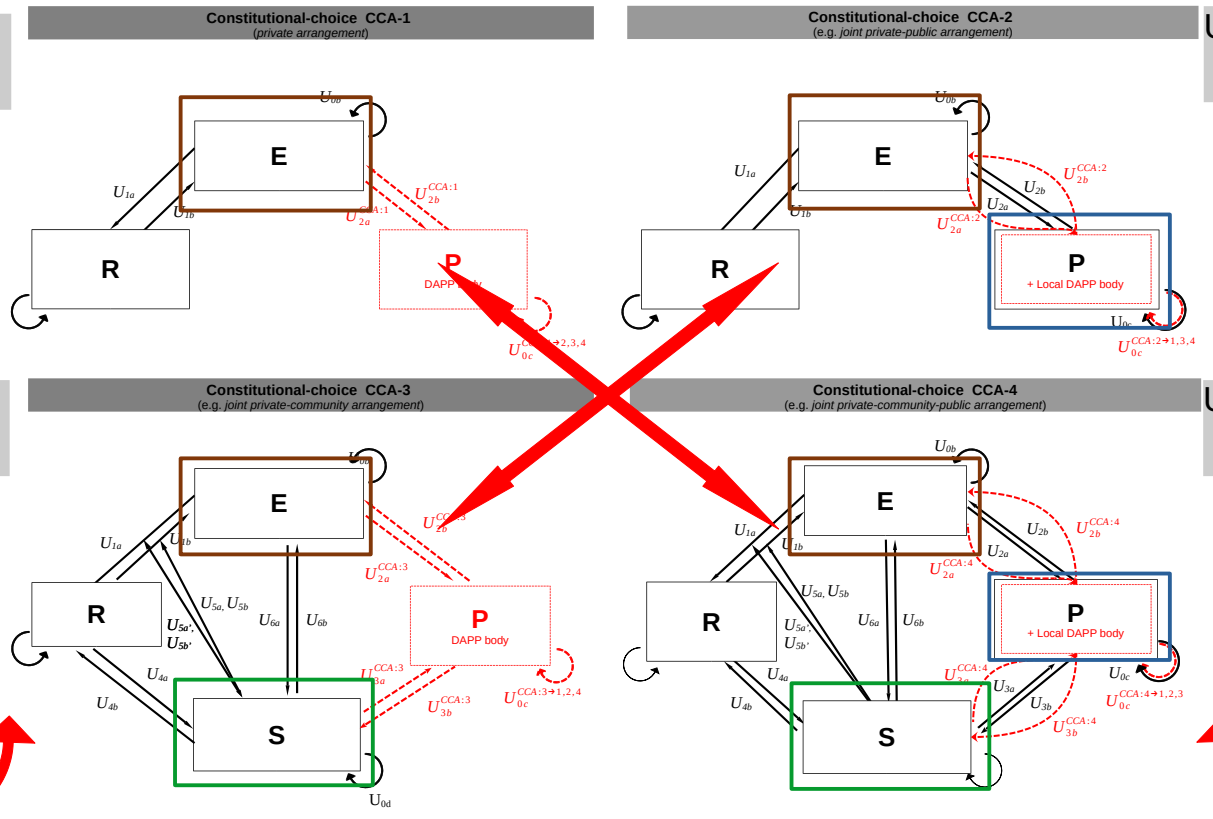
$$U = \{U^{CCA\text{-}1}, U^{CCA\text{-}2}, U^{CCA\text{-}3}, U^{CCA\text{-}4}\}$$

$U^{CCA\text{-}1} = \{U^{CCA\text{-}1\to1}, U^{CCA\text{-}1\to2}, U^{CCA\text{-}1\to3}, U^{CCA\text{-}1\to4}\}$

$U^{CCA\text{-}2} = \{U^{CCA\text{-}2\to1}, U^{CCA\text{-}2\to2}, U^{CCA\text{-}2\to3}, U^{CCA\text{-}2\to4}\}$

$U^{CCA\text{-}3} = \{U^{CCA\text{-}3\to1}, U^{CCA\text{-}3\to2}, U^{CCA\text{-}3\to3}, U^{CCA\text{-}3\to4}\}$

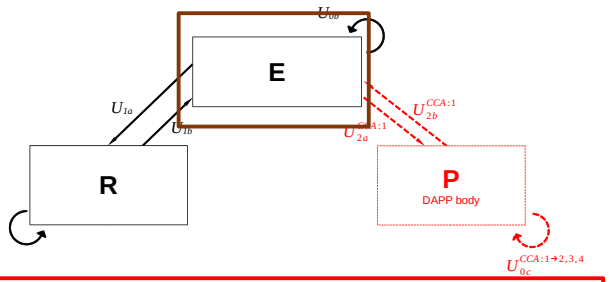
$U^{CCA\text{-}4} = \{U^{CCA\text{-}4\to1}, U^{CCA\text{-}4\to2}, U^{CCA\text{-}4\to3}, U^{CCA\text{-}4\to4}\}$



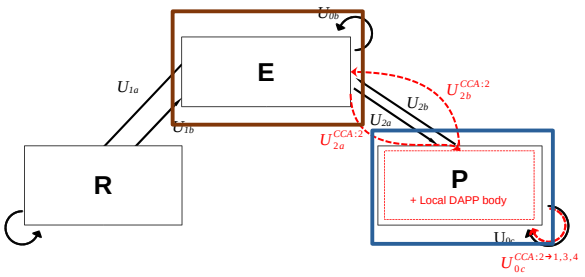
What constitutional choice or who can join ?

Private-Community Arrangement

Constitutional-choice CCA-1
(*private arrangement*)

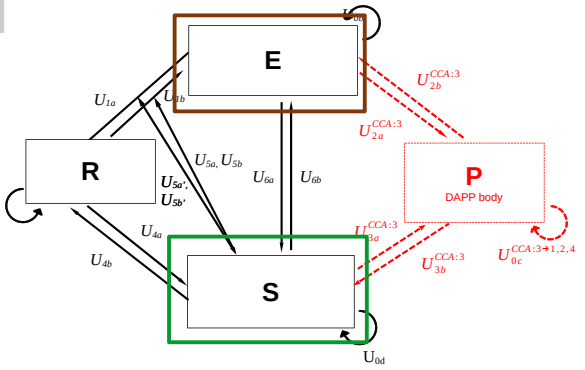


Constitutional-choice CCA-2
(e.g. *joint private-public arrangement*)

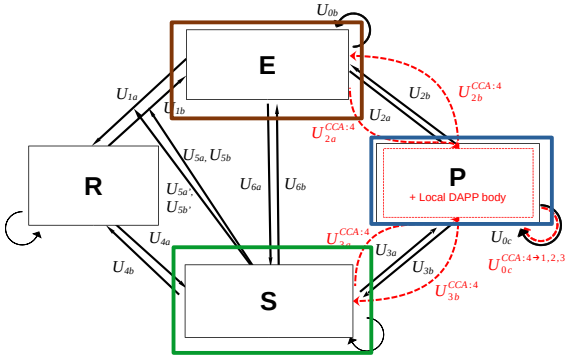


$U^{CCA\text{-}3} = \{U^{CCA\text{-}3\to1}, U^{CCA\text{-}3\to2}, U^{CCA\text{-}3\to3}, U^{CCA\text{-}3\to4}\}$

Constitutional-choice CCA-3
(e.g. *joint private-community arrangement*)



Constitutional-choice CCA-4
(e.g. *joint private-community-public arrangement*)

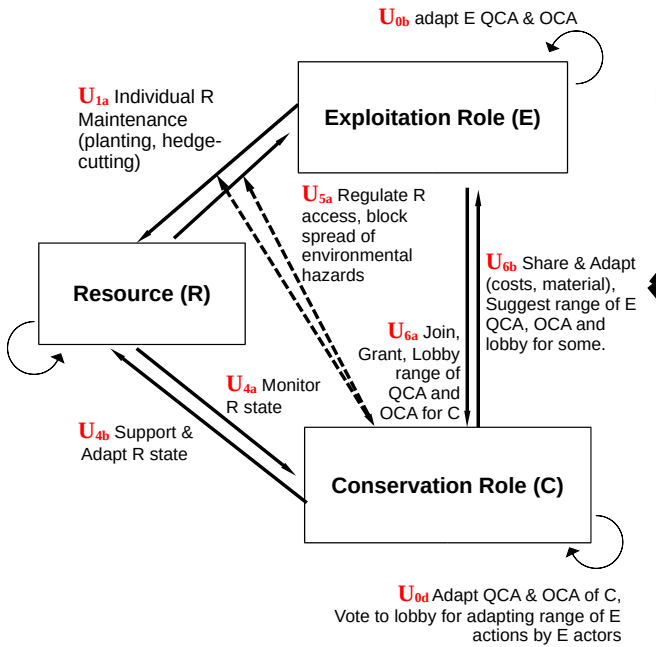


What collective choice or how to join?

Adapt composition (chains / network) of roles & actions ($u_1(x) \circ u_2$)

$U^{KCA} = \{U^{KCA:1}, U^{KCA:2}, U^{KCA:3}\} \in U^{CCA:3}$

Constitutional-choice CCA-3
(e.g. *joint private-community arrangement*)

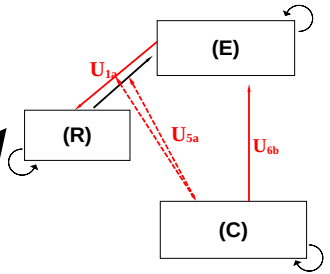


KCA-1

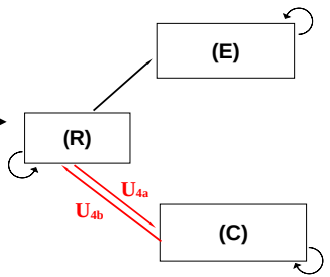
KCA-2

KCA-3

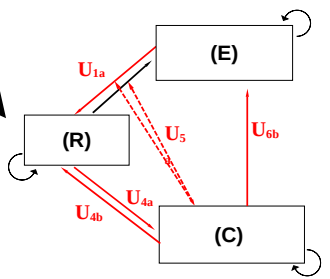
Collective-choice KCA-1



Collective-choice KCA-2



Collective-choice KCA-3



$U^{KCA:1} : u_{1a}(R) \circ (u_{6b} + u_{5a})$

$U^{KCA:1} = \{U^{KCA:1\to1}, U^{KCA:1\to2}, U^{KCA:1\to3}\}$

$U^{KCA:2} : u_{1a}(R) + u_{4b} \circ u_{4a}$

$U^{KCA:2} = \{U^{KCA:2\to1}, U^{KCA:2\to2}, U^{KCA:2\to3}\}$

$U^{KCA:3} : u_{1a}(R) \circ (u_{6b} + u_{5a}) + u_{4b} \circ u_{4a}$

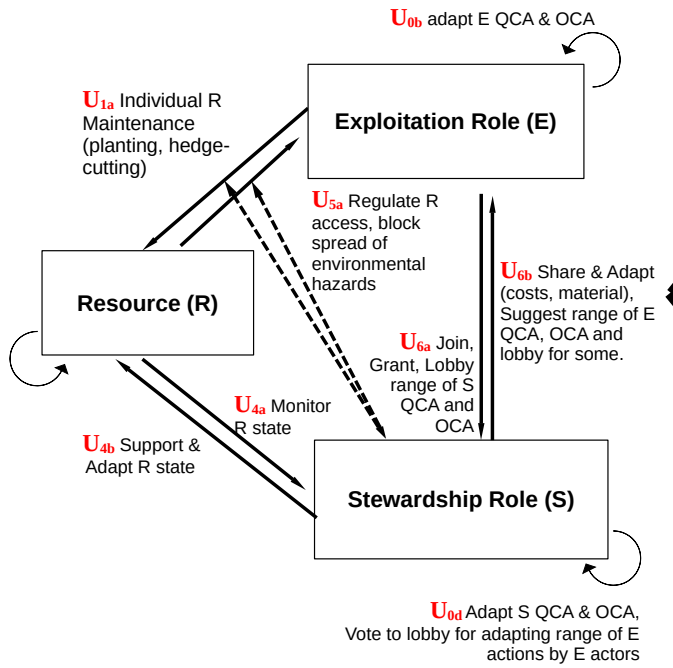
$U^{KCA:3} = \{U^{KCA:3\to1}, U^{KCA:3\to2}, U^{KCA:3\to3}\}$

What collective choice or how to join?

Adapt composition (chains / network) of roles & actions ($u_1(x) \circ u_2$)

$U^{KCA} = \{U^{KCA:1}, U^{KCA:2}, U^{KCA:3}\} \in U^{CCA:3}$

Constitutional-choice CCA-3
(e.g. *joint private-community arrangement*)

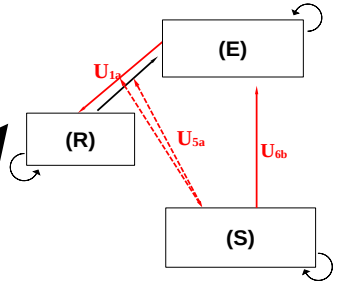


KCA-1

KCA-2

KCA-3

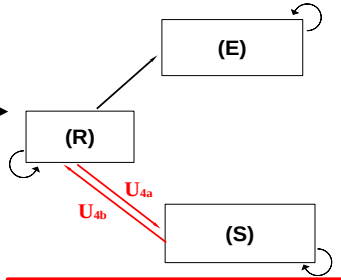
Collective-choice KCA-1



$U^{KCA:1} : u_{1a}(R) \circ (u_{6b} + u_{5a})$

$U^{KCA:1} = \{U^{KCA:1\to1}, U^{KCA:1\to2}, U^{KCA:1\to3}\}$

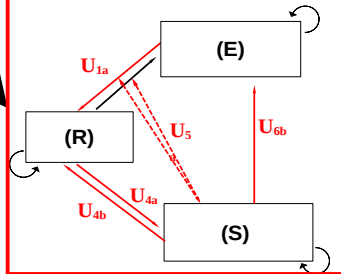
Collective-choice KCA-2



$U^{KCA:2} : u_{1a}(R) + u_{4b} \circ u_{4a}$

$U^{KCA:2} = \{U^{KCA:2\to1}, U^{KCA:2\to2}, U^{KCA:2\to3}\}$

Collective-choice KCA-3



$U^{KCA:3} : u_{1a}(R) \circ (u_{6b} + u_{5a}) + u_{4b} \circ u_{4a}$

$U^{KCA:3} = \{U^{KCA:3\to1}, U^{KCA:3\to2}, U^{KCA:3\to3}\}$

What operational choice or which level of action ?

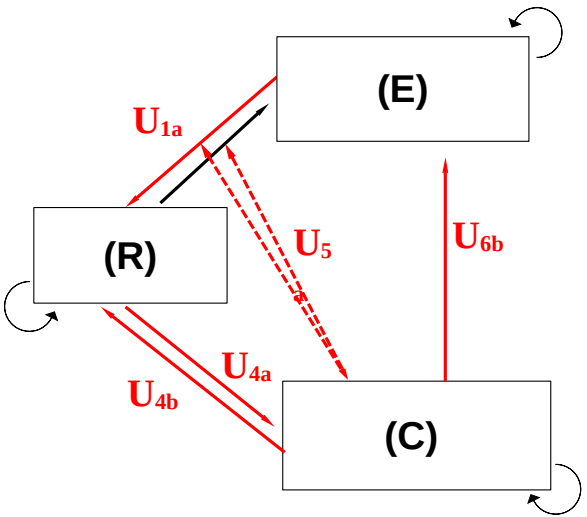
Adapt intensity, frequency of actions

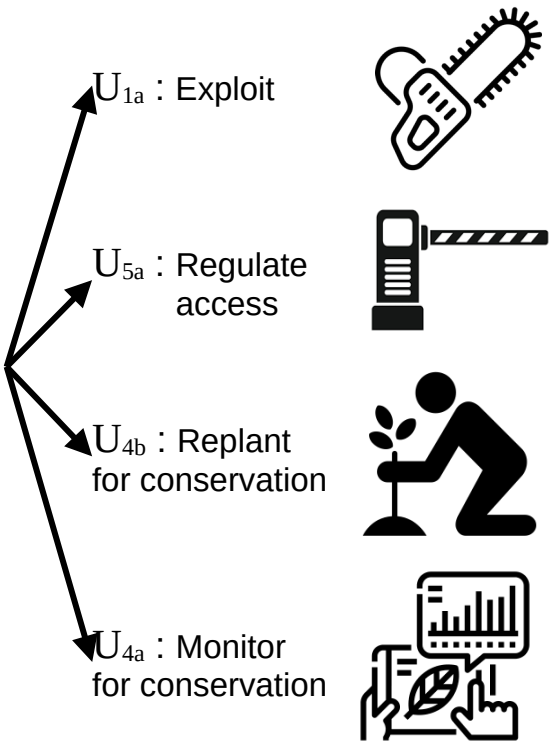
$U^{OCA} = \{U^{OCA:1}, U^{OCA:2}\} \in U^{KCA:3}$

$U^{OCA:1} = \{U^{OCA:1\to1}, U^{OCA:1\to2}\}$

$U^{OCA:2} = \{U^{OCA:2\to1}, U^{OCA:2\to2}\}$

Collective-choice KCA-3





	OCA-1	OCA-2
U_{1a} =	{= [0.1 – 0.5],	= [0.5 – 0.9]}
U_{5a} =	{≤ - 0.05,	≤ - 0.4}
U_{4b} =	{= 0.2,	= [0.3 – 0.4]}
U_{4a} =	{= 0.1,	≥ 0.5}

$U = \{u_1, u_2, \ldots, u_n\}$

SES framework

$U = \{u_1, u_2, \ldots, u_n\}$

Construction the set U of 2nd tier actions based on a version of Ostrom's social-ecological system framework (SESF)

Set of actions related to the social, economic & political Settings (U_S)

- U_{S1} Economic development * †
- U_{S2} Demographic trends * †
- U_{S3} Political stability (rate of political change) * †
- U_{S4} Other governance systems †
- U_{S5} Markets †
- U_{S6} Media organizations †
- U_{S7} Technology †

Set of actions related to the Resource Systems (U_{RS})

- U_{RS1} Sector
- U_{RS2} Clarity of system boundaries
- U_{RS3} Size of resource system
- U_{RS4} Human constructed facilities *
- U_{RS5} Productivity of the system
- U_{RS6} Equilibrium properties
- U_{RS7} Predictability of system dynamics
- U_{RS8} Storage characteristics
- U_{RS9} Location
- U_{RS10} Ecosystem history

Set of actions related to the Resource Units (U_{RU})

- U_{RU1} Resource unit mobility * ** †
- U_{RU2} Growth or replacement rate of resource units
- U_{RU3} Interactions among resource units * †
- U_{RU4} Economic value
- U_{RU5} Number of units
- U_{RU6} Distinctive characteristics
- U_{RU7} Spatial & temporal distribution

Set of actions related to the Governance Systems (U_{GS})

- U_{GS1} Policy area
- U_{GS2} Geographic scale of governance system *
- U_{GS3} Proportion of participating population **
- U_{GS4} Regime type (demo/auto-cratic, mono/poly-centric) *
- U_{GS5} Rule-making organizations *
- U_{GS6} Rules-in-Use *
- U_{GS7} Property rights systems (relations among people in relation to resource units and infrastructures) *
- U_{GS8} Repertoire of cultural knowledge, beliefs, norms, practices (strategies) with no rules and sanctions *
- U_{GS9} Network structure (connections among the rule-making organizations and the population subject to these rules) * **
- U_{GS10} Historical continuity of the governance system (recent vs long-lasting, open vs close to internal adaptation) *

Set of actions related to the Actors (U_A)

- U_{A1} Number of relevant actors *
- U_{A2} Socio-economic attributes *
- U_{A3} History of past experience * **
- U_{A4} Location *
- U_{A5} Leadership / entrepreneurship *
- U_{A6} Norms (trust-reciprocity) / social capital *
- U_{A7} Knowledge of SES / mental models / beliefs *
- U_{A8} Proportion of resource dependent actors *
- U_{A9} Technologies available *

Set of actions related to the Interactions (U_I)

- U_{I1} Harvesting / using resource units by divers users
- U_{I2} Information sharing among actors * **
- U_{I3} Deliberation process * **
- U_{I4} Conflicts among actors * **
- U_{I5} Investment activities * **
- U_{I6} Lobbying activities * ** †
- U_{I7} Self-organizing activities * **
- U_{I8} Networking activities * **
- U_{I9} Monitoring activities * **
- U_{I10} Evaluative activities * **

Set of actions related to the Outcomes (U_O)

- U_{O1} Social performance measures (e.g. efficiency, equity, accountability, sustainability) * **
- U_{O2} Ecological performance measures (e.g. overharvested, resilience, robustness, biodiversity) **
- U_{O3} Externalities to other SES †

CIS framework

$$U = \{u_1, u_2, \ldots, u_n\}$$

Construction the set U of 2nd tier actions based on a version of Ostrom's social-ecological system framework (SESF)

Set of actions related to the social, economic & political Settings (U_S)

U_{S1}	Economic development * †
U_{S2}	Demographic trends * †
U_{S3}	Political stability (rate of political change) * †
U_{S4}	Other governance systems †
U_{S5}	Markets †
U_{S6}	Media organizations †
U_{S7}	Technology †

Set of actions related to the Resource Systems (U_{RS})

U_{RS1}	Sector
U_{RS2}	Clarity of system boundaries
U_{RS3}	Size of resource system
U_{RS4}	Human constructed facilities *
U_{RS5}	Productivity of the system
U_{RS6}	Equilibrium properties
U_{RS7}	Predictability of system dynamics
U_{RS8}	Storage characteristics
U_{RS9}	Location
U_{RS10}	Ecosystem history

Set of actions related to the Resource Units (U_{RU})

U_{RU1}	Resource unit mobility * ** †
U_{RU2}	Growth or replacement rate of resource units
U_{RU3}	Interactions among resource units * †
U_{RU4}	Economic value
U_{RU5}	Number of units
U_{RU6}	Distinctive characteristics
U_{RU7}	Spatial & temporal distribution

Set of actions related to the Governance Systems (U_{GS})

U_{GS1}	Policy area
U_{GS2}	Geographic scale of governance system *
U_{GS3}	Proportion of participating population **
U_{GS4}	Regime type (demo/auto-cratic, mono/poly-centric) *
U_{GS5}	Rule-making organizations *
U_{GS6}	Rules-in-Use *
U_{GS7}	Property rights systems (relations among people in relation to resource units and infrastructures) *
U_{GS8}	Repertoire of cultural knowledge, beliefs, norms, practices (strategies) with no rules and sanctions *
U_{GS9}	Network structure (connections among the rule-making organizations and the population subject to these rules) * **
U_{GS10}	Historical continuity of the governance system (recent vs long-lasting, open vs close to internal adaptation) *

Set of actions related to the Actors (U_A)

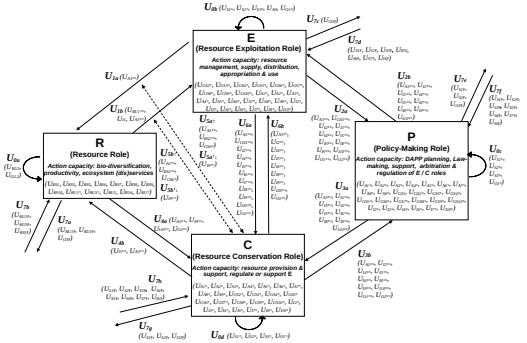
U_{A1}	Number of relevant actors *
U_{A2}	Socio-economic attributes *
U_{A3}	History of past experience * **
U_{A4}	Location *
U_{A5}	Leadership / entrepreneurship *
U_{A6}	Norms (trust-reciprocity) / social capital *
U_{A7}	Knowledge of SES / mental models / beliefs *
U_{A8}	Proportion of resource dependent actors *
U_{A9}	Technologies available *

Set of actions related to the Interactions (U_I)

U_{I1}	Harvesting / using resource units by divers users
U_{I2}	Information sharing among actors * **
U_{I3}	Deliberation process * **
U_{I4}	Conflicts among actors * **
U_{I5}	Investment activities * **
U_{I6}	Lobbying activities * ** †
U_{I7}	Self-organizing activities * **
U_{I8}	Networking activities * **
U_{I9}	Monitoring activities * **
U_{I10}	Evaluative activities * **

Set of actions related to the Outcomes (U_O)

U_{O1}	Social performance measures (e.g. efficiency, equity, accountability, sustainability) * **
U_{O2}	Ecological performance measures (e.g. overharvested, resilience, robustness, biodiversity) **
U_{O3}	Externalities to other SES †



$U = \{u_1, u_2, \ldots, u_n\}$

Construction the set U of 2nd tier actions based on a version of Ostrom's social-ecological system framework (SESF)

Set of actions related to the social, economic & political Settings (U_S)

U_{S1}	Economic development * †
U_{S2}	Demographic trends * †
U_{S3}	Political stability (rate of political change) * †
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U_{S5}	Markets †
U_{S6}	Media organizations †
U_{S7}	Technology †

Set of actions related to the Resource Systems (U_{RS})

U_{RS1}	Sector
U_{RS2}	Clarity of system boundaries
U_{RS3}	Size of resource system
U_{RS4}	Human constructed facilities *
U_{RS5}	Productivity of the system
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U_{RS7}	Predictability of system dynamics
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U_{RS9}	Location
U_{RS10}	Ecosystem history

Set of actions related to the Resource Units (U_{RU})

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U_{RU2}	Growth or replacement rate of resource units
U_{RU3}	Interactions among resource units * †
U_{RU4}	Economic value
U_{RU5}	Number of units
U_{RU6}	Distinctive characteristics
U_{RU7}	Spatial & temporal distribution

Set of actions related to the Governance Systems (U_{GS})

U_{GS1}	Policy area
U_{GS2}	Geographic scale of governance system *
U_{GS3}	Proportion of participating population **
U_{GS4}	Regime type (democratic-cratic, mono/poly-centric) *
U_{GS5}	Rule-making organizations *
U_{GS6}	Rules-in-Use *
U_{GS7}	Property rights systems (relations among people in relation to resource units and infrastructures) *
U_{GS8}	Repertoire of cultural knowledge, beliefs, norms, practices (strategies) with no rules and sanctions *
U_{GS9}	Network structure (connections among the rule-making organizations and the population subject to these rules) * **
U_{GS10}	Historical continuity of the governance system (recent vs long-lasting, open vs close to internal adaptation) *

Set of actions related to the Actors (U_A)

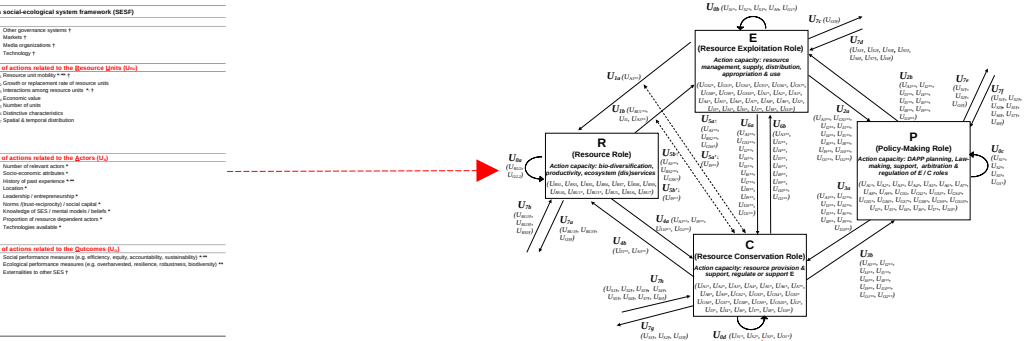
U_{A1}	Number of relevant actors *
U_{A2}	Socio-economic attributes *
U_{A3}	History of past experience * **
U_{A4}	Location *
U_{A5}	Leadership / entrepreneurship *
U_{A6}	Norms (trust-reciprocity) / social capital *
U_{A7}	Knowledge of SES / mental models / beliefs *
U_{A8}	Proportion of resource dependent actors *
U_{A9}	Technologies available *

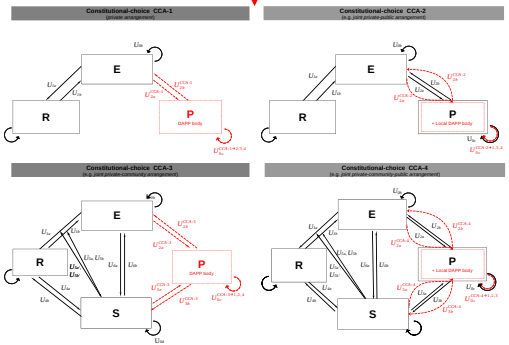
Set of actions related to the Interactions (U_I)

U_{I1}	Harvesting / using resource units by divers users
U_{I2}	Information sharing among actors * **
U_{I3}	Deliberation process * **
U_{I4}	Conflicts among actors * **
U_{I5}	Investment activities * **
U_{I6}	Lobbying activities * ** †
U_{I7}	Self-organizing activities * **
U_{I8}	Networking activities * **
U_{I9}	Monitoring activities * **
U_{I10}	Evaluative activities * **

Set of actions related to the Outcomes (U_O)

U_{O1}	Social performance measures (e.g. efficiency, equity, accountability, sustainability) * **
U_{O2}	Ecological performance measures (e.g. overharvested, resilience, robustness, biodiversity) **
U_{O3}	Externalities to other SES †





Constitutional-level adaptation actions

$U = \{u_1, u_2, \ldots, u_n\}$

Construction the set U of 2nd tier actions based on a version of Ostrom's social-ecological system framework (SESF)

Set of actions related to the social, economic & political Settings (U_S)

- U_{S1} Economic development * †
- U_{S2} Demographic trends * †
- U_{S3} Political stability (rate of political change) * †
- U_{S4} Other governance systems †
- U_{S5} Markets †
- U_{S6} Media organizations †
- U_{S7} Technology †

Set of actions related to the Resource Systems (U_{RS})

- U_{RS1} Sector
- U_{RS2} Clarity of system boundaries
- U_{RS3} Size of resource system
- U_{RS4} Human constructed facilities *
- U_{RS5} Productivity of the system
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- U_{RS7} Predictability of system dynamics
- U_{RS8} Storage characteristics
- U_{RS9} Location
- U_{RS10} Ecosystem history

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- U_{RU2} Growth or replacement rate of resource units
- U_{RU3} Interactions among resource units * †
- U_{RU4} Economic value
- U_{RU5} Number of units
- U_{RU6} Distinctive characteristics
- U_{RU7} Spatial & temporal distribution

Set of actions related to the Governance Systems (U_{GS})

- U_{GS1} Policy area
- U_{GS2} Geographic scale of governance system *
- U_{GS3} Proportion of participating population **
- U_{GS4} Regime type (democlauto-cratic, mono/poly-centric) *
- U_{GS5} Rule-making organizations *
- U_{GS6} Rules-in-Use *
- U_{GS7} Property rights systems (relations among people in relation to resource units and infrastructures) *
- U_{GS8} Repertoire of cultural knowledge, beliefs, norms, practices (strategies) with no rules and sanctions *
- U_{GS9} Network structure (connections among the rule-making organizations and the population subject to these rules) * **
- U_{GS10} Historical continuity of the governance system (recent vs long-lasting, open vs close to internal adaptation) *

Set of actions related to the Actors (U_A)

- U_{A1} Number of relevant actors *
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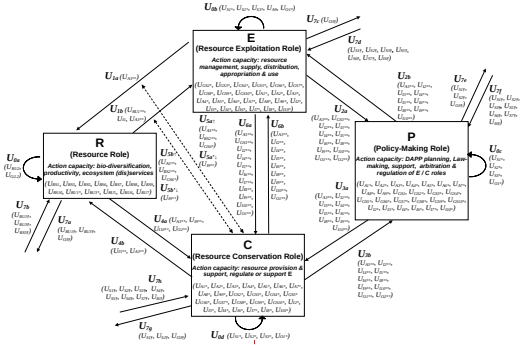
- U_{A3} History of past experience * **
- U_{A4} Location *
- U_{A5} Leadership / entrepreneurship *
- U_{A6} Norms (trust-reciprocity) / social capital *
- U_{A7} Knowledge of SES / mental models / beliefs *
- U_{A8} Proportion of resource dependent actors *
- U_{A9} Technologies available *

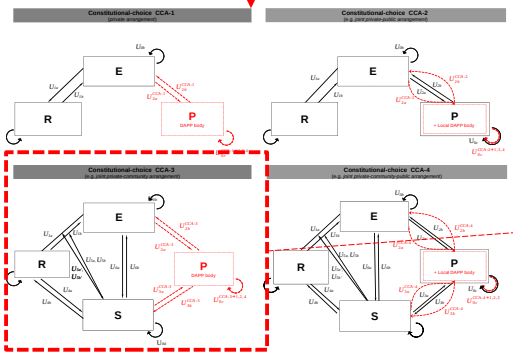
Set of actions related to the Interactions (U_I)

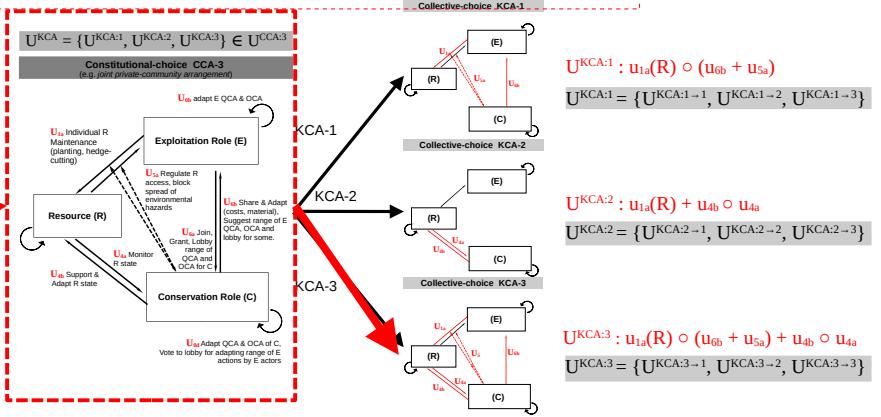
- U_{I1} Harvesting / using resource units by divers users
- U_{I2} Information sharing among actors * **
- U_{I3} Deliberation process * **
- U_{I4} Conflicts among actors * **
- U_{I5} Investment activities * **
- U_{I6} Lobbying activities * ** ‡
- U_{I7} Self-organizing activities * **
- U_{I8} Networking activities * **
- U_{I9} Monitoring activities * **
- U_{I10} Evaluative activities * **

Set of actions related to the Outcomes (U_O)

- U_{O1} Social performance measures (e.g. efficiency, equity, accountability, sustainability) * **
- U_{O2} Ecological performance measures (e.g. overharvested, resilience, robustness, biodiversity) **
- U_{O3} Externalities to other SES †







$U^{KCA:1}$: $u_{1a}(R) \circ (u_{6b} + u_{5a})$

$U^{KCA:1} = \{U^{KCA:1 \rightarrow 1}, U^{KCA:1 \rightarrow 2}, U^{KCA:1 \rightarrow 3}\}$

$U^{KCA:2}$: $u_{1a}(R) + u_{4b} \circ u_{4a}$

$U^{KCA:2} = \{U^{KCA:2 \rightarrow 1}, U^{KCA:2 \rightarrow 2}, U^{KCA:2 \rightarrow 3}\}$

$U^{KCA:3}$: $u_{1a}(R) \circ (u_{6b} + u_{5a}) + u_{4b} \circ u_{4a}$

$U^{KCA:3} = \{U^{KCA:3 \rightarrow 1}, U^{KCA:3 \rightarrow 2}, U^{KCA:3 \rightarrow 3}\}$

Collective-level adaptation actions

$U = \{u_1, u_2, \ldots, u_n\}$

Construction the set U of 2nd tier actions based on a version of Ostrom's social-ecological system framework (SESF)

Set of actions related to the social, economic & political Settings (U_s)

- U_{1s} Economic development * †
- U_{2s} Demographic trends * †
- U_{3s} Political stability (rate of political change) * †
- U_{4s} Other governance systems †
- U_{5s} Markets †
- U_{6s} Media organizations †
- U_{7s} Technology †

Set of actions related to the Resource Systems (U_{RS})

- U_{1RS} Sector
- U_{2RS} Clarity of system boundaries
- U_{3RS} Size of resource system
- U_{4RS} Human constructed facilities *
- U_{5RS} Productivity of the system
- U_{6RS} Equilibrium properties
- U_{7RS} Predictability of system dynamics
- U_{8RS} Storage characteristics
- U_{9RS} Location
- U_{10RS} Ecosystem history

Set of actions related to the Resource Units (U_{RU})

- U_{1RU} Resource unit mobility * ** †
- U_{2RU} Growth or replacement rate of resource units
- U_{3RU} Interactions among resource units * †
- U_{4RU} Economic value
- U_{5RU} Number of units
- U_{6RU} Distinctive characteristics
- U_{7RU} Spatial & temporal distribution

Set of actions related to the Governance Systems (U_{GS})

- U_{1GS} Policy area
- U_{2GS} Geographic scale of governance system *
- U_{3GS} Proportion of participating population **
- U_{4GS} Regime type (democauto-cratic, mono/poly-centric) *
- U_{5GS} Rule-making organizations *
- U_{6GS} Rules-in-Use *
- U_{7GS} Property rights systems (relations among people in relation to resource units and infrastructures) *
- U_{8GS} Repertoire of cultural knowledge, beliefs, norms, practices (strategies) with no rules and sanctions *
- U_{9GS} Network structure (connections among the rule-making organizations and the population subject to these rules) * **
- U_{10GS} Historical continuity of the governance system (recent vs long-lasting, open vs close to internal adaptation) *

Set of actions related to the Actors (U_A)

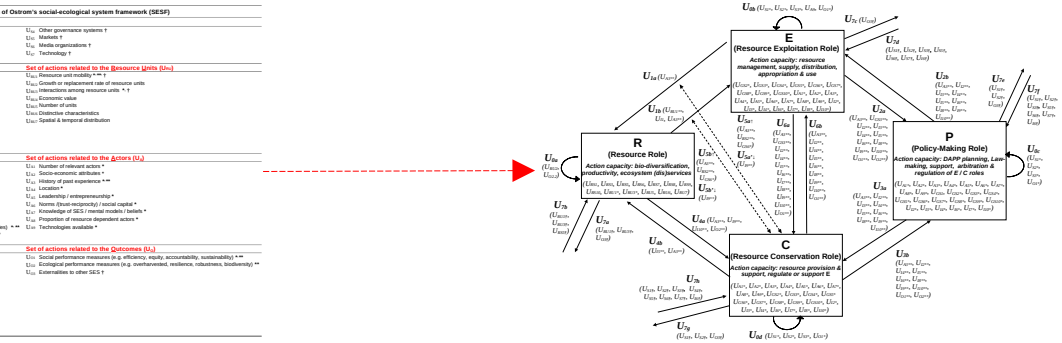
- U_{1A} Number of relevant actors *
- U_{2A} Socio-economic attributes *
- U_{3A} History of past experience * **
- U_{4A} Location *
- U_{5A} Leadership / entrepreneurship *
- U_{6A} Norms (trust-reciprocity) / social capital *
- U_{7A} Knowledge of SES / mental models / beliefs *
- U_{8A} Proportion of resource dependent actors *
- U_{9A} Technologies available *

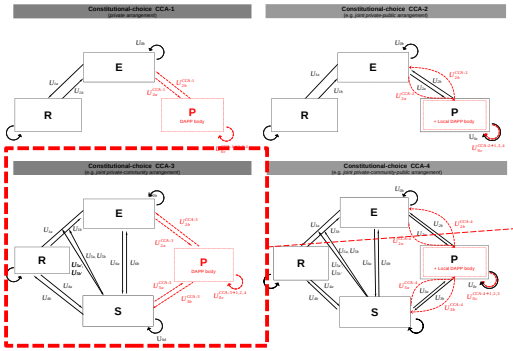
Set of actions related to the Interactions (U_I)

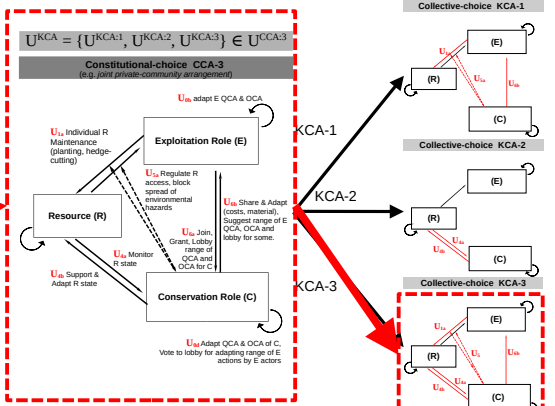
- U_{1I} Harvesting / using resource units by divers users
- U_{2I} Information sharing among actors * **
- U_{3I} Deliberation process * **
- U_{4I} Conflicts among actors * **
- U_{5I} Investment activities * **
- U_{6I} Lobbying activities * ** †
- U_{7I} Self-organizing activities * **
- U_{8I} Networking activities * **
- U_{9I} Monitoring activities * **
- U_{10I} Evaluative activities * **

Set of actions related to the Outcomes (U_O)

- U_{1O} Social performance measures (e.g. efficiency, equity, accountability, sustainability) * **
- U_{2O} Ecological performance measures (e.g. overharvested, resilience, robustness, biodiversity) **
- U_{3O} Externalities to other SES †







$U^{KCA:1} : u_{1a}(R) \circ (u_{6b} + u_{5a})$

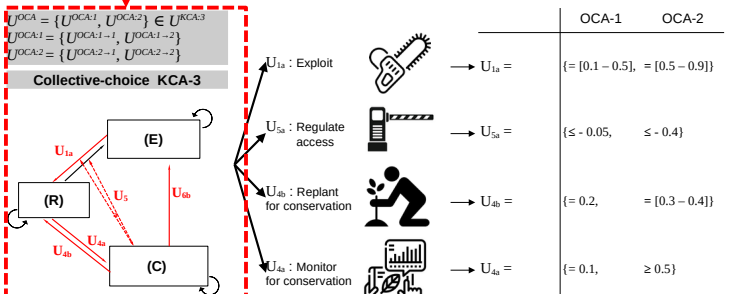
$U^{KCA:1} = \{U^{KCA:1\rightarrow1}, U^{KCA:1\rightarrow2}, U^{KCA:1\rightarrow3}\}$

$U^{KCA:2} : u_{1a}(R) + u_{4b} \circ u_{4a}$

$U^{KCA:2} = \{U^{KCA:2\rightarrow1}, U^{KCA:2\rightarrow2}, U^{KCA:2\rightarrow3}\}$

$U^{KCA:3} : u_{1a}(R) \circ (u_{6b} + u_{5a}) + u_{4b} \circ u_{4a}$

$U^{KCA:3} = \{U^{KCA:3\rightarrow1}, U^{KCA:3\rightarrow2}, U^{KCA:3\rightarrow3}\}$



	OCA-1	OCA-2
U_{1a} =	{= [0.1 – 0.5],	= [0.5 – 0.9]}
U_{5a} =	{≤ - 0.05,	≤ - 0.4}
U_{4b} =	{= 0.2,	= [0.3 – 0.4]}
U_{4a} =	{= 0.1,	≥ 0.5}

Operational-level adaptation actions

$$U = \{u_1, u_2, \ldots, u_n\}$$

Construction the set U of 2nd tier actions based on a version of Ostrom's social-ecological system framework (SESF)

Set of actions related to the social, economic & political Settings (U_S)

U_{1a} Economic development * †	U_{1e} Other governance systems †
U_{2a} Demographic trends * †	U_{2e} Markets †
U_{3a} Political stability (rate of political change) * †	U_{3e} Media organizations †
	U_{4e} Technology †

Set of actions related to the Resource Systems (U_{RS})

U_{1RS} Sector	U_{6RS} Resource unit mobility * ** †
U_{2RS} Clarity of system boundaries	U_{7RS} Growth or replacement rate of resource units
U_{3RS} Size of resource system	U_{8RS} Interactions among resource units * †
U_{4RS} Human constructed facilities *	U_{9RS} Economic value
U_{5RS} Productivity of the system	U_{10RS} Number of units
U_{6RS} Equilibrium properties	U_{11RS} Distinctive characteristics
U_{7RS} Predictability of system dynamics	U_{12RS} Spatial & temporal distribution
U_{8RS} Storage characteristics	
U_{9RS} Location	
U_{10RS} Ecosystem history	

Set of actions related to the Governance Systems (U_{GS})

U_{1GS} Policy area	U_{11} Number of relevant actors *
U_{2GS} Geographic scale of governance system *	U_{12} Socio-economic attributes *
U_{3GS} Proportion of participating population **	U_{13} History of past experience * **
U_{4GS} Regime type (democratic-cratic, mono/poly-centric) *	U_{14} Location *
U_{5GS} Rule-making organizations *	U_{15} Leadership / entrepreneurship *
U_{6GS} Rules-in-Use *	U_{16} Norms (trust-reciprocity) / social capital *
U_{7GS} Property rights systems (relations among people in relation to resource units and infrastructures) *	U_{17} Knowledge of SES / mental models / beliefs *
U_{8GS} Repertoire of cultural knowledge, beliefs, norms, practices (strategies) with no rules and sanctions *	U_{18} Proportion of resource dependent actors *
U_{9GS} Network structure (connections among the rule-making organizations and the population subject to these rules) * **	U_{19} Technologies available *
U_{10GS} Historical continuity of the governance system (recent vs long-lasting, open vs close to internal adaptation) *	

Set of actions related to the Actors (U_A)

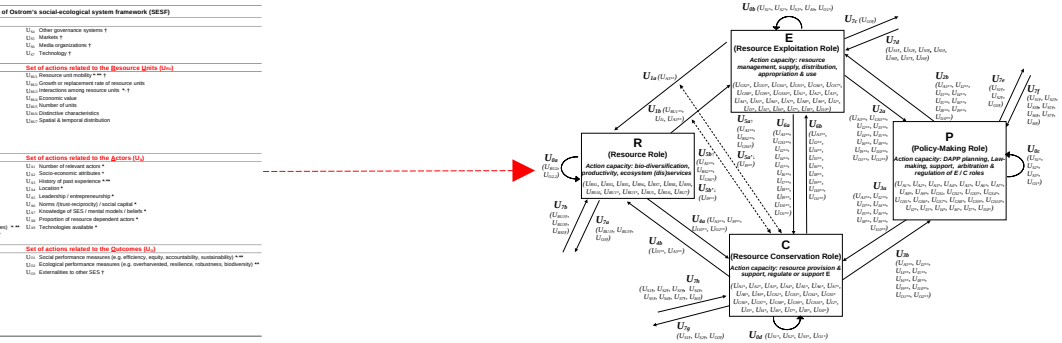
U_{1A} Number of relevant actors *
U_{2A} Socio-economic attributes *
U_{3A} History of past experience * **
U_{4A} Location *
U_{5A} Leadership / entrepreneurship *
U_{6A} Norms (trust-reciprocity) / social capital *
U_{7A} Knowledge of SES / mental models / beliefs *
U_{8A} Proportion of resource dependent actors *
U_{9A} Technologies available *

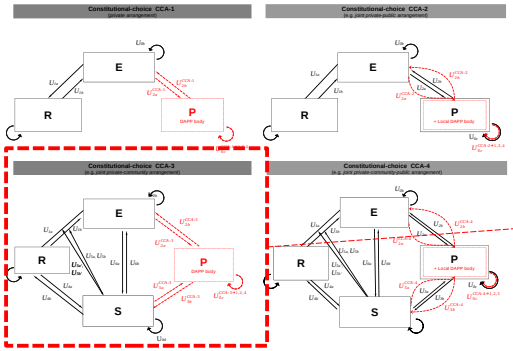
Set of actions related to the Interactions (U_I)

U_{1I} Harvesting / using resource units by divers users
U_{2I} Information sharing among actors * **
U_{3I} Deliberation process * **
U_{4I} Conflicts among actors * **
U_{5I} Investment activities * **
U_{6I} Lobbying activities * ** †
U_{7I} Self-organizing activities * **
U_{8I} Networking activities * **
U_{9I} Monitoring activities * **
U_{10I} Evaluative activities * **

Set of actions related to the Outcomes (U_O)

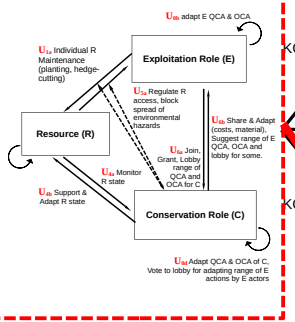
U_{1O} Social performance measures (e.g. efficiency, equity, accountability, sustainability) * **
U_{2O} Ecological performance measures (e.g. overharvested, resilience, robustness, biodiversity) **
U_{3O} Externalities to other SES †



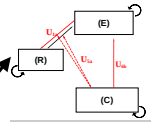


$U^{KCA} = \{U^{KCA:1}, U^{KCA:2}, U^{KCA:3}\} \in U^{CCA:3}$

Constitutional-choice CCA-3
(e.g. *joint private-community arrangement*)



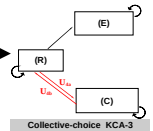
Collective-choice KCA-1



$U^{KCA:1}$: $u_{1a}(R) \circ (u_{6b} + u_{5a})$

$U^{KCA:1} = \{U^{KCA:1\rightarrow1}, U^{KCA:1\rightarrow2}, U^{KCA:1\rightarrow3}\}$

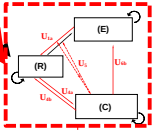
Collective-choice KCA-2



$U^{KCA:2}$: $u_{1a}(R) + u_{4b} \circ u_{4a}$

$U^{KCA:2} = \{U^{KCA:2\rightarrow1}, U^{KCA:2\rightarrow2}, U^{KCA:2\rightarrow3}\}$

Collective-choice KCA-3



$U^{KCA:3}$: $u_{1a}(R) \circ (u_{6b} + u_{5a}) + u_{4b} \circ u_{4a}$

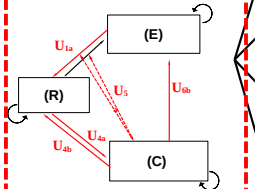
$U^{KCA:3} = \{U^{KCA:3\rightarrow1}, U^{KCA:3\rightarrow2}, U^{KCA:3\rightarrow3}\}$

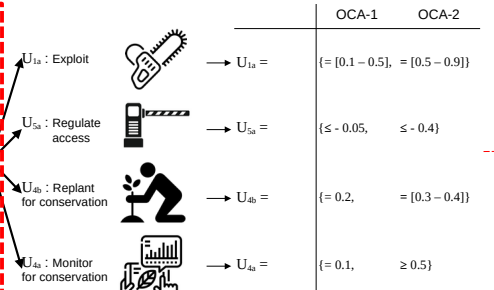
$U^{OCA} = \{U^{OCA:1}, U^{OCA:2}\} \in U^{KCA:3}$

$U^{OCA:1} = \{U^{OCA:1\rightarrow1}, U^{OCA:1\rightarrow2}\}$

$U^{OCA:2} = \{U^{OCA:2\rightarrow1}, U^{OCA:2\rightarrow2}\}$

Collective-choice KCA-3





	OCA-1	OCA-2
U_{1a} =	{= [0.1 – 0.5],	= [0.5 – 0.9]}
U_{5a} =	{≤ - 0.05,	≤ - 0.4}
U_{4b} =	{= 0.2,	= [0.3 – 0.4]}
U_{4a} =	{= 0.1,	≥ 0.5}

$$\frac{dR}{dt} = \overbrace{U_{0a}.R}^{\text{Natural ES Growth}} \pm \overbrace{U_{7b}.R}^{\text{Impact of SES Settings}} - \overbrace{U_{7a}.R}^{\text{ES Externalities}} \quad (1a)$$
$$+ \overbrace{U_{4a}.R.C}^{\text{R Support by C}} - \overbrace{U_{1b}.R.E}^{\text{ES Access \& Flow}} . \overbrace{U_{5b}.C}^{\text{Regulation}} + \overbrace{U_{1a}.E.R}^{\text{Access \& Management}} . \overbrace{U_{5a}.C}^{\text{Regulation}}$$

$$\frac{dE}{dt} = \pm \overbrace{U_{0b}.E}^{\text{Natural Growth/Decay}} \pm \overbrace{U_{7d}.E}^{\text{Impact of SES Settings}} - \overbrace{U_{7c}.E}^{\text{Externalities}} \quad (1b)$$
$$+ \overbrace{U_{1b}.R.E}^{\text{Access R \& ES Flow}} . \overbrace{U_{5b}.C}^{\text{Regulation}} \pm \overbrace{U_{6b}.E.C}^{\text{C Support \& Regulation}} \pm \overbrace{U_{2b}.E.P}^{\text{P Support \& Sanctions}}$$

$$\frac{dC}{dt} = \pm \overbrace{U_{0d}.C}^{\text{Natural Growth/Decay}} \pm \overbrace{U_{7b}.C}^{\text{Impact of SES Settings}} - \overbrace{U_{7g}.C}^{\text{Externalities}} \quad (1c)$$
$$+ \overbrace{U_{1b}.R.E}^{\text{Access \& ES Flow}} . \overbrace{U_{5b}.C}^{\text{Monitoring}} + \overbrace{U_{1a}.R.E}^{\text{Access \& Management}} . \overbrace{U_{5a}.C}^{\text{Monitoring}}$$

$$\frac{dP}{dt} = \pm \overbrace{(U_{6a} - U_{6b}).E.C}^{\text{E Joining/leaving}} \pm \overbrace{U_{3a}.P.C}^{\text{P Support/Sanction}}$$
$$\pm \overbrace{U_{0c}.P}^{\text{Natural Growth/Decay}} \pm \overbrace{U_{7f}.C}^{\text{Impact of SES Settings}} - \overbrace{U_{7e}.C}^{\text{Externalities}} \quad (1d)$$
$$\pm \overbrace{U_{2a}.E.P}^{\text{Join/Support/Sanction}} \pm \overbrace{U_{3b}.C.P}^{\text{Join/Support/Sanction}}$$

Nested conditions (actions, time, states):

- Set of actions: $\mathbf{U} = \{\mathbf{U^{CCA}}, \mathbf{U^{KCA}}, \mathbf{U^{OCA}}\}$,
- Set of constitutional actions: $\mathbf{U^{CCA}} = \{U^{CCA_1}, U^{CCA_2}, \ldots, U^{CCA_{i1}}, \ldots, U^{CCA_{m1}}\}$,
- Set of collective actions: $\mathbf{U^{KCA}} = \{U^{KCA_1}, U^{KCA_2}, \ldots, U^{KCA_{i2}}, \ldots, u_{KCA_{m2}}\}$,
- Set of operational actions: $\mathbf{U^{OCA}} = \{U^{OCA_1}, U^{OCA_2}, \ldots, U^{OCA_{i3}}, \ldots, U^{OCA_{m3}}\}$,
- Time sequence: $T = \{t_0, t_1, \ldots, t_j, \ldots, t_n\}$,
- Set of states: $X = \{R, E, C, P\}$
- Set of Resource states: $R = \{R_1, R_2, \ldots, R_{l1}\}$
- Set of exploitation role states: $E = \{E_1, E_2, \ldots, E_{l2}\}$
- Set of conservation role states: $E = \{C_1, C_2, \ldots, C_{l2}\}$
- Set of policy-making role states: $P = \{P_1, P_2, \ldots, P_{l3}\}$

A nested viable DAPP (nested viable control pathway):

$$\begin{aligned} u_K(.) = & u_{OCA}(u_{KCA}(u_{CCA}(t_0))), u_{OCA}(u_{KCA}(u_{CCA}(t_1))), \ldots, \\ & u_{OCA}(u_{KCA}(u_{CCA}(t_j))), \ldots, u_{OCA}(u_{KCA}(u_{CCA}(t_n))) \\ & \text{such that} \quad u(t_j) \in (\mathbf{U}_K(t_j)\ \forall j) \in \mathbf{U} \end{aligned} \tag{38}$$

Nested regulatory Map (Aubin et al. 2011)[Definition 2.9.4 p.73]:

$$\mathcal{R}(x) = \left\{ u \in U^{OCA} \in U^{KCA} \in U^{CCA} \in U(x) \mid x \in K, f(x, u(x)) \in Viab_K \right\} \tag{39}$$

Nested viable DAPP map (nested graph):

- General DAPP Graph: $\mathcal{G} = V \times E$ with $dim(\mathcal{G}) = U^T$
- CCA level: $\mathcal{G}^{CCA} = V^{CCA} \times E^{CCA}$ with $dim(\mathcal{G}^{CCA}) = (U^{CCA})^T$
- KCA level: $\mathcal{G}^{KCA} = V^{KCA} \times E^{KCA}$ with $dim(\mathcal{G}^{KCA}) = (U^{CCA} \times U^{KCA})^T$
- OCA level: $\mathcal{G}^{OCA} = V^{OCA} \times E^{OCA}$ with $dim(\mathcal{G}^{OCA}) = (U^{CCA} \times U^{KCA} \times U^{OCA})^T$

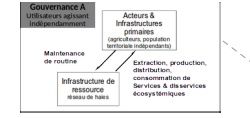
- Vertex V $\rightarrow U \times T$ representing decision nodes at time $t_0, t_1, ..., t_T$ for every possible action u, such that $V = \bigcup_{t=0}^{T} U(x(t))$
- Edges $E = e_{ij} \subseteq V \times V$ representing possible viable transition pathways between decision nodes, which correspond to viable state transitions under control $u(t)$, such that: $E = \{u(t), u(t+1) \mid u(t) \in \mathcal{R}(x(t), u(t)), u(t+1) \in \mathcal{R}(x(t+1), u(t+1))\}$

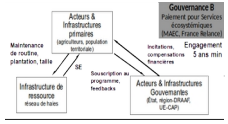
Formal definition of DAPP maps deriving from Ostrom & viability theories

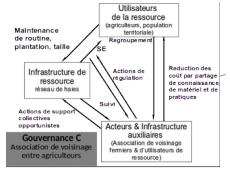
(1) Nested governance (IAD framework)
(2) Polycentric (CIS framework)
(3) Multi-tier (SES framework)
(4) Viable

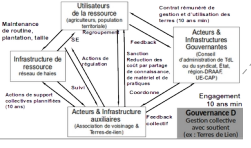
Nested DAPP maps

Adaptation of Constitutional → Operational arrangements

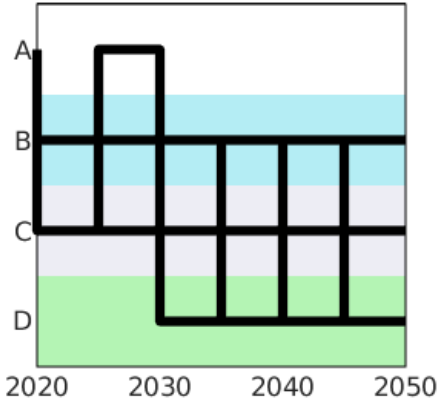






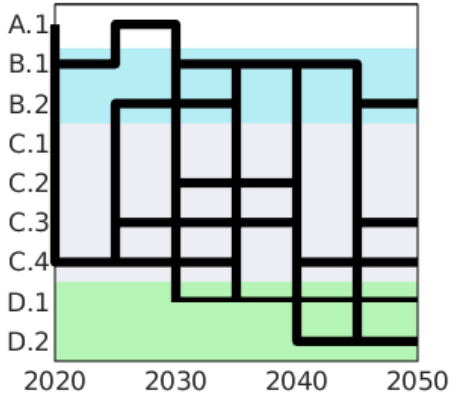


Viable DAPP map
Constitutional level



$U_{CCA} = \{U_{CCA\text{-}A}, U_{CCA\text{-}B}, U_{CCA\text{-}C}, U_{CCA\text{-}D}\}$

Viable DAPP map
Collective level



$U_{KCA} = \{U_{KCA\text{-}1}, U_{KCA\text{-}2}, U_{KCA\text{-}3}\} \in U_{CCA\text{-}3}$

Viable DAPP map
Operational level

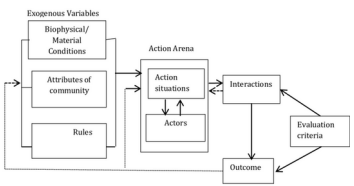
$U_{OCA} = \{U_{OCA\text{-}1}, U_{OCA\text{-}2}\} \in U_{KCA\text{-}3}$

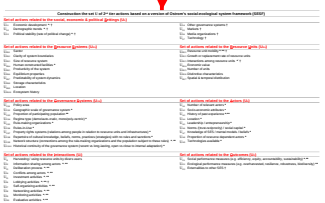
Daily constraints, costs, benefits

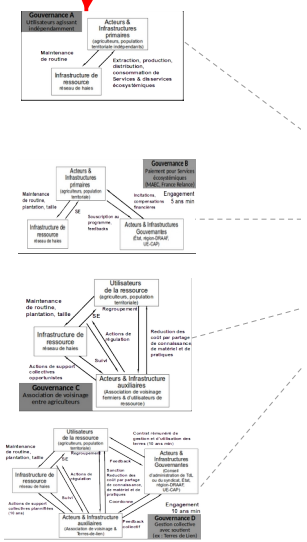
Nested institutional level of adaptation

SES targets of adaptation

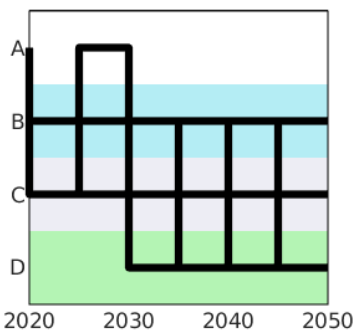
Roles: who ? How ? how much ?







DAPP Control Map (Γ_K)



Practice

Bridge

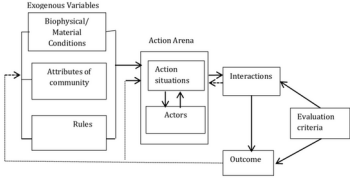
Theory

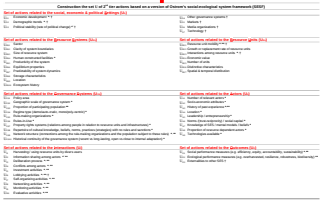
Daily constraints, costs, benefits

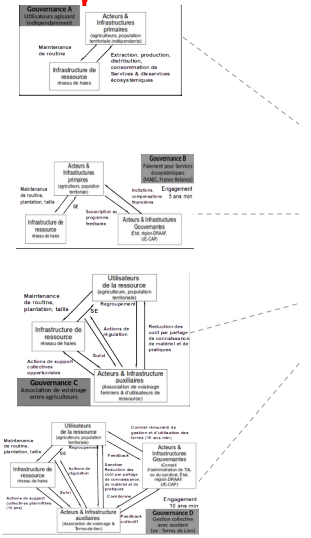
Nested institutional level of adaptation

SES targets of adaptation

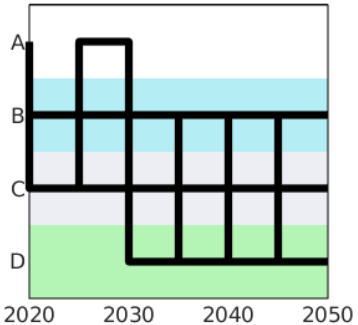
Roles: who ? How ? how much ?





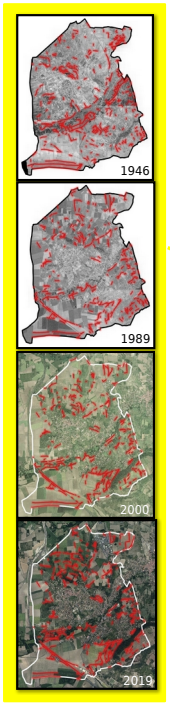


DAPP Control Map (Γ_K)

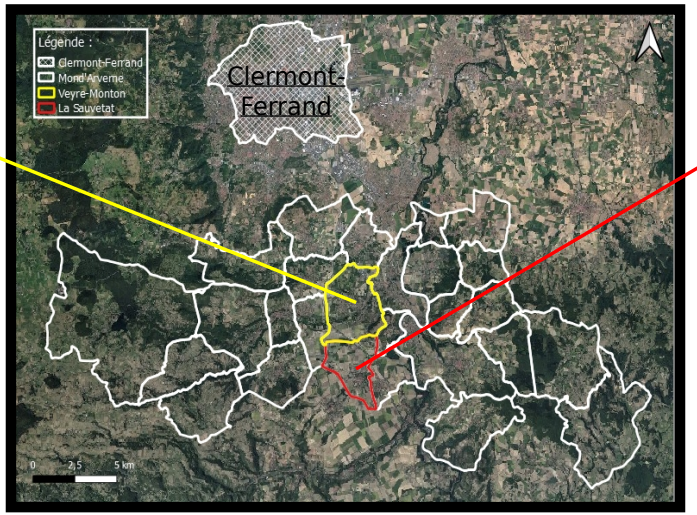


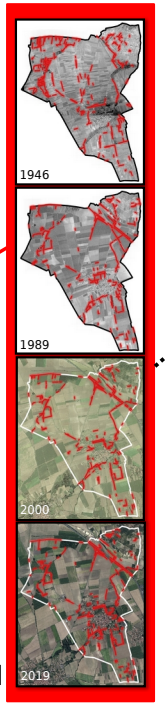
Application example

Rural & Peri-urban SES in France

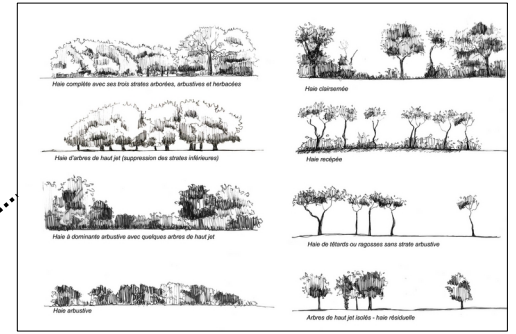


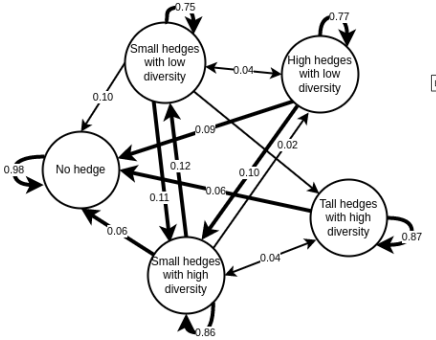
Péri-urbain

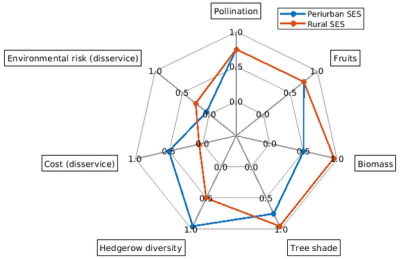




Rural

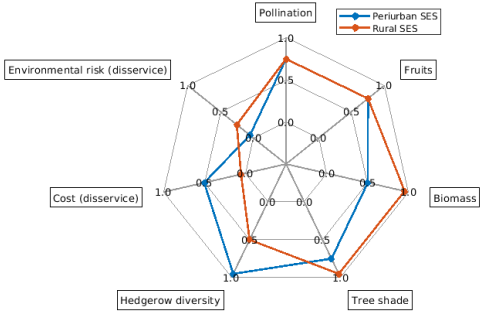






Constitutional-Choice arrangements (CCA)			Associated Collective-Choice Arrangements (KCA)			Consequences on the operational choice arrangement (OCA) for the EAI: proportion of every type of action for link 1a			Effect of the OCA on the resource infrastructure (0a)	Relative cost reduction provided by 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 (#NA)	0%
(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	**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%
			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%
(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 constrains on PIA appropriation practices (e.g. on planting new hedgerows, tractor hedge-cutting, integrated soft management).	no	**C1**	Incentives to share material and reduce costs in order to reduce constrains on tractor hedge-cutting	6a-->1a+1b	0.1	0.8	0.1	#NA	-10%
			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%
(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	**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%
			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%

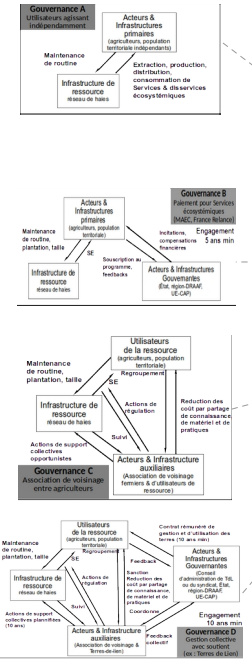
Ecosystem (dis)services (ES) (i.e. link 1b in the CIS model from figure 1)	Weighted limits of satisfaction for every ES deduced from the actors surveyed in the two SES [0-1]		Relative production of ES by type of hedgerow, on a [0-1] scale, with 1 corresponding to the observed maximal production or effect 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 (La Sauvetat)	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 attracting 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



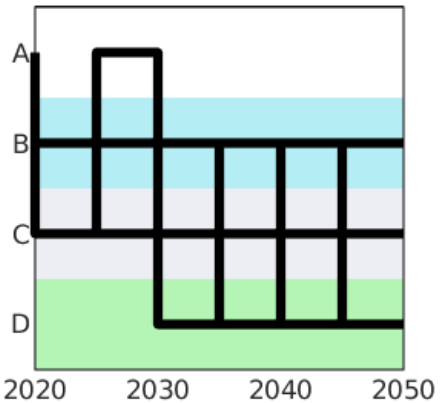
Nested DAPP maps

Adaptation of constitutional & Collective choices

(~~Operational level = fixed~~)

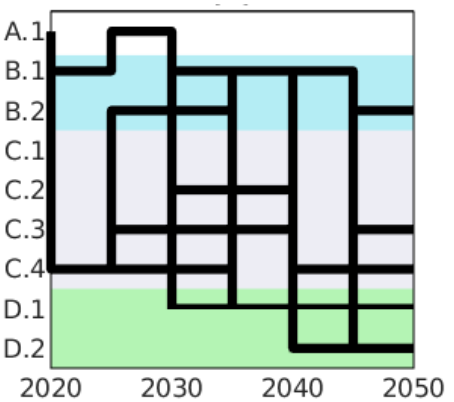


Viable DAPP map
Constitutional level



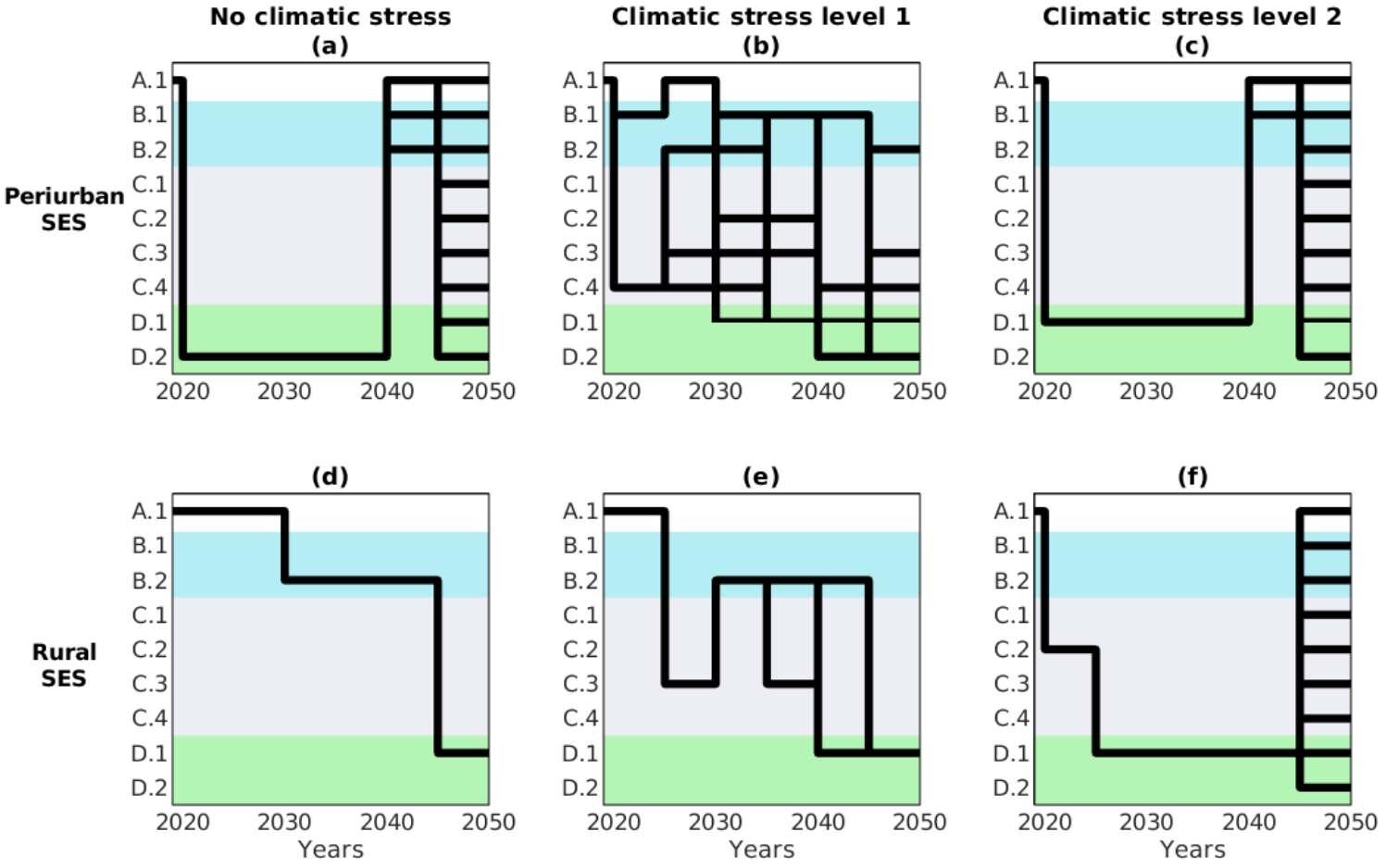
$U_{CCA} = \{U^{CCA-A}, U^{CCA-B}, U^{CCA-C}, U^{CCA-D}\}$

Viable DAPP map
Collective level



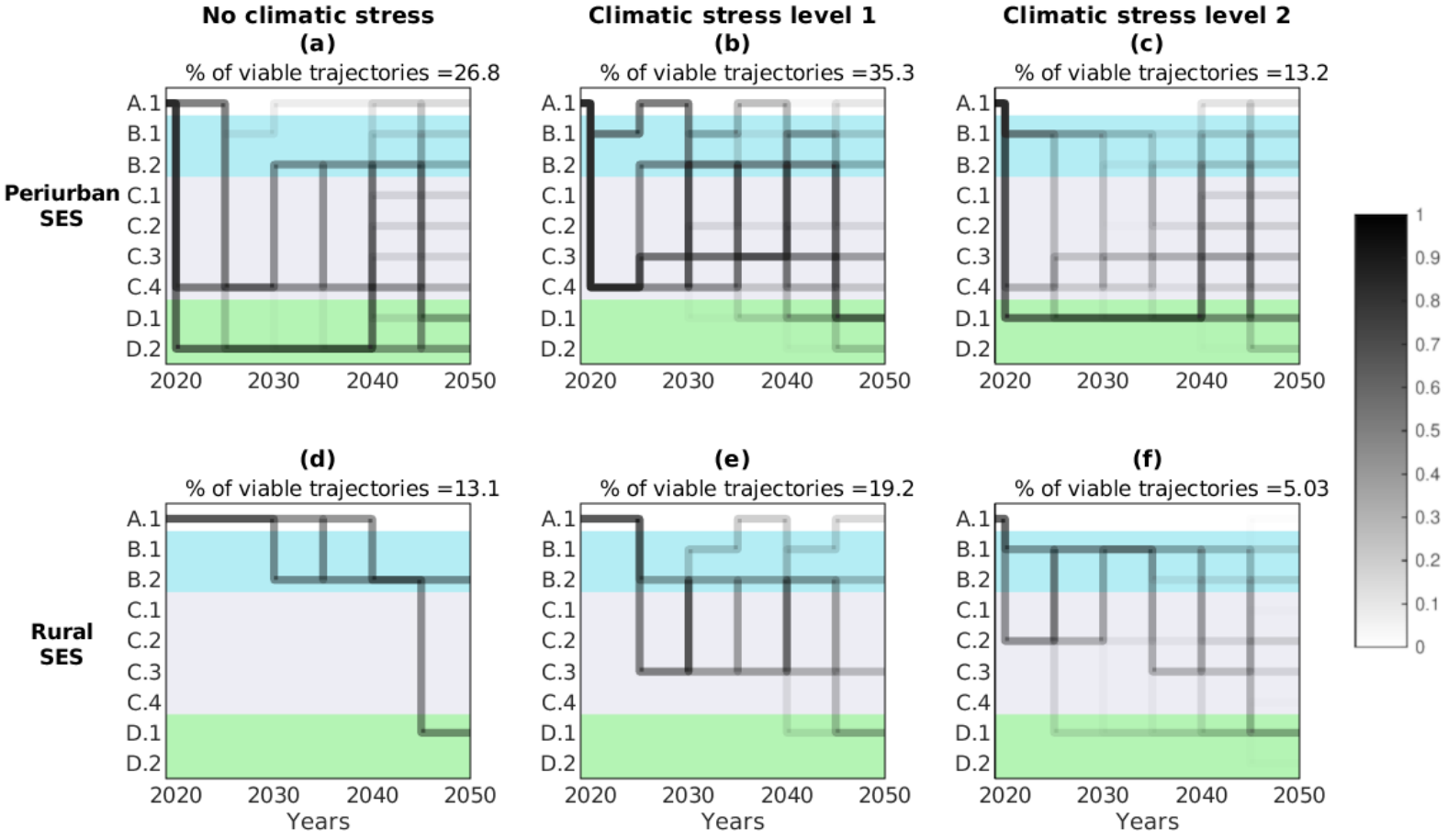
$U_{KCA} = \{U^{KCA-1}, U^{KCA-2}, U^{KCA-3}\} \in U^{CCA-3}$

Secured DAPP maps



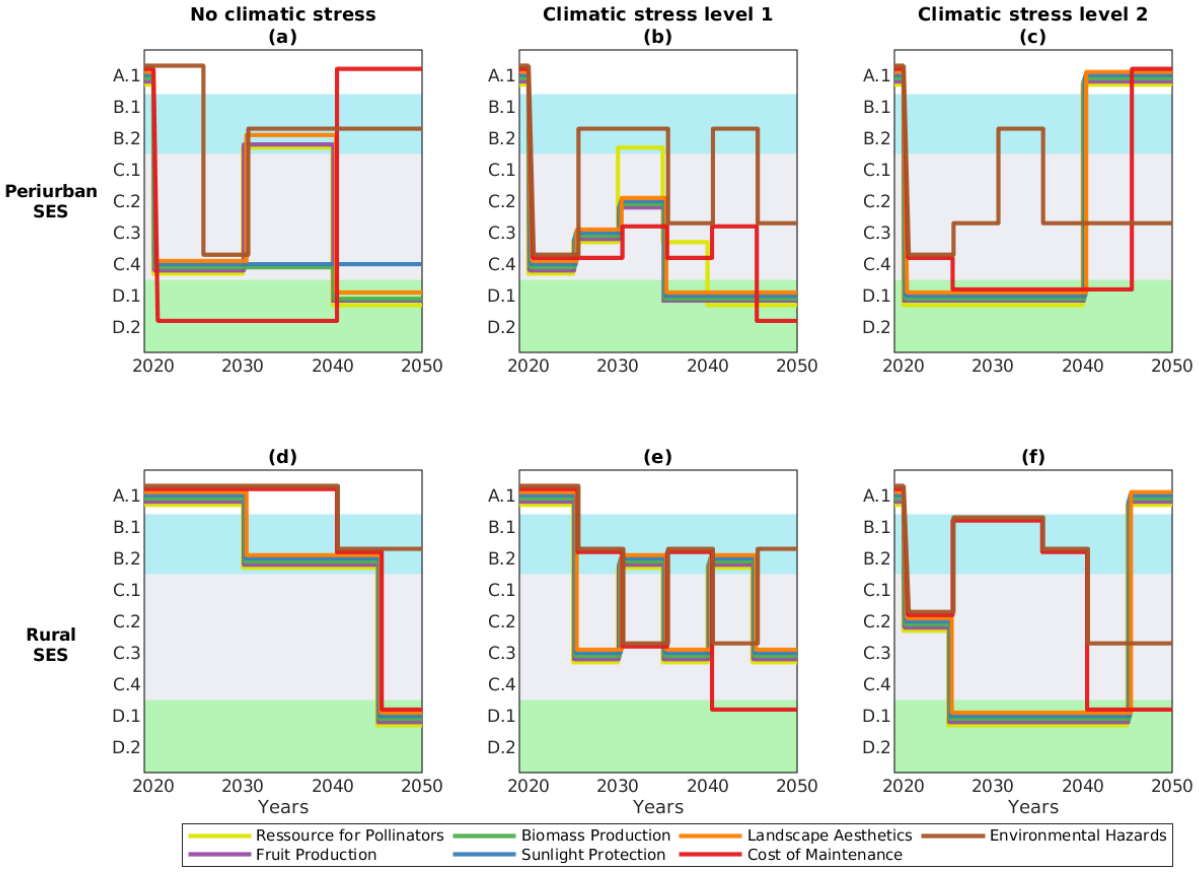
Risk DAPP maps

Pathways that minimize risks of becoming non-viable

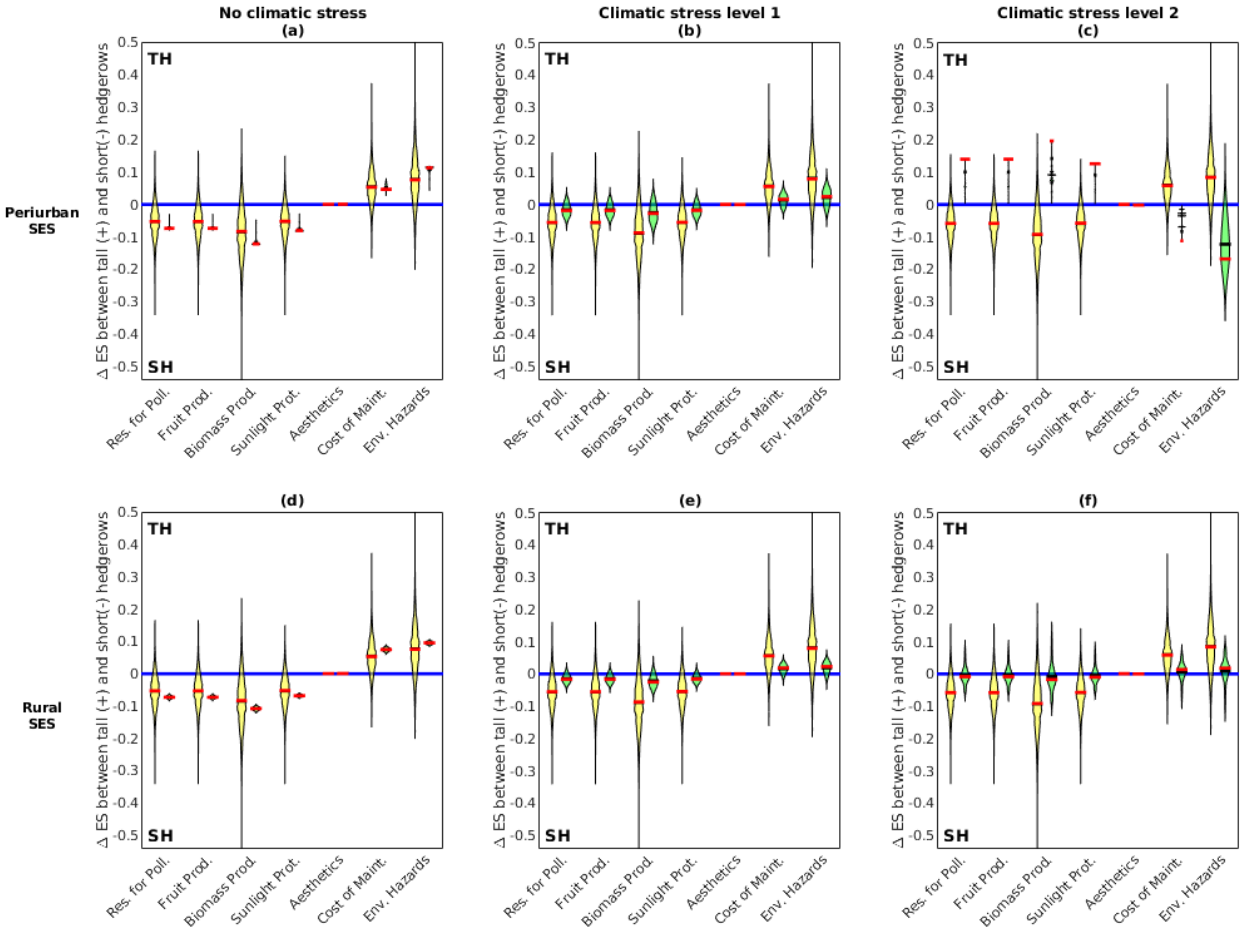


Optimal DAPP maps

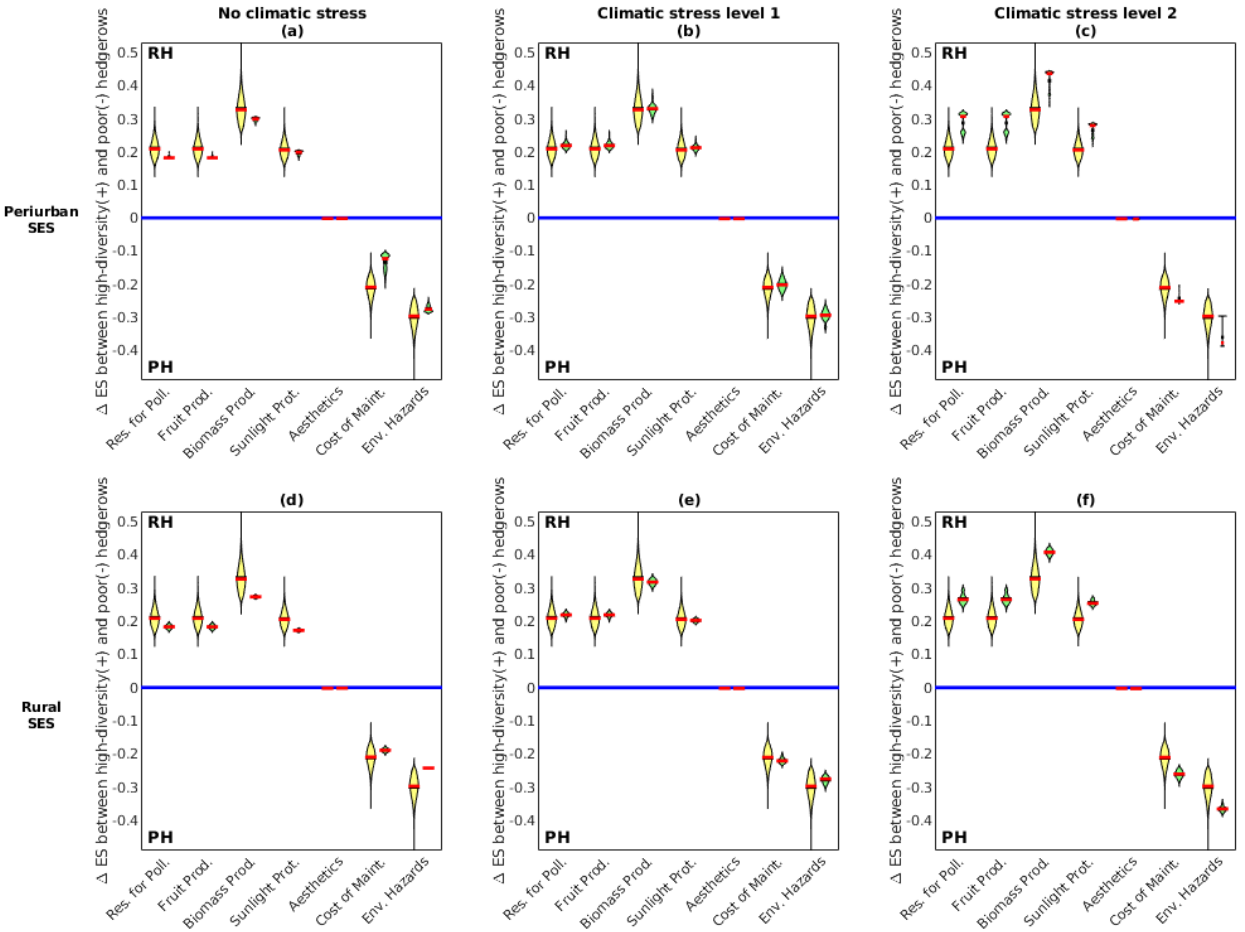
Switching optimization between distinct ecosystem services



Security gains in ES by targeting different hedgerows height



Security gains in ES by targeting different biodiversity levels



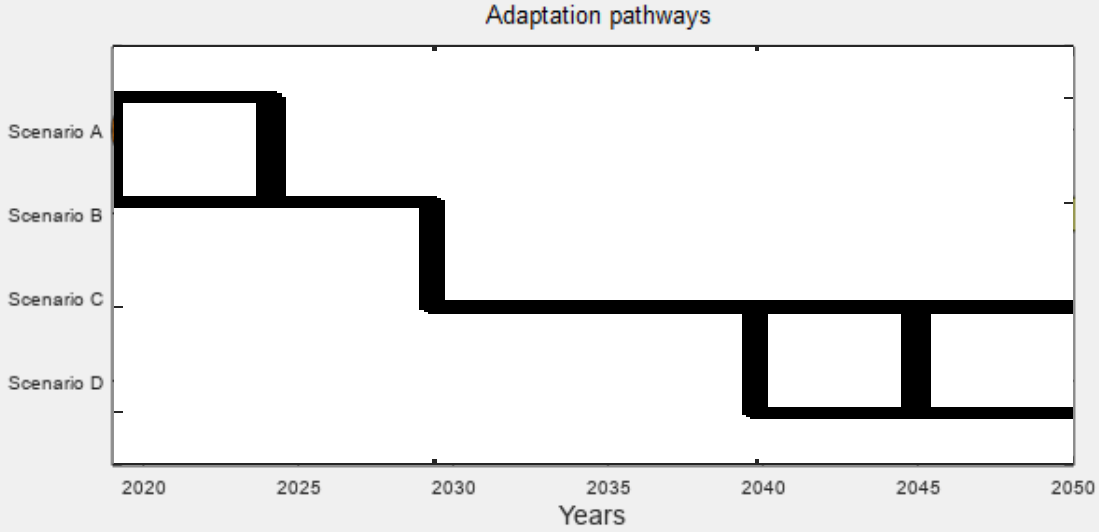
Trajectories selection: Best

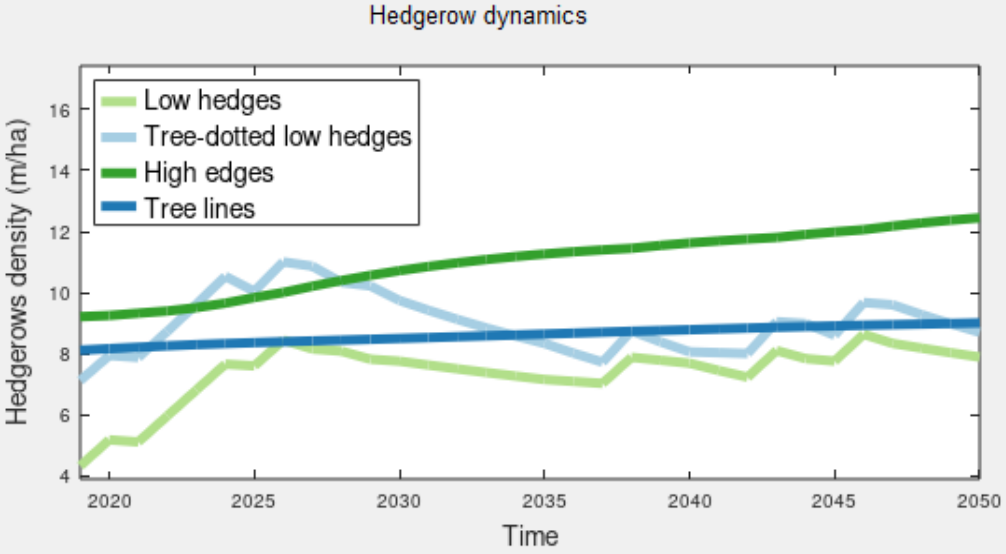
Metric: Sum

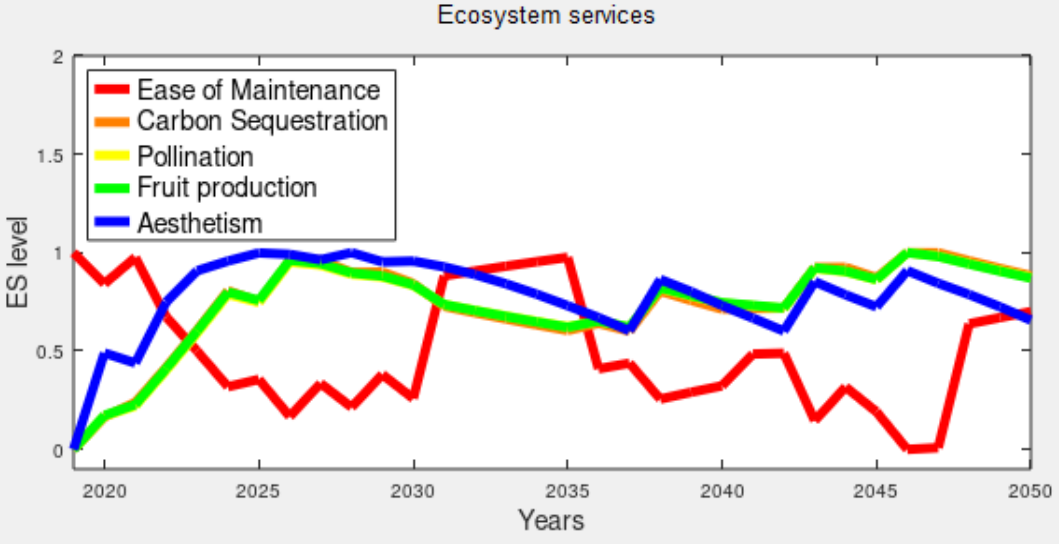
Initial year = 2019

Time horizon = 32

Number of runs = 10000







Load

Update

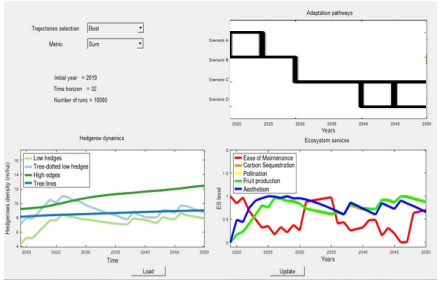
Problem 3

Transform this method

Into a decision support tool ?

Consortium

I-Site : CIR1 :Axe 4 (2024-2025)



gamae

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et Environnementale

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d'espaces naturels
Auvergne

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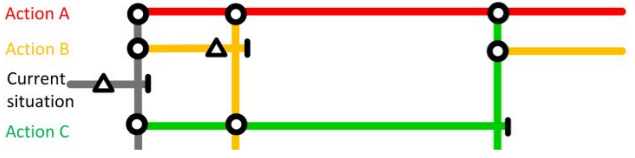
Dynamic Adaptive Policy Pathways: supporting decision making under uncertainty using Adaptation Tipping Points and Adaptation Pathways in policy analysis



Dynamic Adaptive Policy Pathways

Problem 4

Extend to other case studies

Test universality of this method

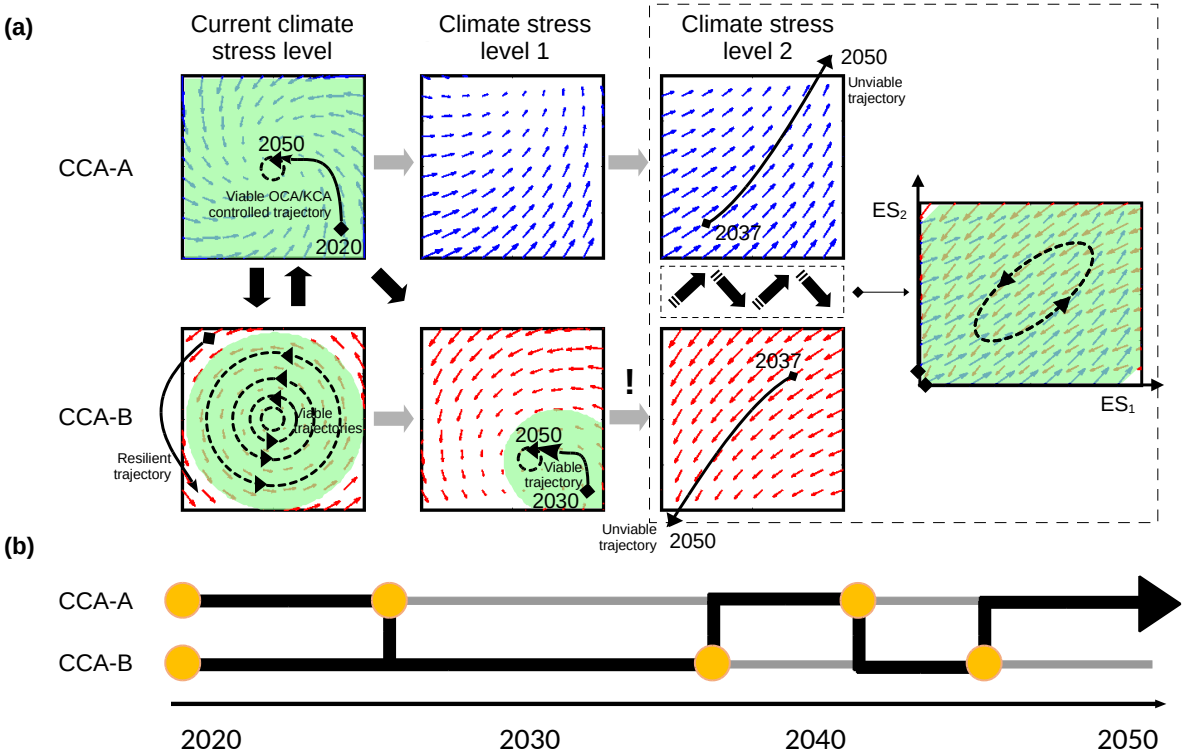
FOREST INN LAB

UMR Silva

esa

European Space Agency
Agence spatiale européenne

Thank you
Questions ?



Constraining domaine of satisfaction ***K***, for two ecosystem services (ES_1 and ES_2). Outside ***K***, the state of the SES is un-viable.

Vector field showing the direction of controlled trajectories of the state at time ***t*** of the two ES for the SES. The sequence of controls involve a nested set OCA and/or KCA actions for every CCA.

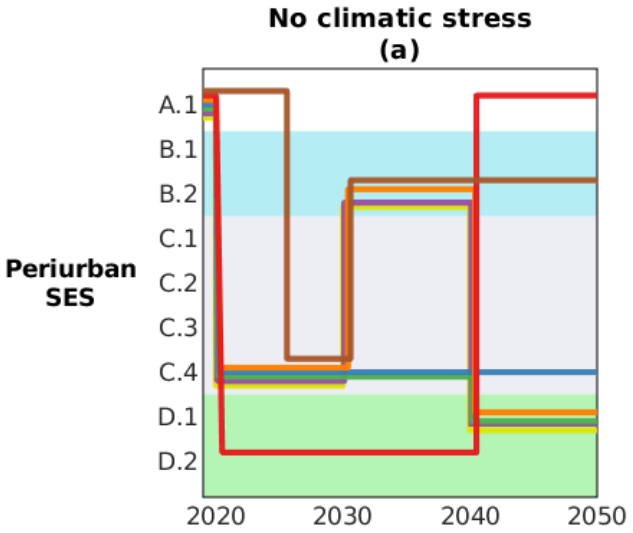
Viability kernel ***Viab(K)*** where at least one trajectory (controlled by nested OCA/KCA actions) will never leave ***K***. Outside this sub-domain, controlled trajectories can either leave to permanently become non-viable or go back and be considered resilient.

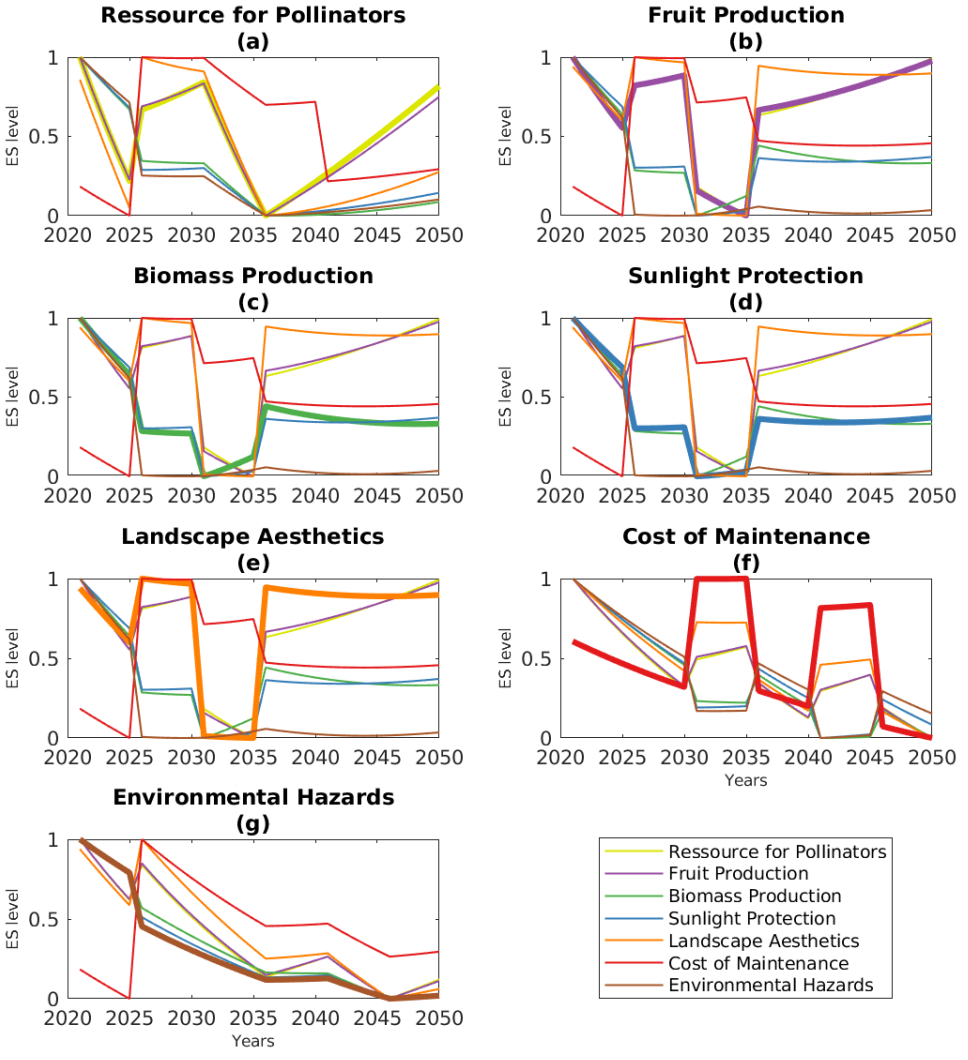
Uncontrolled transition and regime shift leading to a change in the size of ***Viab(K)*** for the same constitutional change arrangement (CCA)

Controlled transitions through adaptation of CCA-A into CCA-B (and vice versa), each possessing unique regime and (null) ***Viab(K)***, but leading sequentially to a globally non-null or larger ***Viab(K)***

Decision node as represented in the DAPP framework, representing the event when actors need to collectively decide whether they want to keep or adapt their CCA in order to stay viable

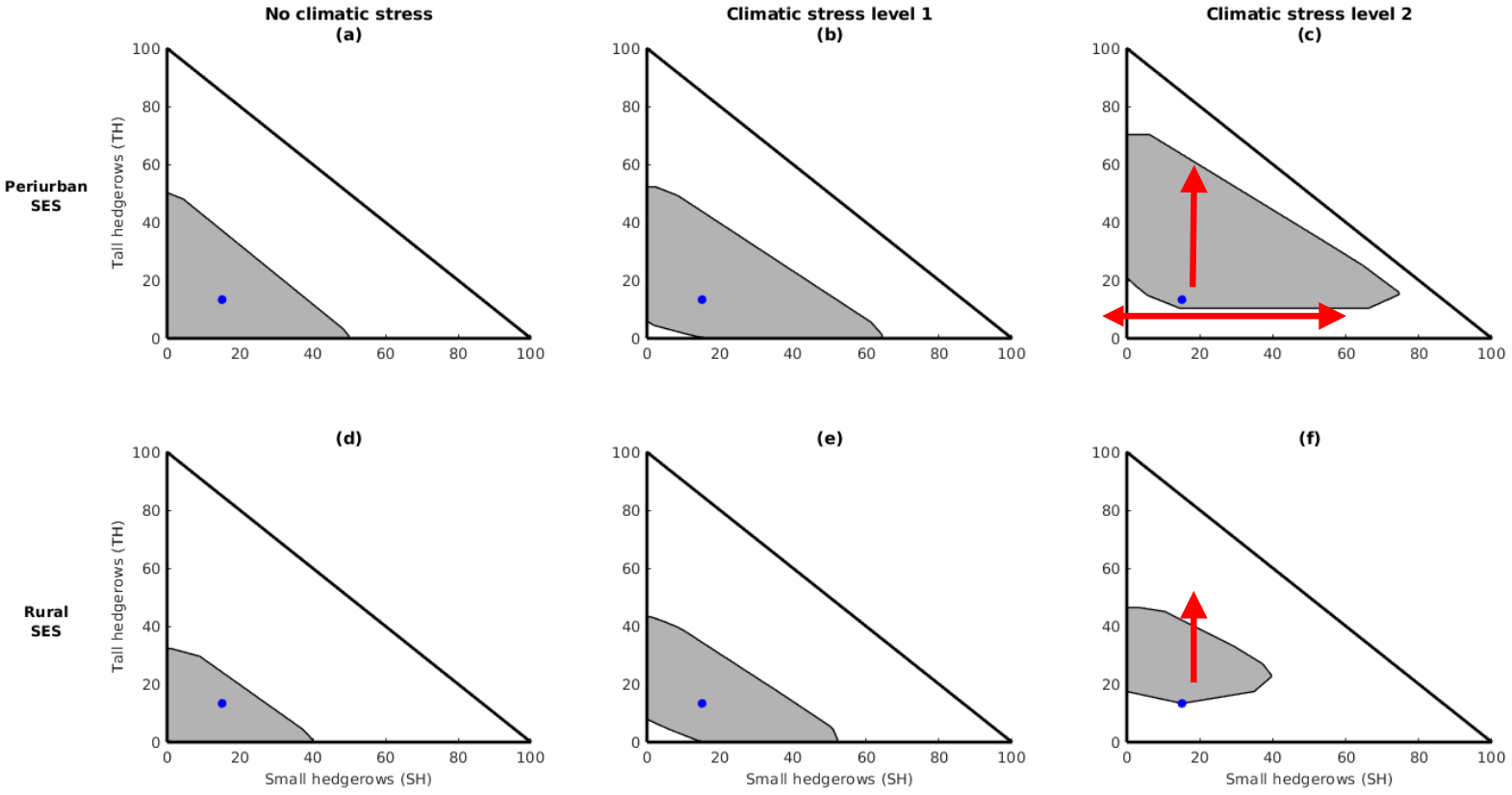
Résultats supplémentaires


No climatic stress
(a)
Periurban
SES
A.1
B.1
B.2
C.1
C.2
C.3
C.4
D.1
D.2
2020
2030
2040
2050


Ressource for Pollinators
(a)
Fruit Production
(b)
Biomass Production
(c)
Sunlight Protection
(d)
Landscape Aesthetics
(e)
Cost of Maintenance
(f)
Environmental Hazards
(g)
ES level
Years
Ressource for Pollinators
Fruit Production
Biomass Production
Sunlight Protection
Landscape Aesthetics
Cost of Maintenance
Environmental Hazards

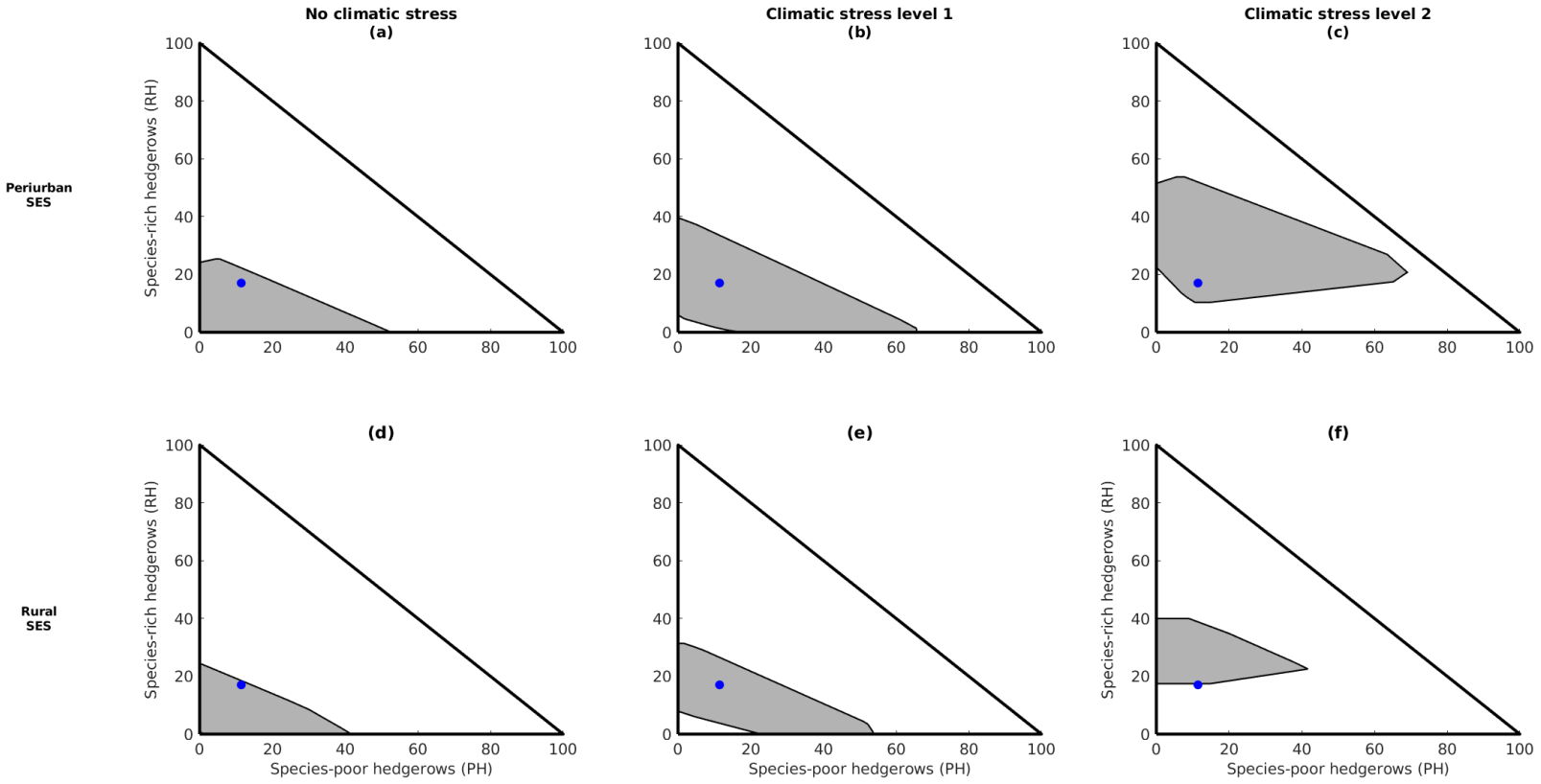
Analyse de viabilité

Coupe en fonction de la taille de haies



Analyse de viabilité

Coupe en fonction de la biodiversité des haies



Evaluer les gains en sécurisation des SE quand on adapte l'action opérationnelle

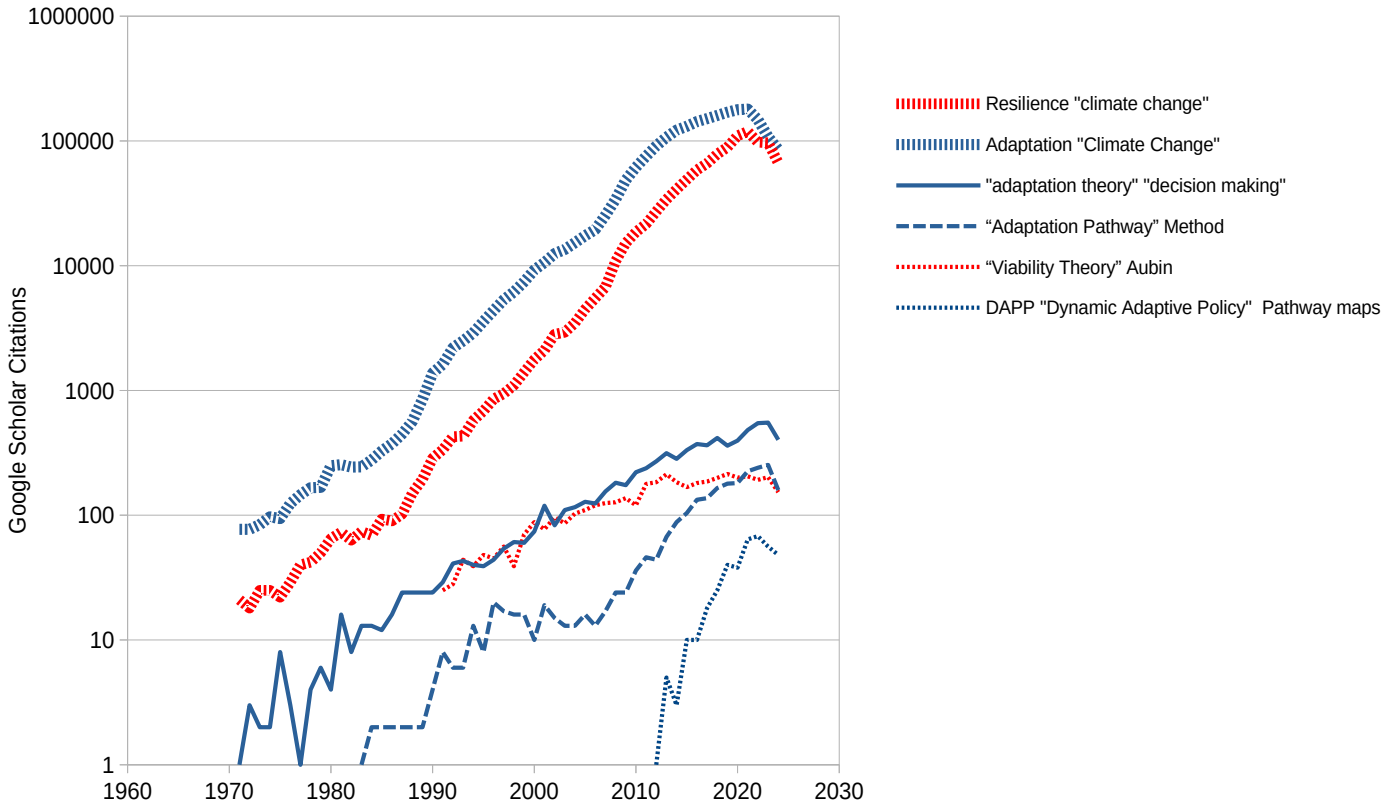
Analyse de sensibilité : changer type de haie

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

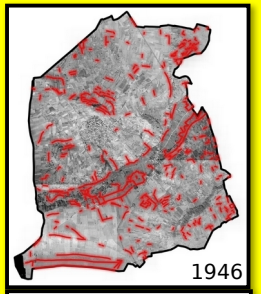
$$\Delta ES_i^{TH} = ES_i\left(a_{OCA}^{TH}(.)\right) - ES_{i,min}$$

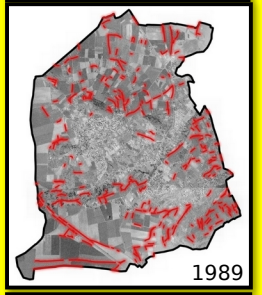
$$\Delta ES_{TH-SH} = \Delta ES_{TH} - \Delta ES_{SH} = \left[ES\left(a_{OCA}^{TH}(.)\right) - ES_{i,min}\right] - \left[ES\left(a_{OCA}^{SH}(.)\right) - ES_{i,min}\right]$$

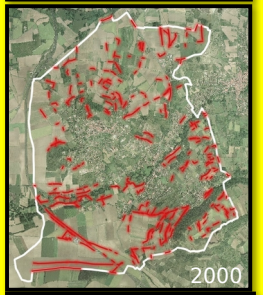
Resilience (viability) & Adaptation

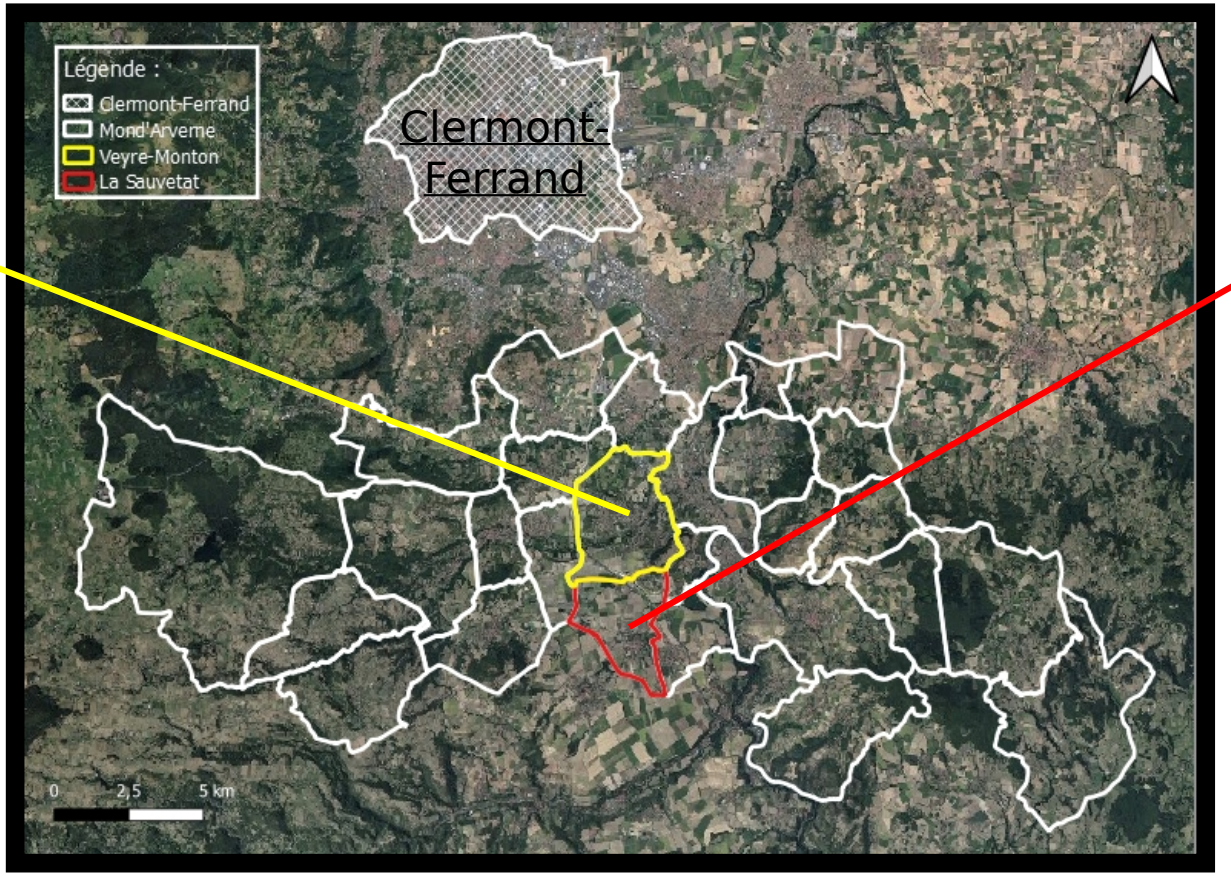


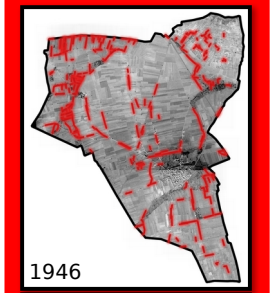
Paramètetres du modèle (terrain + entretients)

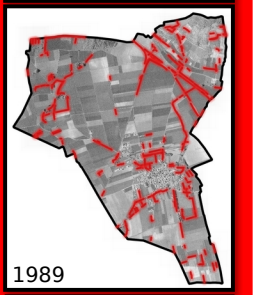






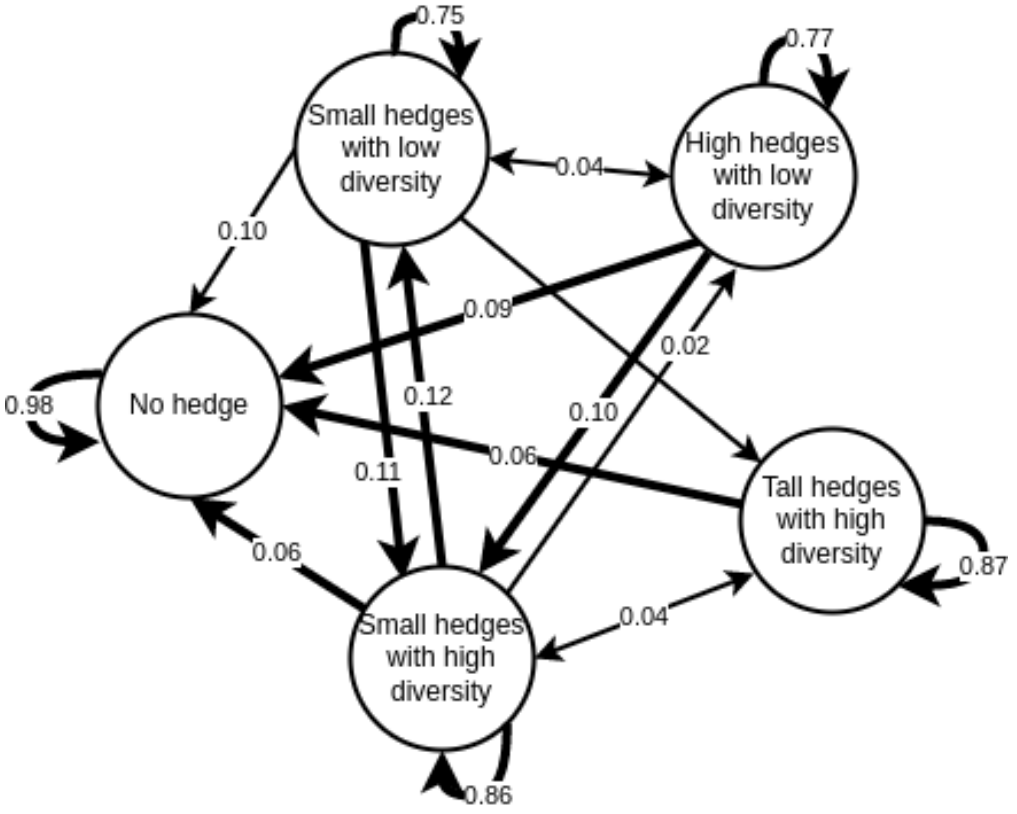






Péri-urbain

Rural

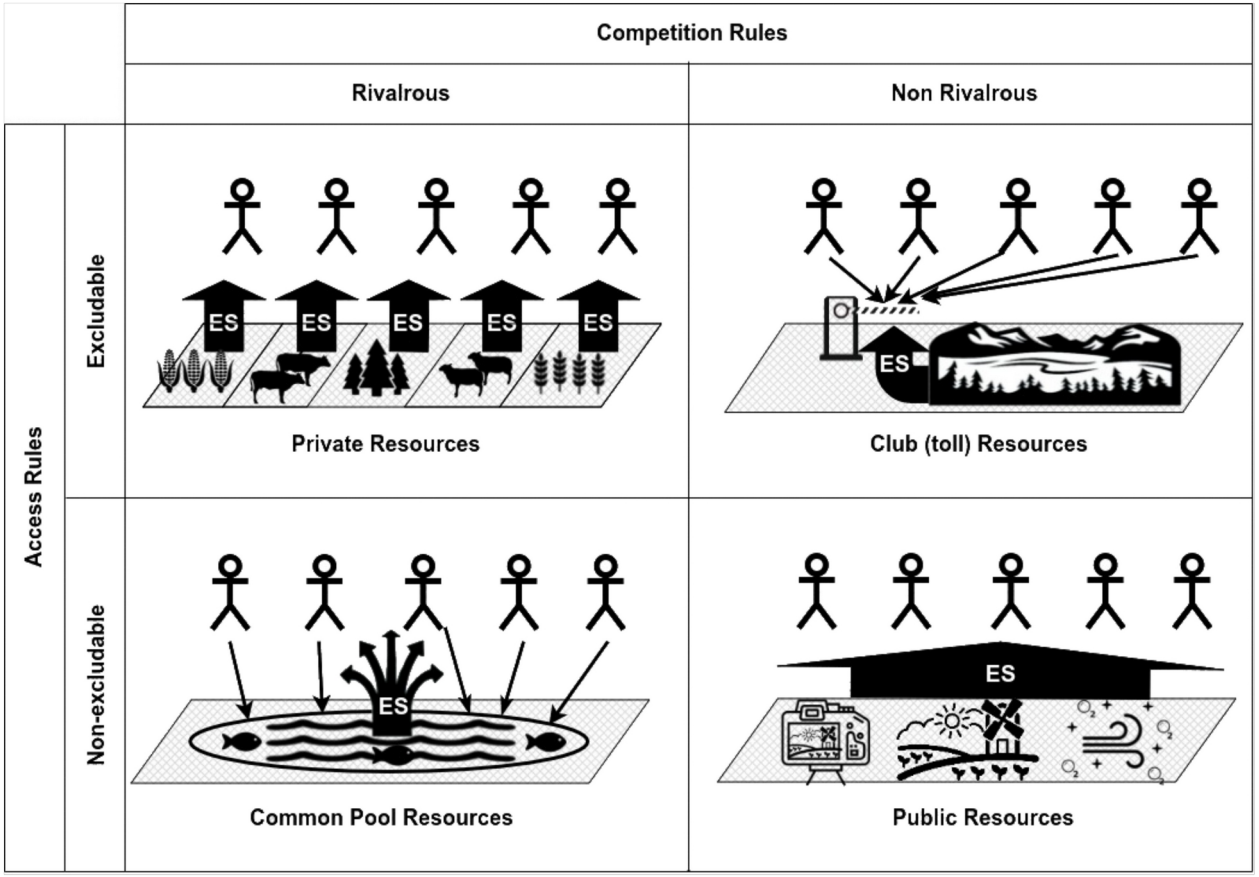


Veyre-Monton

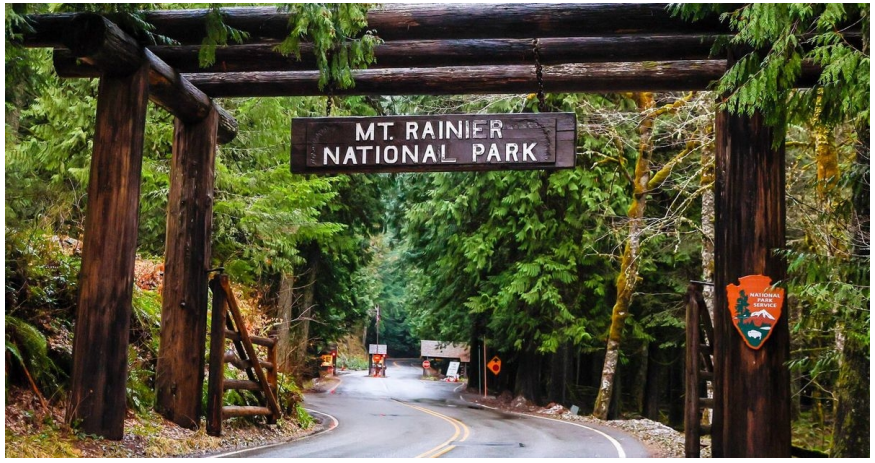
La Sauvetat

Typologie biens & services écosystémiques (théorie économique)

Adaptation depends on type of actors organization around goods and services



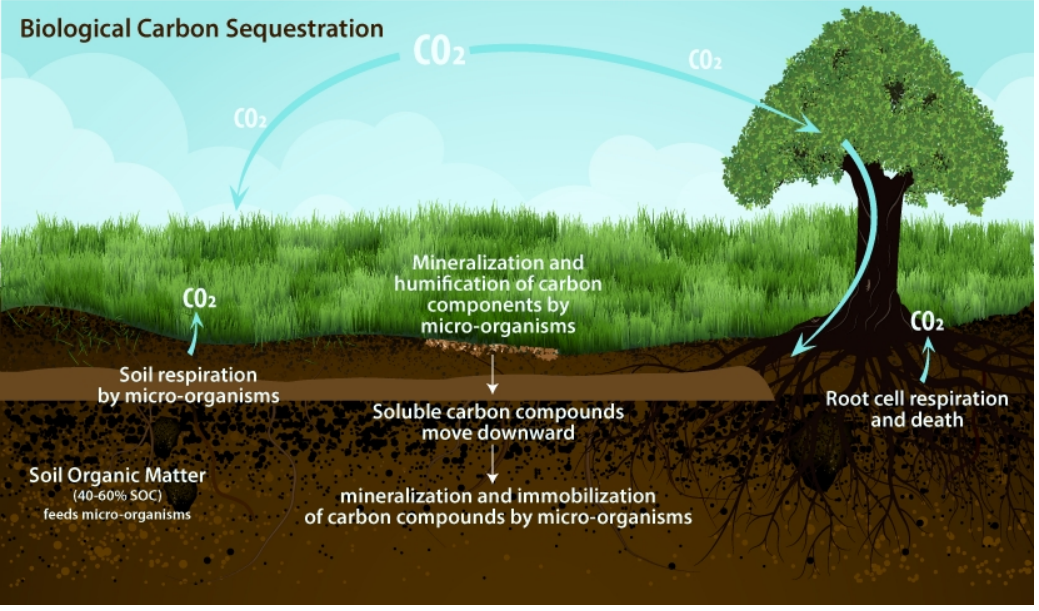
Strawberry fields forever !



National Parks

Japanese Iriai-satoyama forests

Hunting in Alsace



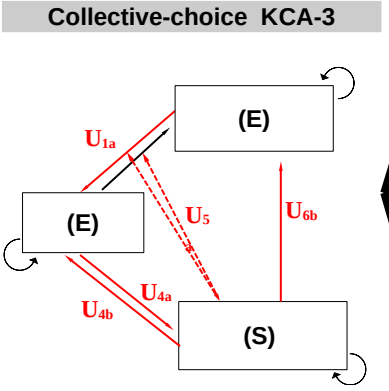
Climate

Scenary

Originaux

Choix opérationnels ou quel niveau d'action ?

Adapter l'intensité, la fréquence des actions



U_{1a} : Exploit

U_{5a} : Regulate access

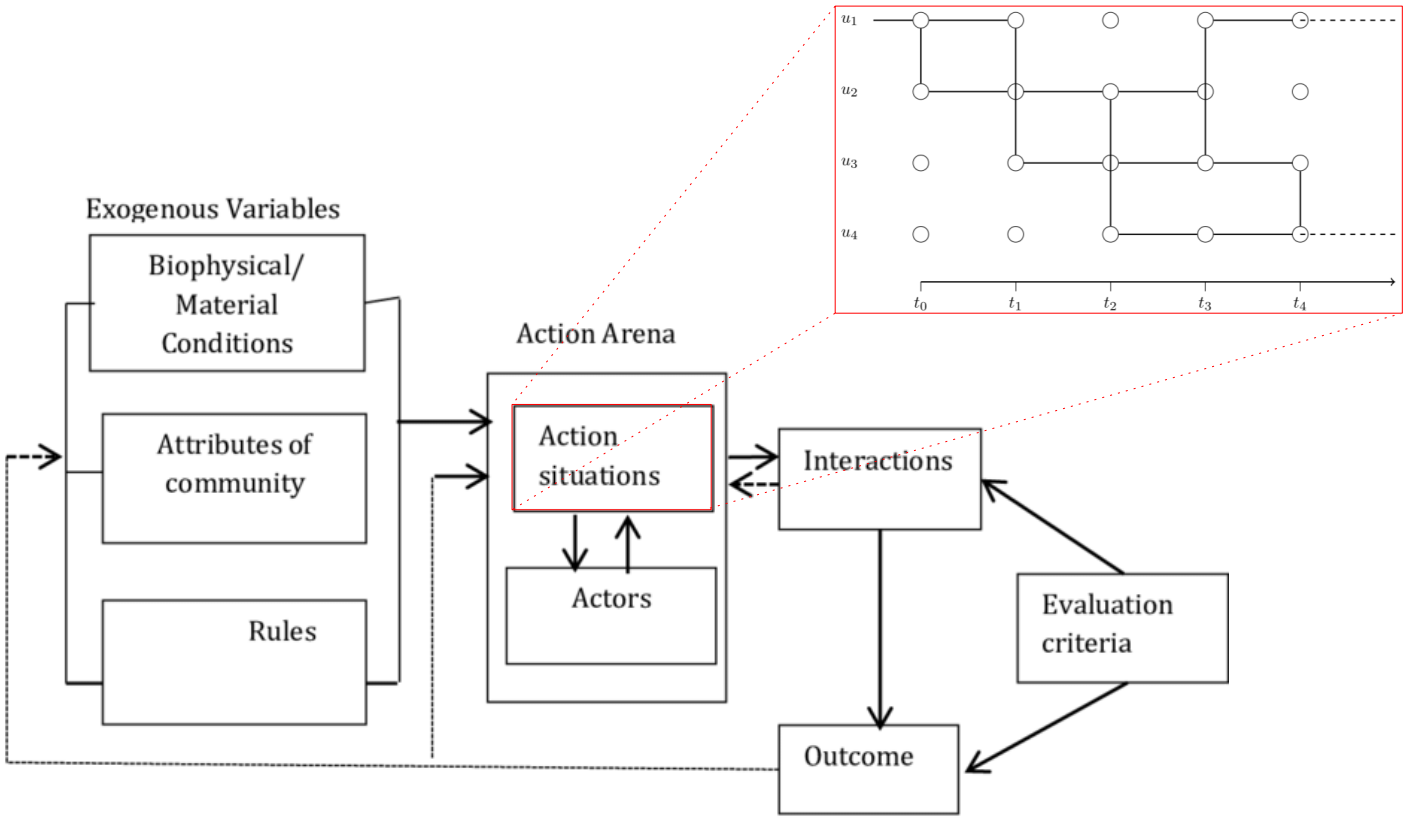
U_{4b} : Replant for conservation

U_{4a} : Monitor for conservation

	OCA-1	OCA-2
$U_{1a} =$	{= [0.1 – 0.5],	= [0.5 – 0.9]}
$U_{5a} =$	{≤ - 0.05,	≤ - 0.4}
$U_{4b} =$	{= 0.2,	= [0.3 – 0.4]}
$U_{4a} =$	{= 0.1,	≥ 0.5}

Re-situer DAPP dans le cadre IAD

DAPP = représentation de la “situation d’action”



Conditions (actions, time, states):

- set of actions: $\mathbf{U} = \{u_1, u_2, u_3, \ldots, u_m\}$,
- time sequence: $T = \{t_0, t_1, \ldots, t_n\}$,
- set of states: $X = \{x_1, x_2, x_3, \ldots, x_l\}$

A viable dynamic policy pathway (control pathway):

$$u_K(.) = u(t_0), u(t_1), \ldots, u(t_n) \quad \text{such that} \quad u(t_j) \in (\mathbf{U}_K(t_j)\ \forall j) \in \mathcal{U}$$

Viable control map (viable DAPP map):

$$\Gamma_K(\mathbf{u_i}, t) = \{\mathbf{u_j} \in \mathbf{U_K}(x(t)) \mid \exists u_i \to u_j \quad \text{such that} \quad f(x(t), \mathbf{u_j}) \in T(K, x(t))\}$$

Tangent Cone:

$$T(K, x(t)) = \{\dot{x}(t) = f(x(t), u_j) \mid u_j \in U_K(x(t)), f(x(t), u_j) \in K\}$$

Ostrom, E. (1990). Governing the commons: The evolution of institutions for collective action. Cambridge University Press.