RESONATE

Resilient Forests for Society

Deliverable 1.1

Inventory of forest resilience indicators and metrics reported in the literature with an assessment on their applicability to RESONATE case studies

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Executive Summary

This deliverable (D1.1) is a structured list of **forest resilience indicators** obtained from literature (143 manuscripts published from 2000 to 2018), including information about the spatial and temporal scale in which they apply, their units and unit type, resilience metric used for their identification, their potential applicability in case studies and references supporting their use. Furthermore, D1.1 informs about the system variables predicted by the set of resilience predictors identified during the literature review. Finally, D1.1 also includes a structured list of resilience co-drivers obtained from literature (118 manuscripts published from 2000 to 2018).

Keywords

Co-drivers, Forest social-ecological resilience, Operational Resilience Framework (ORF), ORF Graphical Abstract, ORF Visual glossary, Resilience indicators, Resilience predictors, System variables

1. Introduction

This deliverable (D1.1) presents a structured list of forest resilience indicators, with specific examples, obtained from literature. This inventory aims to offer a set of pre-established indicators to be applied and tested, when convenient, in the different RESONATE case studies (Tasks 2.2, 2.4), and in the analysis of value chain resilience (Tasks 3.2, 3.3). Two types of parameters are recognized, those describing the forest social-ecological systems (system variables) and those predicting the performance of resilience (resilience predictors). This inventory lays the groundwork for further assessment on forest resilience and metrics (D1.2) and the reference guide of resilience indicators and metrics (D1.6).

2. Methodological approach

2.1 Resilience indicators

The concept of **indicators** can be described as "parameters which can be measured and correspond to a particular criterion. They measure and help monitor the status and changes of forests in quantitative, qualitative and descriptive terms that reflect forest values as seen by those who defined each criterion" (FAO, Criteria and Indicators for Sustainable Forest Management. Available online: http://www.fao.org/forestry/ci/en/, accessed on 18 March 2022). When applied to the resilience of forest social-ecological systems, this broad definition of the term "indicators" is used in two different ways: (1) **descriptors** of the properties of the system which is experiencing resilience (e.g., resilience of carbon storage under climate change can be estimated by the performance of the indicator "forest stand biomass"), and (2) **predictors** of the resilience of given properties of the system (e.g., higher "stand tree diversity" can be an indicator of higher resilience of timber production under climate change).

In order to avoid further misunderstandings, in RESONATE we have adopted two different terms describing the abovementioned distinct meanings of indicators: respectively, "system variables" and "resilience predictors". A detailed definition of these terms is provided in section 2.2.2.

2.2 Operational Resilience Framework (ORF)

2.2.1 Operational Resilience Framework Synthesis

We have developed a framework to assess resilience of forest social-ecological systems, in order to offer a common scheme for RESONATE tasks, and also with the aim to be further applied beyond this project in future projects dealing with forest resilience. Specifically, this Operational Resilience Framework (ORF) **aims** to:

- Provide a **unified terminology** for the resilience-related concepts that could be applied under different perspectives and disciplines, from natural to social sciences.
- Provide an **operational way** to address resilience in the assessment and management of forests and the forest value chain, in relation to disturbances or stressors.

In our context, the **meaning of "operational"** implies:

1) Being able to allow the comparison of resilience between different contexts (e.g., regions, normative, management practices, types or magnitude of disturbances/stressors, etc.). Therefore, a quantitative resilience assessment approach would be preferable.
2) Being suitable to:
   - supply information on current forest resilience, also providing estimations of future resilience

- establish targets for action plans
- monitor the effects of policy implementation.
- statistically and mechanistically predict the resilience of social-ecological systems by analysing the performance of their variables in response to disturbances or stressors.
- support the identification of key factors that challenge resilience

The ORF is based on several **basic principles:**

- The forest social-ecological system is described by a set of **system variables** (e.g., variables related to ecosystem services), which are measurable, preferably quantitatively.
- Resilience must be defined as "resilience **of what to what**" (Carpenter et al. 2001), i.e., it refers to the system variable's performance through time in response to particular disturbances or stressors.
- Resilience of a system affected by disturbance(s) or stressor(s) is quantitatively compared to a **reference state.**

Adopting and applying the ORF **consists of:**

- A **Glossary** of terms, which describes the components of the ORF. These terms constitute the basis for building and implementing the ORF (see Figure 1).
- A **rationale report** describing the relationships between the components of the ORF. It constitutes the core of the ORF (see Figure 2).
- A **sequence of steps** to apply the ORF, including:
  1. Identification and quantification of system variables.
  2. Identification and description of potential disturbance regimes and stressors.
  3. Identification of the reference states, and temporal scale at which resilience is evaluated.
  4. Measure the system resilience by means of a metric, always comparing the change in system variables to the reference state.
  5. Selection of resilience predictors and identification of resilience co-drivers.
  6. Combining sets of resilience predictors for single or multiple system variables.
  7. Assessment of trade-offs and synergies affecting resilience (between resilience predictors or between system variables). For example, those describing ecosystem services vs. value chain resilience.

Examples of statements resulting from the ORF application *[ORF components are shown in brackets]:*

> "Soil depth *[Resilience predictor]* improves forest canopy *[System variable]* recovery *[Metric]* after *[Reference state: pre-fire]* wildfire *[Disturbance]*"
>
> "High functional diversity *[Resilience predictor]* maintains *[Metric]* Primary Production *[System variable]* when confronting *[Reference state: pre-drought]* drought episodes *[Disturbance/Stressor]*"
>
> "Sawmill adaptation capacity *[Resilience predictor]* promotes the regular maintenance *[Metric]* *[Reference state: base-line production]* of wood commodity production *[System variable]* under climate change *[Stressor]*"

2.2.2 Operational Resilience Framework Glossary

The operational resilience framework is based on 8 main concepts defined as follows:

1. **Resilience approach: Types of resilience**
   - **Engineering resilience:** Recovery of a system (i.e., to the pre-disturbance or undisturbed state) after a disturbance.

- **Ecological resilience**: Maximum change that a system can absorb without shifting to an alternative stable state.
- **Social-ecological resilience:** Capacity of the social-ecological system to reorganize, adapt and provide ecosystem services after disturbance or under continued stress, often associated with environmental/socioeconomic transformations.

2. System variables: Resilience OF what?

Quantitative variables describing characteristics of the social-ecological system that respond to disturbances, stressors and other co-drivers. In the RESONATE context, they often correspond to ecosystem services or value chain components. Some of them, but not all of them, may also be resilience predictors. Notice that many parameters currently identified as "indicators" in literature correspond to system variables.

3. Reference state: Resilience COMPARED to what?

Scenario that serves as a basis for comparison with the system state after disturbance or under stress. Given the many possible reference states, it is an appreciation of the performance of the system in relation to an undisturbed situation or a desired state, not an absolute value of the system. In the social-ecological approach this reference state often corresponds to the maintenance or the improvement of ecosystem service provisioning or the value chain performance. In the engineering resilience approach, the reference state would correspond to pre-disturbance or undisturbed situations. Also, different reference states may arise from different climate change scenarios and management strategies.

4. Disturbance/stress: Resilience TO what?

Relevant environmental or socioeconomic changes affecting the social-ecological system. This change can be episodic, gradual or chronical. Different disturbances may affect the same social-ecological system. Thus, resilience assessment would refer to these compound disturbances.

5. Spatio-temporal scale: WHERE and WHEN is resilience operating?

Resilience must be explicitly referred to the time extent at which recovery to disturbances or response to stressors occurs. Also, the spatial scale is relevant and should be explicitly addressed.

6. Co-drivers: Are there factors that INFLUENCE the resilience of what to what?

Factors that mediate the response of the social-ecological system in response to disturbances or stressors, but conversely to resilience predictors, they are hardly suitable to be manipulated to increase the resilience of the system. They often correspond to physical characteristics (e.g., region, climate, disturbance intensity) or political (e.g., national normative) contexts. They can be sensitive to the spatiotemporal scale, and at some level they can become resilience predictors (e.g., intensity of a past disturbance event is a co-driver, but management actions contributing to reduce disturbance intensity could be considered resilience predictors).

7. Resilience metric: HOW is resilience quantified?

Quantitative methods to measure the performance of system variable(s) of a social-ecological system in response to disturbances or stressors. This measuring implies some kind of comparison of the system variable(s) after disturbance or under stress vs. a reference state.

8. Resilience predictor: Are there parameters which allow to PREDICT resilience, and which can be MODIFIED/MANAGED to enhance resilience?

Measurable predictor of the resilience response of social-ecological systems relative to a reference state, in front of disturbances or stressors often associated to environmental/socioeconomic transformation. Resilience predictors reflect the underlying mechanisms of the system functioning and provide estimations of prospective resilience.

Furthermore, they are operational, meaning that they can become a target of management to enhance resilience (i.e., the current levels of resilience predictors inform on the expected resilience of the system). Thus, resilience predictors are a key concept within the ORF, since they address the operational need to plan and develop actions to promote resilience (see 2.2.1).

Figure 1. Visual glossary describing the main concepts of the Operational Resilience Framework.

To better understand the main concepts that comprise the operational resilience framework, these concepts have been identified in two specific examples modified from literature (Gazol et al. 2017, Walker et al. 2017) (see Annex 1).

2.2.3 Operational Resilience Framework Graphical Abstract

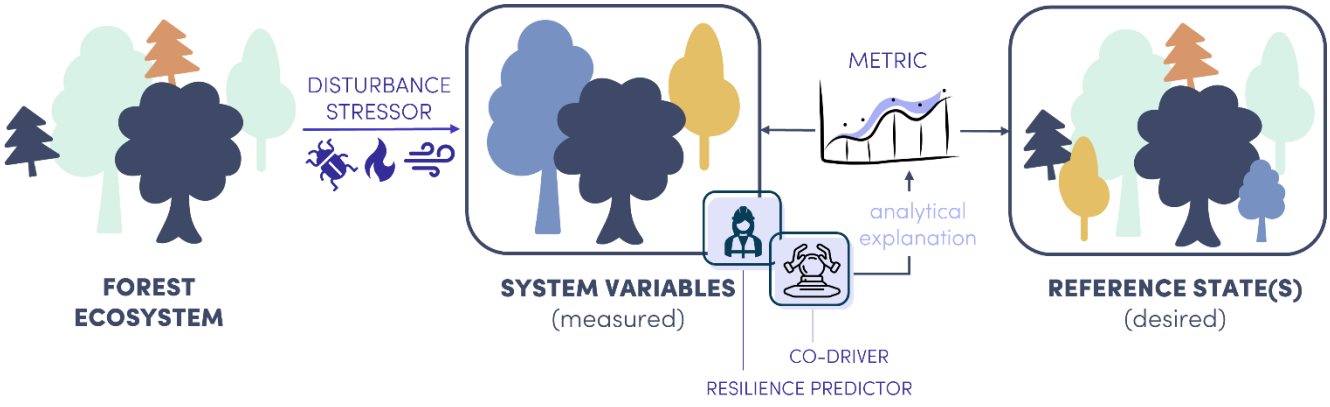

Figure 2. Graphical abstract summarizing the main concepts of the Operational Resilience Framework. Tree icons made by Gabriela Rueda.

2.3 Sources and procedure to build the inventory of resilience predictors and metrics

Following Nikinmaa et al. (2020), we checked 255 studies published in the peer-reviewed scientific journals from 2000 to 2018. These studies fulfilled 5 criteria: (1) written in English, (2) with an active verb associated to the word "resilience", (3) focused on forest related systems, natural resource management or landscape management, (4) including a definition of resilience and (5) with a qualitative or quantitative method for assessing resilience (Nikinmaa et al. 2020). We screened all 255 studies for identifying the concepts of the Operational Resilience Framework (ORF), as described in 2.2.2. As a result, 143 out of the 255 papers identified **resilience predictors** while 118 out of the 255 papers identified **co-drivers**. The references of the publications used in the inventory of resilience predictors and co-drivers are listed in Annex 2 and 3, respectively. Here we focus on components directly related to indicators: system variables, resilience predictors, co-drivers and metrics.

Given the great variation in the procedures used to measure resilience, we grouped **resilience metric** in the following categories:

Quantitative procedures:

- Equilibrium analysis of the likelihood of the system to remain in a reference state while experiencing disturbance(s) or stressor(s). It corresponds to an ecological resilience approach, in which estimations of early warning signals (e.g., critical slowing down) are often used (e.g., Dakos et al. 2015).
- Indices based on algorithms that synthesize the relationships of system variables recorded after disturbances to those corresponding to pre-disturbance or undisturbed conditions. They often consider different components of resilience, such as resistance and recovery (e.g., Lloret et al. 2011).
- Multivariate analyses combining multiple system variables that compare the performance of the system relative to disturbance(s) or stressor(s) and to a reference state in the space defined by the system variables. These comparisons often involve distances and trajectories through time (e.g., Sanchez-Pinillos et al. 2018).
- Recovery time based on estimations of the time required by system variables to attain pre-disturbance levels (e.g., Senf & Seidl 2021)
- Significant differences between the system variable(s) after disturbance or under stress and the reference state (e.g., Mallik et al. 2013).
- Statistical modelling addressing the effect of resilience predictors on system variables confronting disturbance(s) or stressor(s) (e.g., Waltz et al. 2014).
- Time-series analysis focused on patterns of change (i.e., variability) of system variables in relation to a reference state, which is often defined by baseline levels of disturbance(s) or stressor(s) (e.g., Huang & Xia 2018).

Non-quantitative procedures:

- Causal-loop diagrams identifying those resilience predictors determining the performance of forest social-ecological systems confronting disturbance(s) or stressor(s) (e.g., Knoot et al. 2010).
- Interviews of stakeholders to assess the influence of resilience predictors on forest social-ecological systems confronting disturbance(s) or stressor(s) (e.g., Ballard & Belsky 2010).

The use of these metrics in the different publications can be tracked in the references from which resilience predictors were reported (see Tables 1, 3 and Annex 2).

3. Inventory of resilience predictors and metrics

3.1 Presentation of resilience predictors and co-drivers

The objective of this inventory is to inform about **resilience predictors** and co-drivers that have been **reported in the literature** to explain the performance in terms of resilience of system variables describing forest social-ecological systems. The resilience performance has been reported to respond to disturbances or stressors related to global change drivers, and particularly to climate change. Thus, the resilience of these forest social-ecological systems is inferred from the performance of their system variables.

In a further step within the RESONATE project, this information will be used for developing D1.2 Resilience indicators and metrics assessment, which aims to inform on the more relevant resilience predictors and metrics for significant system variables under different disturbance(s) and stressor(s).

3.1.1 Inventory of resilience predictors

The inventory is presented in a set of tables including specific resilience predictors found in the literature, grouped within broader categories. **Ecological** resilience predictors (Table 1) and **socio-economic** resilience predictors (Table 3) are shown in different lists. The specific references reporting these resilience predictors are provided in Annex 2.

Further, information on the type of system variables predicted or explained by the different resilience predictors is also presented, both for ecological (Table 2) and socio-economic (Table 4) parameters. Based on the literature review, these tables identify those system variables (resilience **OF what**) for whose resilience have been explained and by which type of resilience predictors. These tables allow the reader to identify which resilience predictors have been reported for a given system variable. In some cases, particularly in the socio-economic literature, the system variables explained by resilience predictors are not specific enough, resulting that some resilience predictors listed in Tables 1 and 3 do not appear in Tables 2 and 4.

The inventory includes information on:

- **Resilience predictor category:** broad types of resilience predictors, according to their relationship with forest ecological or socio-economic contexts.
- **Resilience predictor**: brief description of resilience predictors.
- **Specific resilience predictor:** examples of specific parameters found in the literature acting as resilience predictors. For ecological resilience predictors, examples are provided in Table 1, while for socio-economic ones, examples are in Annex 4.
- **Spatial and temporal scale:** spatiotemporal scale on which the resilience predictors have proven their predictive ability or explanatory value.
- **Units and unit type:** units of the resilience predictors found in literature, specifying if they are quantitative or qualitative.
- **Resilience metric:** quantitative and non-quantitative methods used for measuring resilience in literature.
- **Case study:** output of the RESONATE WP1 case studies workshop where the representatives of each case study identified the resilience indicators (system variables and resilience predictors) to be considered in their specific case.
- **References:** literature references supporting the role of the resilience indicators as predictors.

Table 1. List of ecological resilience predictors reported in the literature to explain the resilience of system variables describing ecological components of forest social-ecological systems (see 2.2.2). Resilience predictors are grouped in broader categories. See text in 3.1.1 for further details.

RESILIENCE PREDICTOR CATEGORY	RESILIENCE PREDICTOR	SPECIFIC RESILIENCE PREDICTOR	SPATIAL SCALE						TEMPORAL SCALE						UNIT TYPE			UNITS	RESILIENCE METRIC									CASE STUDY	REFERENCES
			site	local	landscape	regional	national/continental	global	days	months	years	decades	century	qualitative	quantitative	not specified			equilibrium analysis	indices	multivariate	trajectories	recovery time	significant differences	statistical modelling	time series analysis	non-quantitative	interview	other non-quantitative	not specified		
biodiversity	animal functional diversity	bird site fidelity, bird species identity, birds mobility, insects age, mammals habitat preference and specialization	X	X	X	-	-	-	X	X	X	-	X	X	-	levels, %, species	-	X	-	-	X	-	-	-	-	-	110, 128, 171, 191	
	invasive species	invasion of non-native plants in the understory, invasive species	-	-	-	X	(X)	X	-	X	X	X	-	X	-	X	species	-	X	-	-	-	-	-	X	-	-	65, 239	
	other groups taxonomic diversity	taxonomic group	X	-	-	X	-	-	-	-	X	X	-	X	-	-	taxonomic group	-	-	X	-	X	-	-	-	-	-	174, 211	
	plant functional diversity	plant functional groups richness, plant trait diversity (fecundity, fire response/tolerance traits, leaf anatomy, leaf dry matter content, maturity, maximum age, maximum tree height, seed dispersal distance, shade tolerance, specific leaf area, wood density), species habitat preference	X	X	X	X	X	-	-	X	X	X	X	X	X	-	area/mass, density, length, levels, mass, pressure, time, unitless	-	X	X	-	X	X	-	-	-	CAT, CZ, FR	9, 10, 45, 64, 97, 113, 145, 163, 194, 202
	plant life form	growth form, life form	-	X	X	(X)	X	-	-	-	X	X	X	X	-	-	life forms	X	X	-	-	X	-	-	-	-	-	56, 133, 151	
	plant taxonomic diversity	(common species and nonvascular cryptogams) abundance, (moss community, plant and tree species) composition, tree species diversity, (dominant plant, moss and tree species) identity, forest type, (plant, tree, woody, and extirpated vs colonized species) richness	X	X	X	X	X	X	X	X	X	X	X	X	X	X	density, %, pure vs mixed, species, taxonomic group, unitless	X	X	X	X	X	-	-	-	X	CZ, FR, GB, IE	9, 11, 13, 23, 26, 29, 30, 32, 37, 42, 48, 52, 54, 55, 57, 59, 61, 63, 70, 77, 80, 81, 86, 92, 99, 104, 107, 108, 111, 112, 113, 125, 131, 135, 141, 151, 160, 161, 174, 185, 190, 196, 205, 215, 237
	tree origin	biogeographic origin	-	-	-	-	X	-	-	-	X	X	-	X	-	-	provenances	-	X	-	-	-	-	-	-	-	-	197	
forest features	composition type	ecosystem, forest, stand, habitat and tree species type, tree taxonomic class	-	X	X	X	X	X	-	X	X	X	X	X	-	-	coniferous vs broadleaved, pure vs mixed, vegetation types	-	X	X	-	X	X	-	-	-	-	10, 16, 35, 48, 64, 84, 100, 107, 114, 122, 180, 196	
	forest age	forest age, forest age after pasture abandonment	-	-	X	-	-	X	-	-	X	X	-	-	X	-	time	-	X	X	X	X	-	-	-	-	-	65, 109, 114, 141	
	forest structure	(tree and plot) basal area, (canopy and tree) cover, crown volume, dbh, (regeneration, stand and tree) density, (growth and species) dominance, remnant old-growth trees or native vegetation, (gap and patch) size, stand condition score and development, (stand, forest and size) structure	X	X	X	X	X	-	X	X	X	X	X	X	X	X	area, density, length, levels, %, pure vs mixed, unitless, vegetation types, volume, y/n	-	X	X	X	X	-	-	-	X	CAT, CZ, FR, IE	11, 15, 26, 28, 42, 46, 61, 64, 89, 92, 95, 99, 109, 110, 111, 121, 123, 131, 141, 144, 167, 169, 184, 185, 189, 191, 200, 208, 213, 253, 255
	forest successional stage	structural stage, successional stage/state, vegetation transition type	-	X	X	(X)	X	-	-	X	X	X	X	X	-	-	levels, vegetation types	X	X	X	-	X	-	-	-	-	-	12, 31, 76, 113, 131, 133, 166	
	leaf litter production	variation in leaf litter production	-	-	X	-	-	-	-	-	X	-	-	-	X	-	unitless	-	X	-	X	-	-	-	-	-	-	144	
	light conditions	photosynthetically active radiation	-	X	(X)	X	-	-	-	-	X	-	-	-	X	-	%	-	-	X	-	X	-	-	-	-	-	17, 86	
	microhabitat type	microhabitat, plant community type	-	-	X	-	-	-	-	X	X	-	-	X	-	-	levels	-	X	-	-	X	-	-	-	-	-	5, 8, 12	
	stand structure and functioning	biomass, height growth, leaf litter lignin and nitrogen content, mineralizable nitrogen, stem and tree height, stem and tree size	X	X	X	X	X	-	X	X	X	X	-	X	X	-	density, length, levels, mass/time, %	-	X	-	-	X	-	-	-	-	-	48, 46, 54, 61, 70, 76, 80, 81, 99, 111, 154, 163	
	tree age structure	ontogenic state, sapling or tree age	X	X	X	X	-	-	-	-	X	X	-	X	X	-	levels, time	-	X	-	-	-	-	-	-	-	CZ, FI, GB, IE	4, 5, 21, 28, 45, 52, 63, 135, 159, 163, 178, 185
	tree social status	tree social class/status	-	-	X	X	-	-	-	-	X	X	-	X	X	-	levels, unitless	-	X	-	-	-	-	-	-	-	-	36, 95, 121	
forest management	fire management	fire and fuel management strategy, fire and fuel reduction treatment	-	-	X	X	-	-	-	-	X	-	-	X	-	X	management categories, y/n	-	-	-	-	X	X	-	X	-	-	8, 100, 210, 249	
	management regime	management regimen or scenarios, time since last intervention	X	(X)	X	-	-	X	-	-	X	X	X	X	X	-	management categories, time	-	X	X	-	X	-	-	-	-	CZ	39, 114, 150
	provenance management	sapling provenance, tree provenance	X	-	-	X	X	-	-	-	X	X	-	X	-	-	provenances	-	X	-	-	-	-	-	-	-	-	4, 46, 118	
	stand planning and management	common property resource use, forest management practices (intensity, method and regime), forest parcelization, future management scenarios, land ownership, sustainable and traditional management strategy	X	X	X	X	X	X	-	X	X	X	X	X	X	X	area, levels, management categories, unitless, y/n	-	X	X	-	X	-	X	X	X	CAT, CZ, FI, FR, GB, IE	8, 9, 18, 28, 29, 36, 72, 74, 89, 95, 114, 117, 127, 129, 130, 145, 165, 168, 169, 182, 185, 219, 220, 229, 231, 232, 234, 236, 237, 239, 254
land use	land use intensity	agricultural pressure, field size, forest fragmentation	-	X	-	-	-	X	-	-	X	X	-	-	X	X	area, unitless	-	X	-	X	-	-	-	-	X	-	65, 181, 237	
	land use regime	land use patterns (changes vs stable patterns)	-	-	X	X	-	-	-	-	X	X	-	X	-	-	levels, management categories	-	X	-	-	X	-	-	-	-	-	20, 245	
	landscape connectivity	landscape connectivity	-	-	X	-	-	-	-	-	-	-	-	X	-	-	y/n	-	-	-	-	-	-	-	-	X	-	255	
	vegetation type	land cover change, vegetation cover, vegetation type	-	X	(X)	X	-	-	-	-	X	X	-	X	X	X	%, vegetation types	X	-	X	-	X	-	-	X	X	-	6, 44, 205, 211, 237	
	vehicle traffic	disturbance type, traffic intensity	-	-	X	-	-	-	-	X	-	-	-	X	-	-	levels, road destinations	-	-	-	-	X	-	-	-	-	-	122	
pests and herbivory	bark beetle host	bark beetle host	-	X	-	-	-	-	-	-	X	-	-	X	-	-	levels	-	-	-	-	X	-	-	-	-	-	168	
	browsing intensity	fencing, pest mammals control	-	-	X	-	-	-	-	-	X	X	-	X	-	-	animal density, management categories	-	-	-	-	X	-	-	-	-	GB	155
	grazing pressure	deer herbivory, distance from water, herbivore pressure (ungulates, mammalian herbivores)	X	X	X	X	-	-	-	X	X	X	X	X	X	X	length, %, y/n	-	X	-	-	X	X	-	X	-	-	129, 174, 180, 189, 239
regulation	forest legal status	habitat type, legal status	-	-	X	-	-	-	-	X	-	-	-	X	-	-	protection categories, vegetation types	-	-	-	-	X	-	-	-	-	CAT, GB	122, 157

NOTES: ***Spatial and temporal scale*** as (X) indicates that this level has not been reported but is likely to be appropriate to apply the resilience predictors since the immediate higher and lower level have been reported, ***Units*** in alphabetical order, ***Resilience***

metric (firstly quantitative and then non-quantitative) is indicated as "not specified" when resilience predictors are reported from narrative rationale, ***Case study*** *abbreviations: CAT-Catalonia, CZ-Czech Republic, FI-Finland, FR-France, GB-United Kingdom, IE-Ireland*, ***References*** in Annex 2

Table 2. List of the system variables explained by the ecological resilience predictors (see 2.2.2). System variables and predictors are grouped in broader categories. See text in 3.1.1 for further details.

Resilience predictor / System variable		biodiversity							forest features											forest management				land use				pests and herbivory			regulation
		animal functional diversity	invasive species	other groups taxonomic diversity	plant functional diversity	plant life form	plant taxonomic diversity	tree origin	composition type	forest age	forest structure	forest successional stage	leaf litter production	light conditions	microhabitat type	stand structure and functioning	tree age structure	tree social status	fire management	management regime	provenance management	stand planning and management	land use intensity	land use regime	vegetation type	vehicle traffic	bark beetle host	browsing intensity	grazing pressure	forest legal status
biodiversity	animal functional diversity	-	-	-	-	-	X	-	-	-	X	-	-	-	-	-	-	-	-	-	-	X	-	-	-	-	-	-	-	X
	animal taxonomic diversity	X	-	X	-	-	X	-	-	-	X	X	-	-	X	X	-	-	-	-	-	X	-	-	X	-	-	X	-	X
	life forms	-	-	-	-	-	-	-	X	-	-	-	-	-	X	-	-	-	X	-	-	X	-	-	-	X	-	-	-	X
	other groups taxonomic diversity	-	-	X	-	-	X	-	-	-	X	-	-	-	-	X	-	-	-	-	-	X	-	-	X	-	-	-	-	-
	plant functional diversity	-	-	-	-	-	X	-	X	X	X	-	-	-	X	-	X	-	-	X	-	X	-	-	-	-	X	X	-	-
	plant taxonomic diversity	-	-	X	X	X	X	-	X	X	X	X	-	X	X	-	-	-	X	X	-	X	-	-	X	-	X	X	X	-
disturbance	disturbance severity	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-	-	-	-	-	-	-	-	-	-	-
forest features	forest structure	-	X	-	X	X	X	X	X	X	X	X	X	X	-	X	X	X	X	X	X	X	X	-	X	X	X	X	X	X
	litterfall dynamics	-	-	-	-	-	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	microhabitat type	-	-	-	-	-	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	NDVI	-	-	-	X	-	X	-	X	-	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	productivity	-	-	-	X	-	X	-	-	X	X	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	stand structure	-	X	X	X	-	X	-	X	X	X	X	-	-	-	-	-	X	-	X	X	X	X	-	-	-	-	-	X	-
	tree age structure	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-	-	-	-	-	-	-	-
	urban forests	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-	-	-	-	-	-	-	-
land use	vegetation type	-	-	-	-	X	X	-	-	-	X	X	-	-	-	-	-	-	-	-	-	X	-	X	X	-	-	-	-	-
management	traditional practices	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-	-	-	-	-	-	-	-
social features	community resources	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-	-	-	-	-	-	-	-
	self-development	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-	-	-	-	-	-	-	-
pests	bark beetle infestation	-	-	-	-	-	-	-	X	-	-	-	-	-	-	-	-	-	X	-	-	X	-	-	-	-	X	-	-	-
physical environment	erosion	-	-	-	-	-	-	-	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-	-	-	X
	soil characteristics	-	-	-	X	X	X	-	-	X	X	-	-	-	-	-	-	-	-	-	-	X	-	X	-	-	-	X	-	-
value chains and trade	energetic wood use	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-	-	-	-	-	-	-	-
	timber harvest	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-	-	-	-	-	-	-	-
	non-timber products production	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-	-	-	-	-	-	-	-

NOTES: Those resilience predictors in Table 1 for which the type of predicted system variable is not specified in the literature are not included in this table.

Table 3. List of socio-economic resilience predictors reported in the literature to explain the resilience of system variables describing socio-economic components of forest social-ecological systems (see 2.2.2). Resilience predictors are grouped in broader categories. See text in 3.1.1 for further details.

RESILIENCE PREDICTOR CATEGORY	RESILIENCE PREDICTOR	SPATIAL SCALE					TEMPORAL SCALE				UNIT TYPE			UNITS	RESILIENCE METRIC							CASE STUDY	REFERENCES
		site	local	landscape	regional	national/continental	global	months	years	decades	qualitative	quantitative	not specified		indices	significant differences statistical modelling	time series analysis	non-quantitative	interview	other non-quantitative	not specified		
adaptation	adaptive capacity	-	-	-	X	-	-	-	-	-	-	X	-		-	-	-	-	X	-		-	249
	alternatives[1]	X	-	-	-	-	-	-	X	-	-	-	X	-		-	-	-	X	-	-		-	229
	creativity[2]	-	-	-	X	-	-	-	-	-	-	-	X	-		-	-	-	X	-	-		-	243
	innovations[3]	-	-	-	X	-	-	-	-	-	-	-	X	-		-	-	-	-	X	-		CZ	241, 242
economics	activity[4]	-	X	X	X	-	-	-	X	X	X	-	X	categories, range		X	-	-	X	-	-		CZ	230, 235
	credits	-	-	-	X	-	-	-	-	-	-	-	X	-		-	-	-	-	-	X		-	254
	livelihood[5]	X	(X)	X	-	-	-	-	X	-	-	X	X	unitless		-	X	-	X	-	-		-	229, 253
	management costs[6]	-	X	X	X	-	-	-	-	-	-	-	X	-		-	-	-	-	X	-		-	238, 249
education	learning[7]	-	-	X	X	-	-	-	X	-	-	-	X	yes/no		-	X	-	X	-	-		-	219, 223, 243
	local knowledge[8]	-	X	X	-	-	-	-	X	-	-	X	X	unitless		-	X	-	X	X	-		-	230, 241, 251, 253
	preparedness of youth	-	-	-	-	-	-	-	-	-	-	-	X	-		-	-	-	-	X	-		-	241
land use	agriculture[9]	X	X	X	-	-	X	-	X	-	X	X	X	%, species		-	X	-	X	X	-		-	229, 238, 253, 255
	geographic isolation	-	X	-	-	-	-	-	-	-	-	-	X	-		-	-	-	-	-	X		-	237
	urban[10]	-	-	-	X	X	-	X	(X)	X	-	-	X	-		-	-	-	X	X	-		-	234, 239
management	control and access to resources	-	-	-	X	-	-	-	-	-	-	-	X	-		-	-	-	X	-	-		-	243
	development actions[11]	-	X	X	X	-	-	-	X	X	X	-	X	categories, range		X	X	-	-	X	-		-	217, 235, 237, 241, 254
	networking[12]	X	X	X	X	-	-	X	X	-	X	X	X	categories, unitless		-	X	-	X	X	-		CZ	217, 223, 229, 230, 237, 239, 241, 253, 255
	traditional practices	-	X	-	-	-	-	-	X	-	-	-	X	-		-	-	-	X	-	-		-	251
recreational activities	tourism	-	X	X	-	-	-	-	-	-	-	X	-	area		-	-	-	-	X	-		GB	238
regulation and institutions	autonomy of the town	-	-	-	X	-	-	-	-	X	X	-	-	range		X	-	-	-	-	-		-	235
	institutional credibility[13]	-	-	-	X	-	-	-	-	-	-	-	X	-		-	-	-	X	-	-		-	243
	legislative framework[14]	-	X	(X)	X	X	-	-	X	X	X	-	X	categories, range		X	-	-	X	-	-		CZ	234, 235, 248, 254
	local institutions[15]	-	-	-	X	-	-	-	-	-	-	-	X	yes/no		-	X	-	-	-	-		-	223
	political vulnerability	-	-	X	-	-	-	-	X	-	-	-	X	-		-	-	-	X	-	-		-	219
	political will	-	X	-	-	-	-	-	-	-	-	-	X	-		-	-	-	-	-	X		-	237
social features	community resources[16]	-	X	(X)	X	-	-	-	X	X	X	X	X	categories, range		-	-	X	X	X	-		CZ, GB	241, 248, 251, 252
	health problems[17]	-	-	-	X	-	-	-	-	-	-	-	X	-		-	-	-	-	X	-		-	249
	household capabilities	-	X	X	-	-	-	-	X	-	X	-	-	categories		-	X	-	-	-	-		-	217
	insurgency level	-	-	-	X	-	-	-	-	-	-	-	X	-		-	-	-	X	-	-		-	243
	migration	X	-	-	-	-	-	-	X	-	-	-	X	-		-	-	-	X	-	-		-	229
	natural resource dependence	-	-	-	X	-	-	-	-	X	-	X	-	%		-	-	X	-	-	-		-	252
	public values	-	-	-	-	X	-	-	-	X	-	-	X	-		-	-	-	X	-	-		-	234
	social equity[18]	-	-	-	-	-	-	-	-	-	-	-	X	-		-	-	-	-	X	-		-	241
	social identity[19]	-	-	-	X	-	-	-	-	-	-	-	X	-		-	-	-	X	-	-		-	243
	social quality of life	-	-	-	X	-	-	-	-	X	X	-	-	range		X	-	-	-	-	-		-	235
value chains and trade	energetic wood use[20]	-	-	X	-	-	-	-	X	-	-	-	X	-		-	-	-	X	-	-		-	220
	forest resources[21]	-	-	-	-	-	-	-	-	-	-	-	X	-		-	-	-	-	X	-		-	241
	infrastructures	-	X	-	-	-	-	-	-	-	-	-	X	-		-	-	-	-	-	X		CZ	237
	wood products and trade[22]	-	-	-	X	-	-	-	X	-	X	X	X	categories, volume		-	X	-	-	-	-		CZ	244
working force	employement[23]	-	-	-	X	-	-	-	X	-	-	X	X	days, unitless		-	X	-	-	X	-		IE	241, 244

NOTES: Numbers in ***Resilience predictors*** correspond to examples of specific resilience predictors (see examples in Annex 4), ***Spatial and temporal scale*** as (X) indicates that this level has not been reported but is likely to be appropriate to apply the resilience indicators since the immediate higher and lower level have been reported, ***Units*** in alphabetical order, ***Resilience metric*** (firstly quantitative and then non-quantitative) is indicated as "not specified" when resilience predictors are reported from narrative rationale, ***Case study*** *abbreviations: CZ-Czech Republic, GB-United Kingdom, IE-Ireland*, ***References*** in Annex 2

Table 4. List of the system variables explained by the socio-economic resilience predictors (see 2.2.2). System variables and predictors are grouped in broader categories. See text in 3.1.1 for further details.

System variable	Resilience predictor	adaptation	economics				education		land use		management				recreational activities	regulation and institutions				social features							value chains and trade		working force
		alternatives	activity	credits	livelihood	management costs	learning	local knowledge	agriculture	urban configuration and planning	development actions	networking	planning	traditional practices	tourism	autonomy of town	legislative framework	local institutions	political vulnerability	community resources	household capabilities	migration	natural resource dependence	public values	social quality of life	energetic wood use	wood products and trade	employement
biodiversity	plant taxonomic diversity	-	-	-	X	-	-	X	X	-	-	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
economic	activity	-	X	-	-	-	-	-	-	-	X	-	-	-	-	X	X	-	-	-	-	-	-	-	X	-	X	X
	finances	-	-	-	-	-	-	-	-	-	-	-	X	-	-	-	X	-	-	X	-	-	-	-	-	-	-	-	-
	income	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-	-	X	-	-	-	-	-	-
forest features	forest structure	-	-	-	-	-	-	-	X	X	-	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	urban forests	-	-	-	-	-	-	-	-	X	-	-	-	-	-	-	X	-	-	-	-	-	-	-	X	-	-	-	-
land use	land covers	X	-	-	X	X	-	-	X	-	-	X	-	-	X	-	-	-	-	-	-	X	-	-	-	-	-	-	-
management	development actions	-	-	-	-	-	-	-	-	-	X	X	-	-	-	-	-	-	-	-	X	-	-	-	-	-	-	-	-
	network	-	-	-	-	-	X	-	-	-	X	X	-	-	-	-	-	X	-	X	X	-	X	-	-	-	-	-	-
	traditional practices	-	-	X	-	-	-	-	-	-	X	-	-	-	-	-	X	-	-	-	-	-	-	-	-	-	-	-	-
social features	attractiveness	-	X	-	-	-	-	-	-	-	X	-	-	-	-	X	X	-	-	-	-	-	-	-	X	-	-	-	-
	community resources	-	-	-	-	-	X	X	-	-	-	-	-	X	-	-	-	-	X	X	-	-	X	-	-	-	-	-	-
	demography	-	-	-	-	-	X	-	-	-	X	X	-	-	-	-	-	X	-	-	X	-	-	-	-	-	-	-	-
	household capabilities	-	-	-	-	-	-	-	-	-	X	X	-	-	-	-	-	-	-	-	X	-	-	-	-	-	-	-	-
	leadership	-	X	-	-	-	-	-	-	-	X	-	-	-	-	X	X	-	-	-	-	-	-	-	X	-	-	-	-
	natural resource dependence	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-	-	X	-	-	-	-	-	-
	self-development	-	-	-	-	-	X	-	-	-	-	-	-	-	-	-	-	-	X	-	-	-	-	-	-	-	-	-	-
	social organization	-	X	-	-	-	-	-	-	-	X	-	-	-	-	X	X	-	-	-	-	-	-	-	X	-	-	-	-
value chains and trade	energetic wood use	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-	-
	non-timber products production	-	-	-	-	-	X	-	-	-	-	-	-	-	-	-	-	-	X	-	-	-	-	-	-	-	-	-	-

NOTES: Those resilience predictors in Table 3 for which the type of predicted system variable is not specified in the literature are not included in this table.

3.1.2 Inventory of co-drivers

Based on literature review, the inventory of co-drivers (Table 5) includes those factors that mediate the response of the social-ecological system in response to disturbances or stressors, but that are not possible or difficult to be managed/modified. Co-drivers are categorized into **ecological** and **socio-economic** co-drivers. Furthermore, we propose broad (in **dark blue**) and more specific categories (in **green**), and we provide some examples (in *italics*). For example, *ecosystem type* acts as a co-driver since it has been proven that resilience of vegetation composition to bark beetles performs differently in xeric, submesic and mesic forests (Clason et al. 2014).

Table 5. List of ecological and socio-economic co-drivers, i.e., factors that influence the resilience of what to what but cannot be managed, and thus are not operational.

CO-DRIVERS
ECOLOGICAL
Biotic environment and status
▫ **Biome:** *Mediterranean vs temperate vs continental biomes*
▫ **Ecosystem type:** *Forests vs shrublands vs grasslands/savannas; grassland vs forest; tundra vs temperate forest; xeric vs submesic vs mesic; dry conifer forest vs moist conifer forest; streamside vs upland boreal forests; subalpine forests vs mountainous forests vs submountainous forests vs xerophytic forests vs floodplain forests vs submediterranean mountainous forests vs Mediterranean forests vs maquis; moist vs dry forests; forest-woody*

savanna vs shrubland vs savanna-grassland; short-canopy littoral forest vs tall-canopy littoral forest

- **Seasonal vegetation phenology:** *Mid-seasonal vs annual indices of resilience*
- **Tree status:** *Tree vigor, declining vs non-declining trees*

Climate

- **Climatic region:** *Humid vs subhumid-semiarid vs dry; climate-vegetation-productivity index (CVPI); equatorial humid vs equatorial winter wet and dry vs arid-semiarid vs montane*
- **Temperature and precipitation related variables:** *Annual temperature, annual precipitation, annual range of temperature, aridity, climate change scenario, compensated summer ombrothermic index, monthly mean temperature and precipitation, P/PET, seasonality of precipitation, throughflow rate*

Disturbance

- **Disturbance intensity:** *Burnt area, deforestation intensity, distance to edge of severe fire, drought duration, exposure to disturbance, fire temperature, hurricane intensity, number of uprooted trees, warming rate*
- **Disturbance regime:** *Disturbance scenario type (pulse vs pulse + press), fire frequency, fire history, fire recurrence, previous disturbance events, successive drought periods*
- **Disturbance severity:** *Defoliation, damage by wildlife, drought severity class, hurricane and typhoon impact*
- **Disturbance timing:** *Burn time, drought year*
- **Spatial variation in disturbance intensity:** *Areas without disturbance vs areas with low disturbance intensity vs areas with high disturbance intensity*
- **Time elapsed since last disturbance:** *Time elapsed since last fire, years after cultivation abandonment, years since treatment*

Land use

- **Land cover type:** *Forest vs grassland vs cropland*
- **Land use legacy:** *Historical land use category (e.g., intensive logging vs shade coffee plantations vs light and selective logging)*

Physical environment

- **Altitude**
- **Erosion:** *Erosion potential, soil erosion*
- **Flooding:** *Coastal flooding, sea flooding due to sea level rise*
- **Geological substrate:** *Clay vs till, schist vs breccia*
- **Latitude**
- **Longitude**
- **Microhabitat characteristics:** *Microhabitat moisture level*
- **Proximity to streams**
- **River basin type:** *Ecosystem water use efficiency*
- **Season**
- **Site productivity:** *King's site index*
- **Soil characteristics:** *Nutrient loading, soil pH, soil organic matter, soil moisture, soil depth*
- **Solar radiation:** *Mean solar radiation ($W/m^2 \cdot d$)*
- **Topography:** *Aspect, elevation, position on the slope, slope*

Region

- **Ecoregion**
- **Site**

Survey

- **Sampling characteristics:** *Survey period, sampling unit*
- **Year**
- **Location**

SOCIO-ECONOMIC
Disturbance
▫ **Disturbance impact on society:** *Number of homes lost owing to wildfire*
Land use
▫ **Industry:** *Dominant industry (farming, timber, ranching, tourism)*
Social features
▫ **Demography:** *Age, population size, town size*
▫ **Local identity:** *Village-based identity*
Socio-economic trends
▫ **Market forces**
▫ **Political changes**
▫ **Technological changes**

3.2 Applicability to RESONATE case studies

The list of resilience predictors, co-drivers and metrics presented in previous sections summarizes the results obtained from the literature review. These lists do not intend to prioritize or select the most suitable predictors, co-drivers or metrics for the different RESONATE case studies. Instead, it aims to provide an overview of those predictors that have been reported to explain the resilience of specific system variables when confronting disturbance(s) or stressor(s) related to climate change. The selection of system variables and resilience predictors to be applied in each case study will respond to their specificities in terms of biogeography, climate, management practices and socio-economic context. Therefore, this selection should be carried out when developing the corresponding WPs, with the aim of applying common criteria to facilitate comparisons between case studies. As a first demonstration of this selection process, we present in Table 6 the output of the workshop organized by WP1 in January 2022 with participation of representatives of RESONATE case studies. This workshop aimed to support the use of the RESONATE operational resilience framework (ORF) in the analysis planned for WP2 in the different case studies. Table 6 summarizes the identification of the ORF concepts by the participants in the workshop for their respective case study, thus providing an insight of resilience predictors, co-drivers and metrics that are currently planned to be used. This procedure will be carried out in more detail during the implementation of WP2, WP3 and WP4. By adopting this procedure consistently, we aim to harmonize the use of ORF throughout the RESONATE project.

Table 6. Identification of the terms of the Operational Resilience Framework (see 2.2.2.) in seven RESONATE case studies. Grey files correspond to headings of resilience predictor categories.

case study	CATALONIA	CZECH REPUBLIC	FINLAND	FRANCE	IRELAND	NEW FOREST-GB	UPPER RHINE
SYSTEM VARIABLES: Resilience OF WHAT							
Abundance of specific habitats	-	X	-	X	-	-	-
Aesthetic value	-	-	-	-	-	X	-
Age structure	-	-	-	-	-	X	-
Biodiversity	-	X	X	-	X	X	-
Carbon (flux, sequestration, stock), volume and biomass stock	-	X	X	X	X	X	-
Fresh water	X	-	-	-	-	-	-
Mortality	-	-	-	-	-	-	X
Non-wood forest products	X	-	-	-	-	-	-
Primary production	X	-	-	-	-	-	-
Recreational value	-	-	-	-	-	X	-
Soil carbon or nitrogen stock	-	-	-	-	-	X	-
Tree height and basal area increment	-	-	-	-	-	-	X
Wood/timber production/volume/unit price	X	X	X	X	X	X	-
DISTURBANCE/STRESS: Resilience TO WHAT							
Bark beetles	-	X	-	X	-	-	X
Browsing	-	-	X	-	-	X	-
Climate change	X	X	-	X	-	-	X
Diseases	-	-	-	-	-	X	-
Drought	X	X	X	X	-	X	X
Heatwave	X	-	-	-	-	-	-
Management (thinning, salvage logging, mismanagement)	-	X	X	-	-	X	-
Snowload	-	-	X	-	-	-	-
Wildfire	X	-	-	-	-	-	-
Windthrow	-	X	X	X	X	X	X
METRIC: HOW is resilience quantified?							
Pattern of change (sudden or gradual)	-	-	-	-	-	X	-
Recovery time	-	-	-	-	X	X	X
Significant differences and statistical modelling	X	X	X	X	X	X	X
Time series analysis	-	-	X	X	-	-	-
Two-dimensional resistance-recovery framework	-	X	-	-	-	-	-
CO-DRIVERS: Are there factors that INFLUENCE the resilience of what to what?							
Biogeographical gradient	-	-	X	-	-	-	-
Climate (temperature and precipitation)	X	-	X	-	-	X	-
Land-use legacies	X	-	-	-	-	-	-
Phase of the economic cycle	-	X	-	-	-	-	-
Policy changes	-	-	-	-	-	X	-
Societal changes	-	-	-	-	-	-	X
Soil characteristics	X	-	-	-	-	X	-
Stochastic events	-	-	-	-	-	X	-
Topography	X	-	-	-	-	-	-
RESILIENCE PREDICTORS: Are there parameters which allow to PREDICT resilience, and which can be MODIFIED/MANAGED to enhance resilience?							
Adaptation							
Social and technological innovations	-	X	-	-	-	-	-
Technologies	-	X	-	-	-	-	-
Animal interactions							
Browsing intensity	-	-	-	-	-	X	-
Biodiversity							
Functional tree diversity, functional diversity	X	X	-	X	-	-	-
Tree species diversity	-	X	-	X	-	X	-
Tree species identity	-	X	-	X	-	-	-
Species richness	-	-	-	-	X	-	-
Economics							
Availability of capital	-	X	-	-	-	-	-
Forest features							
Abundance of advance regeneration	-	-	-	X	-	-	-
Age distribution, age structure, multiage structure including large trees	-	X	X	-	X	X	-
Forest landscape heterogeneity	-	-	-	-	X	-	-
Growing stock levels	-	X	-	-	-	-	-
Proportion and distribution of spruce	-	X	-	-	-	-	-
Size distribution and stocking, stand size structure	X	-	-	-	-	-	-
Structural complexity	-	-	X	X	-	-	-
Forest management							
Landscape-scale pattern of management goals	-	X	-	-	-	-	-
Management strategy, managemen systems, management (tree selection, size structure), management practice	X	X	X	X	X	X	-
Proportion of unmanaged stands	-	X	-	-	-	-	-
Land use							
New housing development	-	-	-	-	-	X	-
Management							
Multi-owner coordination	-	X	-	-	-	-	-
Regulation							
Protection status	X	-	-	-	-	-	-
Protection/access to areas	-	-	-	-	-	X	-
Lesgislative framework, legislation	-	X	-	-	-	-	-
Recreational activities							
Tourists number	-	-	-	-	-	X	-
Social features							
Ownership structure	-	X	-	-	-	-	-
Value chains and trade							
Consumption pathways	-	X	-	-	-	-	-
Industry structure	-	X	-	-	-	-	-
Working force							
Public-private ability to coordinate for rapid harvesting deployment	-	-	-	-	X	-	-

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Annex 1: Identification of ORF terms in two specific examples

Example 1:

Modified from Gazol et al. 2017- *Agricultural and Forest Meteorology* 232: 186-194

Drought-induced growth decline is a phenomenon widely described in forests growing in regions subjected to seasonal water shortage such as the Mediterranean Basin. However, how tree species react to drought by modifying their growth pattern across the species distribution range is a question that remains to be answered. We investigate this question using a network of 27 Aleppo pine forests distributed across the eastern Spain and encompassing diverse site characteristics and climatic conditions. Using dendrochronology, we quantify the **radial growth** responses of this Mediterranean tree species in 1994–1995, when the most severe drought after 1950 affected the study area. To quantify the **basal area increment** (BAI) responses of trees to the 1994–1995 drought, we calculated resistance (Rt), recovery (Rc) and resilience (Rs) growth **indices following Lloret et al. (2011).** To quantify the three indices, we defined a period of **three years before and after** the 1994–1995 drought. We quantify the variation between trees and sites in terms of growth resilience to drought, i.e., **the resistance to the drought event and the recovery after it**. Then, we quantify the relationship of these responses to **tree traits** (tree diameter and height, tree age, sapwood area) at the individual tree level, and to **site characteristics** (climate conditions, stand structure–tree density, basal area and the presence of co-dominant tree species) at the site level. We found that 1994–95 dry spell strongly impacted tree growth since 25 out of 27 sites and about 88%of trees showed a marked growth reduction of around 60% in radial growth. **Climatic conditions** were by far more important than tree traits on explaining resilience indices. In particular, the resistance to drought decreased with the increase in **drought intensity**, whereas the post-drought recovery was linked to **site precipitation**. Trees from dry sites were less resistant but recovered faster than trees from wet sites. At the site level, the impact of drought on growth varied across the **species distribution range**. In addition, resilience (Rs) was negatively linked with precipitation and drought severity and positively linked with **mean tree age**.

- **Resilience approach:** Engineering resilience
- **System variables (OF):** Tree radial growth (basal area increment)
- **Reference state (COMPARED TO):** Pre-disturbance state
- **Disturbance/stress (TO):** Drought
- **Temporal scale (WHEN):** Six years (3 pre- and 3 post-drought)
- **Co-drivers (INFLUENCE):** Tree traits (tree diameter and height, tree age, sapwood area) and site characteristics (climate conditions, stand structure–tree density, basal area and the presence of co-dominant tree species)
- **Resilience measuring (HOW):** Three indices: resistance, recovery and resilience (Lloret et al. 2011)
- **Resilience predictor (PREDICTORS/OPERATIONAL):** Mean tree age

Example 2:

Modified from Walker et al. 2017 – *Ecosystems* 20: 1137-1150

Climate change has increased the occurrence, severity, and impact of disturbances on forested ecosystems worldwide, resulting in a need to identify factors that contribute to an ecosystem's resilience or capacity to recover from disturbance. Forest resilience to disturbance may decline with climate change if mature trees are able to persist under stressful environmental conditions that do not permit successful recruitment and survival after a disturbance. In this study, we used the **change in proportional representation of black spruce pre- to post-fire** as a surrogate for resilience. Changes in the proportion of black spruce before and after **fire** are a reasonable proxy for ecosystem resilience, as this measurement directly estimates potential **shifts from black spruce to deciduous canopy dominance** over the next fire-free period. We explored links between patterns of resilience and tree ring signals of drought stress across topographic moisture gradients within the boreal forest. We sampled 72 recently **(2004)** burned stands of black spruce in interior Alaska (USA) and we sampled in the summers of **2012 or 2013.** The relative dominance of black spruce after fire ranged from almost no change (high resilience) to a 90% decrease (low resilience). As a proxy for ecosystem resilience, we estimated the change in tree composition (black spruce dominance) after fire as the **difference in the proportion of total trees** that were black spruce in the pre-fire vs. post-fire stand at the same site. Variance partitioning analysis indicated that resilience was related to **site environmental characteristics** (latitude, moisture class, elevation, slope, aspect, heat load, pH, organic layer depth, mean stand age) and **climate–growth responses** (% trees responding negatively to temperature, %trees responding positively to precipitation, average radial growth from 1970 to 2003), with no unique contribution of **pre-fire stand composition** (black spruce density, black spruce basal area, trembling aspen density, trembling aspen basal area, paper birch density, paper birch basal area, total deciduous density). The largest shifts in post-fire species composition occurred in sites that experienced the compounding effects of pre-fire drought stress and shallow post-fire **organic layer thickness.** Further, the change in proportional representation of black spruce pre- to post-fire, also responded to **black spruce basal area** and **trembling aspen density.**

- **Resilience approach:** Ecological resilience
- **System variables (OF):** Proportional representation of black spruce
- **Reference state (COMPARED TO):** Black spruce dominated forests compared to deciduous dominance
- **Disturbance/stress (TO):** Wildfire
- **Temporal scale (WHEN):** 8-9 years
- **Co-drivers (INFLUENCE):** Site environmental characteristics, climate-growth responses, pre-fire stand composition
- **Resilience measuring (HOW):** Change in tree composition (black spruce dominance) after fire as the difference in the proportion of total trees that were black spruce in the pre-fire vs. post-fire stand at the same site
- **Resilience predictors (PREDICTORS/OPERATIONAL):** Organic layer depth, black spruce basal area, trembling aspen density

Annex 2: List of references included in the Literature Review for identifying Resilience Predictors

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Annex 4: Examples of socio-economic resilience predictors found in the literature

This list provides examples from literature of specific predictors, corresponding to the broader categories shown in Table 3, as indicated by numbers. The respective references can be tracked in Table 3, and are detailed in Annex 2.

1. Alternative sources of compliance
2. Creativity and commitment to operating actively
3. Optimization in forestry, the extent to which communities affected by change attempt to keep things the same or try new ways of doing things
4. Economic activities, economic diversification and strengthening of community sustenance, economic diversity
5. Alternative livelihood strategies, livelihood diversity
6. Costs of suppression in the wildland–urban interface, investment in coastal afforestation
7. Capacity for learning and adaptation, environmental learning, participatory action research, social learning
8. How well people understand the opportunities and limitations of the natural environment in and surrounding their community, local ecological knowledge, promotion of the local environmental ethic, to what extent community members believe that change is inevitable and that the community can adapt successfully to change
9. Cash-crop intensification, crop cultivation, diversity and climate-appropriate crop portfolios of resource-dependent livelihoods, local revenue, salinity of groundwater, crop species identity
10. Density and configuration of the surrounding built form, exurban development
11. Actions of development agencies, changes in participation and collaboration over time, changes in the community's capacity over time to respond to change, develop new futures for itself, and develop and implement community-centred plans, civil action, collaborative forest management program participation, community members' belief in their ability to affect the community's well-being, community members' involvement in various groups and events, opportunities for people to share lessons, unresolved questions, ideas and innovations from their experiences; the community's self-reliance in addressing major issues and changes affecting the community; the extent to which community members look outside the community to find resources to support its endeavours; the extent to which information on community resources is used in planning community endeavours; the extent to which local planning processes generate a community wide commitment to a common future; town had developed plans involving future change
12. Amount of ecological networks; changes in number and variety of external contacts over time; collective herding practices; development of networks and partnership among state forestry sector, academia, local and regional authorities and local communities; diverse social networks; household connectedness to forest institutions; social network connectivity; social network creation; social relationships between resource professionals and landowners; the extent to which community decision-making processes engage diverse perspectives and reflect cultural differences; the extent to which community leaders facilitate collaboration between groups to work on community objectives; the extent to which people from diverse groups share supports, resources, knowledge, and expertise when confronted with change; to what extent community leaders are networked with resources outside the community, for example, federal, state, county, businesses
13. Ability to assert and demonstrate fairness
14. Government policies, governments do what the public wants, regional plans
15. Internal village institutions
16. Changes in the community's resources over time; built, cultural, financial, human, natural, political and social capital

17. Number of smoke related health problems
18. Access of various groups to the community's natural resources; involvement of various groups in the planning and leadership of the community; the extent to which community organizations welcome and include various groups
19. Neutral identity of community forestry user groups
20. Economic opportunities and constraints of wood-based bioenergy
21. The effectiveness of community government in dealing with important problems facing the community; the extent to which communities affected by change generate ideas to address the change that are new and that involve recombining resources in different and creative ways; the extent to which community organizations contribute leadership and volunteers to community endeavours
22. Degree of log sorting in the woods and the trade in logs of different species, especially among specialty mills, which provides mutual support for specializations; diversity of primary and secondary (value added) wood products; output in relation to capacity, or how far below its capacity a mill was willing to operate; sawmill type
23. New kinds of business and employment opportunities developed in the community over the last ten years, number of jobs per volume of wood consumed and volume output produced, number of jobs produced, number of stable jobs and days of operation in proportion to the amount of tenure held