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]**:


"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 chronic. 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).

**SYSTEM VARIABLES**
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.

| Metric | 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. |

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

**RESILIENCE PREDICTOR**
Measurable predictor of the resilience response of social-ecological systems relative to a reference state, in the face 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).

Are there parameters which allow to predict resilience, and which can be modified/managed to enhance resilience?

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

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.

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<th>RESILIENCE PREDICTOR CATEGORY</th>
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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.

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<th>pests and herbivory</th>
<th>regulation</th>
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<td>-</td>
<td>-</td>
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**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.

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**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.

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</table>

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.

#### 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/m²·d)
- **Topography**: Aspect, elevation, position on the slope, slope

### Region
- **Ecoregion**
- **Site**

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

### SOCIO-ECONOMIC

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<th>Land use</th>
<th>Social features</th>
<th>Socio-economic trends</th>
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<td><strong>Industry:</strong> Dominant industry (farming, timber, ranching, tourism)</td>
<td><strong>Demography:</strong> Age, population size, town size</td>
<td><strong>Market forces</strong></td>
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#### 3.2 Applicability to RESONATE case studies
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.

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4. References


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 (COMPAARED 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 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 (COMPAARED 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


Summerville KS. 2013. Forest lepidopteran communities are more resilient to shelterwood harvests compared to more intensive logging regimes. *Ecol Appl.* 23: 1101–12.


Annex 3: List of references included in the Literature Review for identifying Co-drivers


Helman D, Lensky IM, Yakir D, Osem Y. 2017. Forests growing under dry conditions have higher hydrological resilience to drought than do more humid forests. *Glob Chang Biol.* 23: 2801–17.


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Summerville KS. 2013. Forest lepidopteran communities are more resilient to shelterwood harvests compared to more intensive logging regimes. Ecol Appl 23: 1101–12.


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