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Deliverable 1.2

Resilience indicators and metrics assessment

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Executive Summary

This deliverable (D1.2) is a descriptive assessment of **forest resilience indicators** and **metrics** obtained from literature (455 manuscripts published from 2000 to 2022). The assessment has been done using two methodological approaches: (1) literature review assessment and (2) stakeholder assessment. D1.2 informs and identifies the most relevant predictors and metrics to explain the resilience of system variables describing forest social-ecological systems from literature review and stakeholders' perception.

Keywords

Forest social-ecological resilience, Resilience indicators, Resilience predictors, System variables, Metrics, Ecosystem services, Forest value chain, Stakeholders

1 Introduction

This deliverable (D1.2) presents a descriptive assessment of forest resilience indicators and metrics inventoried from the literature review carried out in deliverable 1.1 (D1.1). The term "resilience indicator" is used to refer to two types of parameters (i) those describing forest social-ecological systems (**system variables**) and (ii) those predicting resilience performance (**resilience predictors**). The metrics imply different procedures to measure the resilience of system variable(s) for a given forest social-ecological system in response to disturbances or stressors. Particularly, the assessment carried out in this document aims to inform and identify the most relevant predictors and metrics to explain system variables describing the resilience of forest ecosystem services and/or the components of the forest value chain under different disturbance(s) and stressor(s). This assessment lays the groundwork to build the reference guide of agreed and tested resilience indicators to be applied by forest managers and value chain decision makers to enhance the resilience of social-ecological forest systems in different biogeographic and socio-economic contexts (deliverable 1.6).

2 Methodology

As stated in D1.1., in the RESONATE project we considered two different terms included in the broad concept of **indicators** when assessing the resilience of forest social-ecological systems: (1) **system variables** as descriptors of the properties of the system which experiences resilience (e.g., the resilience of carbon storage under climate change can be estimated by the performance of the system variable "forest stand biomass"); and (2) **predictors** of the resilience of system variables (e.g., "stand tree diversity" can predict the resilience of timber production under climate change).

The inventory of resilience indicators carried out in D1.1 identified two types of resilience system variables and predictors: **ecological** and **socio-economic** (detailed information in Table 1 and Table 3 of D1.1). Here, we focus on the assessment of both types considering two methodological approaches:

- **Literature review assessment** (see 2.1)

  Both resilience indicators (ecological and socio-economic) were evaluated based on the scientific evidence provided by the literature review for the period 2000-2022 (D1.1 and updated to 2018-2022). Particularly, we analysed the relationship between the resilience predictors and the resilience of system variables under different disturbances and in different biomes. In addition, for ecological indicators, we also assessed resilience metrics and methodologies.

- **Stakeholder assessment** (see 2.2)

  Both types of resilience indicators (ecological and socio-economic) were assessed based on stakeholders' input and perceptions. In this case, we analysed the relationship between resilience predictors and systems variables according to stakeholders' expertise and their scores on the use of each as resilience predictor based on a set of criteria.

2.1 Literature review assessment

Following Nikinmaa et al. (2020), we checked a total of 455 studies published in peer-reviewed scientific journals between 2000 and 2022: i.e., 255 studies from 2000 to 2018 (D1.1), plus 200 studies added from 2019 to 2022. The literature search was conducted using *Scopus*

database, with the search string TITLE-ABSTRACT-KEYWORDS (“resilience” AND “forest”) ALL (“measur*” OR “manage*”) PUBYEAR > 1999. The retrieved studies fulfilled 5 criteria: (1) written in English, (2) with an active verb associated with the word “resilience” (e.g., evaluate, assess, enhance, manage, improve), (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. We then screened each of the 455 studies found between 2000 to 2022 with the search criteria to identify: system variables, resilience predictors, disturbance/stressor, co-drivers, spatial and temporal scale, reference state, resilience metric, and evaluation method. As a result, 303 out of the 455 studies reported **ecological resilience predictors** while 55 out of the 455 studies reported **socio-economic resilience predictors**. In turn, we found that 399 out of the 455 studies reported the use of some **metric** or methodology to assess resilience. The references of the studies reviewed from 2000 to 2018 are listed in Annex 2 and 3 of D1.1 and from 2018 to 2022 in Annex 1 of this document, respectively.

2.1.1 Resilience indicators

Following the extraction of resilience indicators (**system variables** and **resilience predictors**) from literature, they were grouped into a set of broad categories according to their functionality and relationship with forest ecological or socio-economic contexts to facilitate their assessment and interpretation.

The categories established for **ecological indicators** are the following:

- **Biodiversity**: system variables or resilience predictors describing the different components of the variety of life forms within the forest socio-ecological system. This category includes plant and non-plant taxonomic or functional diversity (e.g., Arnan et al., 2006; Granda et al., 2018; Sánchez-Pinillos et al., 2016; Selwood et al., 2015).
- **Forest structure**: system variables or resilience predictors describing the different components of the horizontal and vertical distribution of layers in a forest including trees, shrubs, and ground cover. For instance, canopy characteristics, tree growth, tree/stand age and stand density (e.g., Andivia et al., 2020; Bottero et al., 2017; Lloret et al., 2004; Seidl et al., 2017).
- **Forest functioning**: this category describes indicators related to the functioning of the forest socio-ecological system. For instance, variables related to aboveground biomass, carbon storage, productivity and biogeochemical cycles (e.g., Creed et al., 2014; Gazol et al., 2018; Hlásny et al., 2021).
- **Forest composition**: system variables or resilience predictors describing the different plant species found in a stand or landscape. It may include trees, shrubs, forbs, and grasses. Forest type and species identity were included in this category (e.g., Camarero et al., 2021; Sánchez-Pinillos et al., 2019).
- **Forest management**: It includes resilience predictors related to activities to manage vegetation - specially forests -, restore ecosystems, reduce hazards or maintain forest health. Management intensity, management treatment and time since management treatment were included in this category (e.g., Jones et al., 2019; Manrique-Alba et al., 2022; Sohn et al., 2016).
- **Land use**: System variables or resilience predictors describing the different land covers within the forest socio-ecological system. Landscape vegetation cover and vegetation type were included here (e.g., Harris et al., 2021; Wittkuhn et al., 2011).
- **Soil and herbivory**: Soil category includes soil enzymatic activity as a system variable (Chaer et al., 2009) and herbivory category describes herbivory pressure as a resilience predictor (Moris et al., 2017; Winter at al., 2015).

For **socio-economic indicators**:

- **Adaptation:** system variables or resilience predictors describing activities aiming to adjust the forest socio-ecological system in response to changes (caused by disturbances and/or stressors), also moderating potential damages, taking advantage of opportunities, or coping with the consequences. For instance, adaptive capacity, alternatives, creativity and innovations (e.g., Dessalegn, 2016; Moen et al., 2010; Nightingale et al., 2014; Schoennagel et al., 2017).
- **Biodiversity:** as in ecological indicators, this category includes system variables or resilience predictors describing the different components of the variety and variability of life forms within the forest socio-ecological system. For instance, taxonomic diversity (Ticktin et al., 2018)
- **Economics:** system variables or resilience predictors describing the scarcity, supply and demand, costs and benefits, and incentives related to the social-ecological system. Activity, finances and livelihood were included in this category (e.g., Hahn et al., 2021; Harris et al., 2000; Ticktin et al., 2016).
- **Education:** this category includes activities related to the process of teaching/learning or the development of knowledge, such as resilience predictors learning and local knowledge (Ballard et al., 2010; Ticktin et al., 2018).
- **Forest features:** system variables or resilience predictors describing the different characteristics of the forest social-ecological system related to its structure and composition. Particularly, this category includes forest composition and forest structure (Dymond et al., 2014; Knoot et al., 2010).
- **Land use:** system variables or resilience predictors describing the different economic and cultural activities on land. For instance, land covers, agriculture and urban (Dessalegn 2016; García-Jácome et al., 2020; Knoot et al., 2010).
- **Management:** system variables and resilience predictors related to development actions, forest management strategy, networking and traditional practices (Akamani et al., 2015; Dymond et al., 2015; Knoot et al., 2010; Singer et al., 2015).
- **Recreational activities:** this category covers activities of leisure including tourism (Kim et al, 2017).
- **Regulation and institutions:** system variables or resilience predictors focus on components of the forest socio-ecological system corresponding to imposition rules to control or restrict certain activities. This category includes autonomy of the town, legislative framework and political will (Harris et al., 2000; Kelly et al., 2015; Twidwell et al., 2019).
- **Social features:** system variables or resilience predictors describing components related to social processes in the socio-ecological system. For instance, community resources, household capabilities and natural resource dependence (Akamani et al., 2015; Smith et al., 2012).
- **Value chains and trade:** this category encompasses system variables and resilience predictors of activities that involve bringing a timber- or non-timber product from a forest or agroforest to the final consumer, the consumption of products and the trade of products. For instance, use of wood for energy production, infrastructures and wood products and trade (Beeton et al. 2017, Cooper et al., 2018; Kelly et al., 2015).
- **Working force:** this category refers to the resilience predictor employment (e.g., Pinkerton et al., 2013).

Subsequently, for the assessment, we used the following information obtained from the literature:

- **Resilience predictor category:** as mentioned above, they are broad types of resilience predictors, according to their relationship with forest ecological or socio-economic contexts. The particular categories considered for ecological predictors are biodiversity, forest features (composition, structure and functioning), forest management, land use and herbivory. For socio-economic predictors are adaptation, economics, education, land use, management, recreational activities, regulation & institutions, social features, value chains & trade and working force.
- **Resilience predictor**: specific predictors found in literature. See examples for each category above, and the specific predictors used for the assessment in Table 5 and Table 9.
- **System variable category:** as mentioned above, they are broad types of system variables, according to their relationship with ecological or socio-economic contexts. The particular categories considered for ecological system variables are biodiversity, forest structure, forest functioning, land use and soil. For socio-economic system variables are biodiversity, economics, forest features, land use, management, social features and value chains & trade.
- **System variable:** specific system variables found in literature. See examples for each category above, and the specific variables used for the assessment in Table 5 and Table 9.
- **Disturbance:** relevant environmental or socioeconomic changes affecting the social-ecological system. From literature, we identified the following categories of disturbance: climate change (including drought conditions), wildfires, biotic (pest and insects), management/anthropogenic and natural hazards.
- **Biome:** from the studied systems and geographic information reported in literature review, we identified boreal, mediterranean/semi-arid, temperate and tropical-subtropical biomes.

To identify and inform about the more relevant **resilience predictors** for **system variables** under different **disturbance(s)** and **biome(s)**, we calculated:

For both ecological and socio-economic indicators

- **The prevalence of system variables and predictors**, considering the number and percentage of total studies in which a given system variable or resilience predictor belonging to a particular category are present. Such categories capture broad types of system variables or resilience predictors, according to their relationship with forest ecological or socio-economic contexts (e.g., biodiversity, forest structure, social features and economics).
- **The prevalence of relationships between system variables and predictors**, considering the number and percentage of studies in which a given system variable belonging to a particular category is significantly explained or predicted by a given resilience predictor, or vice versa, a given resilience predictor belonging to a particular category explains or predicts a given system variable.
- **The predictive capacity of resilience predictors on system variables** considering (1) the percentage of studies in which a given relationship is found out of the number of studies in which that predictor is present, and (2) the percentage of studies in which a given relationship is significant out of the total number of studies in which such relationship is present. This analysis allows the reader to identify which system variables have been reported for a resilience predictor and in which cases their

resilience is explained or predicted by it. In some cases, particularly in the socio-economic literature, resilience of the system variables explained by resilience predictors are not specific enough. Therefore, some specific resilience predictors included in broad categories of Figures 1 and 3 do not appear in Tables 4 and 5.

In addition to three points above, for the ecological indicators we also calculated

- According to disturbance(s), (1) the percentage of studies in which a given resilience predictor is present under a given disturbance, and (2) the percentage of studies in which a given resilience predictor significantly explains or predicts a system variable under a given disturbance.
- According to biome(s), (1) the percentage of studies in which a given resilience predictor is present in a given biome, and (2) the percentage of studies in which a given resilience predictor significantly explains or predicts a system variable in a given biome.

We used 303 out of the 455 reviewed studies to assess ecological resilience indicators (system variables and resilience predictors) and 55 out of the 455 reviewed studies to assess socio-economic resilience indicators (system variables and resilience predictors).

2.1.2 Metrics and methodologies

Resilience metrics imply quantitative methods to measure the performance of system variable(s) for a given forest social-ecological system in response to disturbances or stressors. Importantly, this metric must include some kind of comparison between the observed system variable(s) after disturbance or under stress and a given reference state. It is important that the selected metric provides robust information on predictors and, ideally, about its strength effect on resilience under different situations. These different situations correspond to co-drivers such as climate, management legacies, or region. In fact, the estimation of the resilience may be strongly dependent on the used metric, since different metrics emphasise different components of resilience (e.g., resistance or recovery), but they also reflect the availability of data (e.g., discrete vs continuous records), the relationship between different system variables or the temporal scale. This represents an important challenge when comparing different situations, although some techniques of meta-analysis may support overall assessments (Ibañez et al. 2019). For the assessment, we identified the following categories in literature of resilience metrics:

- **Indices:** parameters that describe different components of resilience, such as the immediate impact of disturbances (severity) or the values of system variables at a given time after the disturbance (resilience, *sensu* Lloret et al 2011, recovery *sensu* Hillebrand et al 2018).
- **Recovery analysis:** parameters specifically describing the performance of the forest system after, but not during, the disturbance event; it would correspond to a later stage than resistance.
- **Proxies:** parameters that are assumed to inform about the overall resilience of the variables of interest; for instance, tree regeneration estimations (Winter et al., 2015, Xu et al., 2017), tree density (Wu and Kim, 2013) or growth change (Xu et al., 2017).
- Statistical models: direct comparison between the system variables affected by disturbances/stress and the reference state through different statistical techniques, among which GLMs, GLZMs, and GLMMs stand out.
- **Trajectory analysis:** simultaneous analysis of multiple variables of the system, building multidimensional spaces in which the trajectories through time can be located

for each study replica (i.e., plot), and the distances with respect to the reference system can be calculated.

- **Variability:** measures of the temporal variability of the system variables, assuming equilibrium dynamics.
- **Stable state analysis:** estimators of the range of conditions that maintain a system within a given state (e.g., a type of forest) (Hirota et al 2011).

Finally, the **methodologies** identified in the literature, used to obtain the information needed for the resilience assessment, were grouped as: experimental, observational, theoretical, based on data sources, meta-analysis, remote sensing and simulation models.

Then, to assess the use of these metrics and methodologies in the literature review, we calculated:

- The number and percentage of total studies in which a given category of metric or methodology is present.
- The number and percentage of studies with a significant relationship between resilience predictor(s) and the resilience of system variable(s) in which the use of a given category of metric or methodology is present.

In this case, we used 399 out of the 455 reviewed studies, mainly including ecological resilience indicators because the use of quantitative approaches in socio-economic studies is scarcer.

2.2 Stakeholder assessment

2.2.1 Selection of a shortlist of resilience indicators

From the inventory of ecological and socio-economic resilience indicators based on literature review for the period 2000-2018 (Annex 2 and 3 of D1.1), we selected a shortlist of indicators (linking resilience predictors with the resilience of explained system variables) according to four criteria (1) frequency of use and documented effect of predictors on the resilience of system variables, as supported by the literature review, (2) minimizing the correlation among indicators (resilience predictors), (3) consistency with the resilience indicators (resilience predictors and system variables) selected to analyse ecosystem services and wood value chain in RESONATE study cases (WP2, WP3 and WP4) and (4) consistency with the resilience dashboard in development in Task 1.4.

The shortlist considers the explanatory ability of predictors on the resilience of forest ecosystem services and forest value chains. The name of some grouping categories differs from those considered in the literature review in order to make them more readable by stakeholders, and also due to the criteria applied here. In the case of ecological system variables, the name of each category was adapted from the ecosystem services classification of the Millennium Ecosystem Assessment (Alcamo, 2009). For socio-economic system variables it was adapted from components of the wood forest value chain. See below for more specifications.

For **ecological resilience indicators**, we selected 12 **resilience predictors** (specific parameters with their respective units) belonging to 5 broad categories (forest features, forest management, biodiversity, land use and regulation) overall explaining the resilience of 6 **system variables** (specific parameters with their respective units) belonging to 6 broad categories (biomass as energy, material and non-wood, biodiversity, carbon stock and control soil erosion) which describe different provisioning and regulating ecosystem services. The selected links between ecological resilience predictors and system variables are shown in

Table 1. The explanation/prediction of system variables was based on evidence from literature review. There is one exception, deadwood, a potential predictor of forest biodiversity for which no evidence was found from the literature search criteria. However, we included it based on several studies that note its positive effect on biodiversity and its potential to be manageable/operational (Vítková et al., 2018).

For **socio-economic resilience indicators**, we concluded that the evidence obtained in the literature review was not enough to support an initial selection of an appropriate number of links between resilience predictors and system variables. Therefore, we selected a shortlist of 13 potential **resilience predictors** (specific parameters with their specific units), many of them different to those observed in literature review, and 7 **system variables** (specific parameters with their respective units) related to different categories of the forest-based value chain, based on the resilience indicators chosen in WP3 and the resilience dashboard of Task 1.4. The list of potential links between predictors and system variables is shown in Table 2.

These shortlists of ecological and socio-economic resilience indicators were the basis for the discussion and assessment at the stakeholders' workshop.

Table 1. Shortlist of the most common and consistent links between ecological resilience predictors and system variables related to forest ecosystem services according to literature review, RESONATE case studies and resilience dashboard. It was given as an example to stakeholders to identify the links among socio-economic resilience predictors and system variables.

	System variables	PROVISIONING					REGULATION & MAINTENANCE	
		Biomass (energy)	**Biomass (materials)**	**Biomass (non-wood)**	**Forest biodiversity**		**Carbon stock**	**Control soil erosion**
	Resilience predictors	Wood fuel production (*ton/ha*)	Wood timber production (*ton/ha*)	Non-wood forest production (*ton/ha*)	Tree species richness (*n*)	Insects and fungi diversity (*groups*)	Aboveground biomass stock in forest (*ton/ha*)	Growing stock (*m3/ha per year*)
Forest features	Basal area (m^2/ha)	x	x		x		x	x
	Tree age structure (*yr*)	x	x		x		x	x
	Forest biomass (m^3/ha)	x	x	x	x		x	x
	Forest structure (*vegetation type*)	x	x	x	x		x	x
Forest management	Management strategy (*category*)[1]	x	x	x	x		x	x
	Forest managed for conservation / protection of soil, water, and other ecosystem functions (*ha*)	x	x	x	x		x	x
	Fire treatment (*category*)[2]				x		x	x
Biodiversity	Deadwood (m^3/ha)					(X)	(X)	(X)
	Tree functional diversity (*groups*)[3]	x	x				x	x
	Tree species identity (*species*)				x		x	x
Land use	Land use intensity (*levels*)	x	x		x		x	x
Regulation	Protection status (*category*)[4]				x			

NOTES: (x): not based on literature evidence. (1) e.g., business as usual vs maximizing economic returns vs maximizing carbon storage vs climate change adaption; (2) e.g., fuel reduction vs control (3) e.g., shade tolerant vs shade-intolerant; (4) e.g., nonprotected area vs non-reserve vs protected area-reserve

Table 2. Shortlist of potential links between socio-economic resilience predictors and system variables related to the forest value chain according to literature review, case studies and resilience dashboard. It was filled by participants.

System variables / Resilience predictors	COMPONENTS FOREST VALUE CHAIN						
	Activity	**Economics**	**Cultural**	**Biomass**			
	Employment in forestry (*number of workers*)	Forest products value (*million EUR*)	Area for recreational activities (ha)	Growing stock (m^3/ha per year)	Volume of wood production[1] (*million m^3*)	Quality of wood production[1] (*category*)	Consumption of wood products[1] (*million m^3*)
Deforestation (*ha*)							
Forest expansion (*ha*)							
Naturalness (*ha of plantations or man-undisturbed*)							
Forest connectivity index (%)							
Protection status (*category*)							
Forest area under verified forest management certification (*ha*)							
Fellings in forest available for wood supply (*m^3/ha*)							
Salvage logging (m^3)							
Wood products import or export (*million EUR*)							
Investment in forestry (*million EUR*)							
Education in forestry (*number of graduated students*)							
Forest road network (*m/ha*)							
Forest ownership (*ha of public or private area*)							

NOTES: (1) can include roundwood, wood pellets and other agglomerates, sawnwood, wood-based panels, wood pulp, pulp from fibres other than wood, recovered paper and paper, paperboard and secondary wood products.

2.2.2 Stakeholders' workshop

The workshop was held on 29th September 2022 in Vienna and facilitated by Prospex Institute. The focus of the meeting was related to receiving the perceptions and expectations through feedback from stakeholders for the assessment of resilience indicators.

The workshop was attended by a total of 12 external participants (stakeholders) and 10 internal participants (consortium partners). The 12 external participants were selected among the Stakeholder Board members and the stakeholder map proposed by each RESONATE Case Study, representing the most relevant target groups for the meeting objectives. They corresponded to the following groups:

- Forest owners' association – public (Forest and disturbance management actors)
- Forest owners' association – private (Forest and disturbance management actors)
- Forest actors in hazards' prevention management (Forest and disturbance management actors)
- Recreational and leisure services (Forest value chain actors)
- Wood-based productors and services: sawmill/industry (Forest value chain actors)
- Representatives from regional decision makers (Government and Policy Actors).

For the assessment of resilience indicators, we conducted a set of activities (exercises) during the workshop to collect the stakeholders' input and perceptions about the use of resilience predictors and system variables included in the shortlists (Table 1 and 2, see 2.2.1). The goal

of these activities was to select the most appropriate predictors to describe and enhance the resilience of forest ecosystem services and the components of the forest value chain.

The activities carried out were as follows:

Exercise 1: Identifying resilience indicators.

This exercise consisted in establishing links (relationships) between potential **socio-economic resilience predictors** and **system variables** describing the forest value chain based on the stakeholders' expertise, background and perception. As an example, a table relating ecological resilience predictors and system variables describing forest ecosystem services were provided to the external participants (Table 1, see 2.2.1).

The external participants worked in teams of two people to discuss and identify, filling Table 2 (see 2.2.1), those potential resilience predictors that are likely to explain the resilience to stressors/disturbances of any system variable (those quantitative variables describing characteristics of the system). These exercises didn't consider any specific disturbances or stressors (e.g., wildfires, biotic and natural hazards).

Then, to evaluate the results, we considered the number of replies for each link and applied basic network analysis to identify the more common interactions (links) created among potential socio-economic resilience predictors and system variables related to the forest value chain.

Exercise 2: Scoring.

This exercise consisted of scoring from 1 to 10 a set of criteria for each **ecological and socio-economic resilience predictors** (1 for the worst and 10 for the best; Table 3 and Table 4) to assess their:

Representativeness: sensitivity of the forest system to the properties described by predictors (i.e., explanatory capacity of the predictor).

Comprehensiveness: ability of the predictor to resume and integrate the mechanisms involved in the resilience of ecosystem services and value chains (i.e., a resilience predictor that is linked to multiple system variables describing different forest ecosystem services or components of the value chains)

Measurability: ability to be measured (e.g., existence of available information).

Applicability: possibility of being managed, likely to promote resilience.

The external participants compiled the exercise individually, filling Table 3 and Table 4, and considering the effect of resilience predictors on forest ecosystem services (for ecological predictors) or forest value chain (for socio-economic predictors). They were invited to add other relevant predictors or criteria according to their own experience.

Subsequently, to identify the best-scored predictors, we calculated:

- Mean and standard deviation of each criterion for each resilience predictor.
- Average of the scoring for the four criteria values for each resilience predictor.

We also considered the number of replies for each criterion and resilience predictor as a measure that could be indicative of stakeholders' understanding of the specific criterion or predictor.

Table 3. Assessment of ecological resilience predictors based on the scoring of a set of criteria (representativeness, comprehensiveness, measurability and applicability) filled by participants.

	Resilience predictor	Representativeness (1 to 10)	Comprehensiveness (1 to 10)	Measurability (1 to 10)	Applicability (1 to 10)	Comments
ECOLOGICAL	Basal area (m^2/ha)					
	Tree age structure (*yr*)					
	Forest biomass (m^3/ha)					
	Forest structure (*vegetation type*)					
	Management strategy (*category*)					
	Forest managed for conservation / protection of soil, water, and other ecosystem functions (*ha*)					
	Fire treatment (*category*)					
	Deadwood (m^3/ha)					
	Tree functional diversity (*groups*)					
	Tree species identity (*category*)					
	Land use intensity (*levels*)					
	Protection status (*category*)					

Table 4. Assessment of socio-economic resilience predictors based on the scoring of a set of criteria (representativeness, comprehensiveness, measurability and applicability) filled by participants.

	Resilience predictor	Representativeness (1 to 10)	Comprehensiveness (1 to 10)	Measurability (1 to 10)	Applicability (1 to 10)	Comments
SOCIAL-ECONOMICAL	Deforestation (*ha*)					
	Forest expansion (*ha*)					
	Naturalness (*ha of plantations or man-undisturbed*)					
	Forest connectivity index (*unitless*)					
	Protection status (*category*)					
	Forest area under verified forest management certification (*ha*)					
	Fellings in forest available for wood supply (m^3/ha)					
	Salvage logging (m^3)					
	Wood products import or export (*million EUR*)					
	Investment in forestry (*million EUR*)					
	Education in forestry (*number of graduated students*)					
	Forest road network (*m/ha*)					
	Forest ownership (*ha of public or private area*)					

3 Results

3.1 Ecological resilience indicators (system variables and predictors)

3.1.1 Literature review

Prevalence of system variables and predictors

The literature review reveals that the most frequently used system variables belong to the broad categories of forest structure, biodiversity and forest functioning, followed by land use and soil (Figure 1A). For resilience predictors, the most common categories are forest structure, forest composition, forest management and biodiversity, followed by land use, herbivory and forest functioning (Figure 1B). Note that a single study may involve more than one category of system variable and resilience predictor.

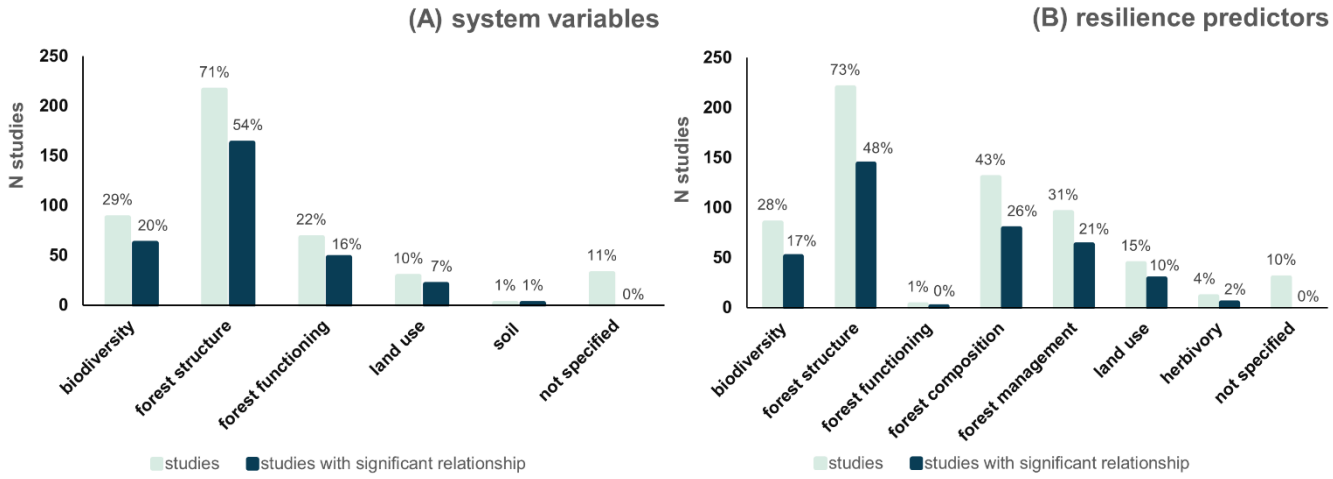

Figure 1. Number of studies (light blue) and number of studies with a significant relationship (dark blue; see 2.1.1) in which a broad category of (A) system variables and (B) ecological resilience predictors are present. The percentage of studies was calculated over 303 studies.

The following paragraphs describe the results for each category of ecological indicator:

Biodiversity: This category is commonly used in literature (as plant and non-plant taxonomic or functional diversity; e.g., Granda et al., 2018; Sánchez-Pinillos et al., 2016), to describe both system variables and resilience predictors (29% and 28% out of the 303 reviewed studies, respectively) and is also frequent in studies in which a statistically significant relationship (significant, hereafter) between predictors of resilience and system variables (20% and 17% out of 303 studies, respectively) was found.

Forest structure: This category is the most used in literature, for both system variables and resilience predictors (71% and 73% out of 303 studies, respectively) and it is also the most frequent in studies with a significant relationship between predictors of resilience and system variables (54% and 48% out of 303 studies, respectively). Some examples of system variables and predictors included in forest structure are canopy characteristics, tree growth, tree/stand age and stand density (e.g., Andivia et al., 2020; Bottero et al., 2017; Lloret et al., 2004; Seidl et al., 2017).

Forest functioning: It is commonly used in literature for system variables related to aboveground biomass, carbon storage, productivity and biogeochemical cycles (e.g., Creed

et al., 2014; Gazol et al., 2018; Hlásny et al., 2021), but not for resilience predictors (22% and 1% out of 303 studies, respectively). Moreover, for system variables, this category shows a significant relationship with resilience predictors in 16% out of 303 studies.

Forest composition: It is the second most used category in literature for resilience predictors (43% out of 303 studies) and the second most frequent in studies with a significant relationship with system variables (26% out of 303 studies). Forest type and species identity were included in forest composition (e.g., Camarero et al., 2021; Sánchez-Pinillos et al., 2019)

Forest management: This category is the third most used in the literature dealing with resilience predictors (31% out of 303 studies) and the third most frequent in studies with a significant relationship with system variables (21% out of 303 studies). It includes management intensity, management treatment and time since management treatment were included in this category (e.g., Jones et al., 2019; Manrique-Alba et al., 2022; Sohn et al., 2016).

Land use: The use of this category is relatively scarce in literature, both for system variables and resilience predictors (10% and 15% out of 303 studies, respectively) and also in studies with a significant relationship between resilience predictor(s) and system variable(s) (7% and 10% out of 303 studies, respectively). Particularly, landscape vegetation cover and vegetation type were included in this category (e.g., Harris et al., 2021; Wittkuhn et al., 2011).

Soil and herbivory: Both categories are the least used in literature for system variables, and resilience predictors. Soil category includes soil enzymatic activity as a system variable (Chaer et al., 2009) and represents only 1% out of 303 studies. Herbivory category describes herbivory pressure as a resilience predictor (Moris et al., 2017; Winter at al., 2015) and represents 4% out of 303 studies, with 2% of studies with a significant relationship for system variables.

Prevalence and statistical significance of relationships between system variables and predictors

Regarding the relationship between resilience indicators, the literature review reveals that 7 resilience predictors from 4 broad categories (forest composition, forest structure, management and biodiversity) are present in more than 10% out of 303 reviewed studies. These 7 predictors significantly explain at least one system variable in more than 50% of the cases, mainly under conditions of climate change disturbance and in temperate biomes (Tables 5, 6 and 7).

For **forest composition**, **species identity** and **forest type** are the most common resilience predictors used (29% and 14% out of 303 studies, respectively) to significantly explain 12 and 11 different system variables (64% and 55% respectively). For both species identity and forest type, the most frequent combinations with system variables are with **tree growth** (80% and 57% studies in which the resilience predictor is respectively present), with statistical significance in 70% and 46% of the cases, respectively. As for disturbance(s) and biome(s) in which species identity and forest type have been analysed, more than 65% of the cases are referred to **climate change** - including drought - and more than 40% of cases correspond to **temperate** biomes (>60% and >50% significantly).

For **forest structure**, **tree size**, **non-canopy stand structure** and **tree/stand age** are the more common resilience predictors (20%, 18% and 15% out of 303 studies) which explain between 9 and 12 different system variables (75%, 56% and 62% significantly). Within the combinations with system variables, for all tree size, non-canopy stand structure and tree/stand age, the most frequent relationship is with **tree growth** (70%, 52% and 80%, respectively) with statistical significance in the 76%, 56% and 67% of the cases, respectively.

As for disturbance(s) in which these three resilience predictors have been analysed, tree size and tree/stand age are studied referred to **climate change** conditions in more than 70% of the cases (>60% significantly), whereas non-canopy stand structure did in the 48% of the cases (64% significantly). For biome(s), tree size and non-canopy structure are studied in **temperate** biomes in more than 45% of the cases (>65% significantly) and tree/stand age in both temperate and **mediterranean/semi-arid** biomes in more than 28% cases, with statistical significance in more than 68% of the cases.

Table 5. Relationship between ecological resilience predictors and system variables explained by them. See text in 2.1.1 for further details.

	System variables / Resilience predictor					biodiversity								forest structure										forest functioning						land use				soil	
						non-plant functional diversity		non-plant taxonomic diversity		plant functional diversity		plant taxonomic diversity		canopy characteristics		demographic rates		height		non-canopy stand structure		tree growth		biogeochemical cycles		stand biomass		stand primary production		landscape vegetation cover		vegetation type		soil enzymatic activity	
		N¹	N²	N³	N⁴	%¹	%²	%¹	%²	%¹	%²	%¹	%²	%¹	%²	%¹	%²	%¹	%²	%¹	%²	%¹	%²	%¹	%²	%¹	%²	%¹	%²	%¹	%²	%¹	%²	%¹	%²
biodiversity	non-plant functional diversity	5	2	2	100	-	-	80	100	20	100	-	-	-	-	20	100	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	plant functional diversity	17	6	3	59	-	-	-	-	12	100	29	40	6	100	-	-	6	0	18	67	29	40	6	100	24	75	24	75	6	0	-	-	-	-
	plant functional traits	20	7	4	55	-	-	5	0	5	0	15	0	5	100	5	100	5	0	20	0	40	63	10	50	15	67	-	-	15	67	-	-	-	-
	plant taxonomic diversity	39	13	7	56	-	-	5	0	8	33	28	45	-	-	3	0	3	100	10	25	31	33	10	50	18	57	21	63	10	75	-	-	-	-
	type of admixture	4	1	1	75	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	75	67	-	-	-	-	-	-	25	100	-	-	-	-
composition	forest type	42	14	8	55	-	-	-	-	14	50	21	33	2	100	2	0	7	33	10	25	57	46	5	100	7	67	10	100	5	50	-	-	-	-
	species identity	88	29	18	64	-	-	3	0	7	33	7	17	1	100	5	0	1	0	9	13	80	70	1	0	3	0	5	75	2	50	-	-	1	100
forest structure and functioning	tree/stand age	45	15	9	62	-	-	-	-	2	100	4	50	-	-	2	100	2	0	9	50	80	67	11	60	2	100	4	0	-	-	-	-	-	-
	canopy characteristics	6	2	1	67	-	-	17	0	-	-	-	-	-	-	-	-	-	-	-	-	50	100	17	0	-	-	17	100	-	-	-	-	-	-
	competition	11	4	2	64	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	100	64	-	-	-	-	-	-	-	-	-	-	-	-
	non-canopy stand structure	52	17	10	56	2	100	4	50	6	33	17	56	-	-	4	50	2	0	19	60	52	56	8	25	6	67	10	0	2	0	-	-	-	-
	tree size	60	20	15	75	-	-	2	100	7	75	13	25	3	50	7	100	2	100	13	63	70	76	2	100	3	100	2	0	2	0	-	-	-	-
	stand density	29	10	5	55	-	-	3	0	-	-	21	33	-	-	3	100	3	0	34	40	52	67	3	0	10	67	-	-	3	0	-	-	-	-
	size increment	14	5	4	86	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	100	86	-	-	-	-	-	-	-	-	-	-	-	-
	successional stage	6	2	1	50	-	-	50	33	-	-	-	-	-	-	17	100	-	-	33	50	17	100	-	-	17	100	17	100	-	-	17	0	-	-
	aboveground biomass	3	1	0	33	-	-	-	-	-	-	-	-	-	-	-	-	-	-	33	0	-	-	-	-	33	100	-	-	33	0	-	-	-	-
management	management intensity	19	6	4	58	-	-	-	-	5	0	16	67	5	0	11	50	11	0	26	60	74	43	5	100	5	0	5	0	5	0	-	-	-	-
	management treatment	55	18	13	69	2	100	5	100	16	67	38	71	5	100	22	50	9	60	22	75	29	75	11	67	16	56	11	33	15	75	-	-	-	-
	time since treatment	13	4	2	46	-	-	-	-	15	0	31	50	8	0	-	-	15	0	23	67	46	33	-	-	8	0	8	0	31	50	-	-	-	-
	provenance	8	3	3	100	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	100	100	-	-	-	-	-	-	-	-	-	-	-	-
land use	land use	14	5	2	50	7	100	21	67	7	0	14	50	-	-	-	-	-	-	14	50	29	75	29	25	7	0	-	-	7	100	7	100	-	-
	landscape vegetation cover	15	5	4	87	-	-	-	-	-	-	20	67	-	-	-	-	-	-	40	83	20	33	-	-	-	-	13	100	20	100	7	100	-	-
	vegetation type	15	5	3	60	7	100	13	100	7	100	13	50	-	-	7	100	-	-	7	100	7	100	20	67	13	50	7	100	13	50	20	0	7	100
herbivory	herbivore pressure	11	4	2	45	-	-	9	0	-	-	9	100	-	-	27	33	9	100	18	100	18	0	18	0	36	25	9	0	36	0	9	100	-	-

*NOTES: **Calculations for resilience predictors: N¹** number of studies for a given resilience predictor; **N²** percentage of studies for a given resilience predictor in relation to the 303 assessed studies; **N³** percentage of studies with a significant relationship for a given resilience predictor in relation to the 303 assessed studies; **N⁴** percentage of studies with a significant relationship for a given resilience predictor in relation to the number of studies in which such predictor is present. **Calculations for the relationship between resilience predictor(s) and system variable(s): %¹** percentage of studies in which a given relationship is found out of the total number of studies in which that predictor is present (N¹) **%²** percentage of studies in which a given relationship is significant out of the total number of studies in which such relationship is present. Those resilience predictors for which the type of predicted system variable is not specified in the literature are not included in this table.*

For **forest management**, the most common resilience predictor is **management treatment** (20% out of 303 studies) which explains 13 system variables (significantly in 69% of studies). Within these combinations, the more common relationships are with **plant taxonomic diversity** and **tree growth** (38% and 29% out of studies in which this predictor is present) explaining them significantly in more than 70% of the cases. As for disturbance(s) and biome(s) in which management treatment has been analysed, more than 26% of the cases

are referred to **climate change** and **management/anthropogenic** disturbances (>59% significantly) and more than 55% of the cases correspond to **temperate** biomes (70% significantly).

Finally, for **biodiversity**, the most common resilience predictor is **plant taxonomic diversity** (13% out of 303 studies) which explains 11 system variables (in 56% of studies significantly). The effect of this predictor is usually analysed on **tree growth** and **stand primary production** (31% and 21%, respectively) and it significantly explained them in more than 30% of the cases. Regarding the disturbance(s) and biome(s) in which plant taxonomic diversity has been analysed, more than 40% of the cases are referred to **climate change** conditions (56% significantly) and more than 45% of cases correspond to **temperate** biomes (44% significantly).

Table 6. Relationship between ecological resilience predictors and disturbances. See text in 2.1.1 for further details.

	Resilience predictor \ Disturbance					climate (including drought)		climate (including drought) combined		wildfires		wildfires combined		biotic		biotic combined		management / anthropogenic		management / anthropogenic comb.		natural hazards		natural hazards combined		others	
		N^1	N^2	N^3	N^4	$\%^1$	$\%^2$	$\%^1$	$\%^2$	$\%^1$	$\%^2$	$\%^1$	$\%^2$	$\%^1$	$\%^2$	$\%^1$	$\%^2$	$\%^1$	$\%^2$	$\%^1$	$\%^2$	$\%^1$	$\%^2$	$\%^1$	$\%^2$	$\%^1$	$\%^2$
biodiversity	non-plant functional diversity	5	2	2	100	20	100	-	-	20	100	-	-	-	-	-	-	20	100	-	-	40	100	-	-	-	-
	plant functional diversity	17	6	3	59	41	43	6	100	12	100	18	67	-	-	12	50	-	-	-	-	24	50	12	1	6	100
	plant functional traits	20	7	4	55	45	89	5	0	15	33	10	0	-	-	10	0	25	20	-	-	5	100	-	-	-	-
	taxonomic diversity	39	13	7	56	41	56	5	50	8	67	13	80	8	33	15	50	13	60	5	50	15	50	10	1	3	0
	type of admixture	4	1	1	75	75	67	-	-	-	-	-	-	25	100	25	100	-	-	-	-	-	-	-	-	-	-
composition	forest type	42	14	8	55	67	61	5	100	12	40	2	100	2	100	5	50	10	25	5	50	2	0	5	1	-	-
	species identity	88	29	18	64	75	71	6	80	5	25	5	50	2	50	2	50	6	40	-	-	5	25	2	1	-	-
forest structure and functioning	tree/stand age	45	15	9	62	84	63	-	-	7	0	-	-	2	100	2	100	7	100	-	-	-	-	-	-	-	-
	canopy characteristics	6	2	1	67	83	60	-	-	-	-	-	-	-	-	-	-	-	-	-	-	17	100	-	-	-	-
	competition	11	4	2	64	100	64	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	non-canopy stand structure	52	17	10	56	48	64	8	0	12	50	2	0	8	50	8	50	13	57	2	100	12	50	2	0	-	-
	tree size	60	20	15	75	73	77	-	-	12	71	-	-	2	0	3	50	10	67	2	100	2	100	-	-	-	-
	stand density	29	10	5	55	45	62	3	0	34	60	3	0	7	0	7	0	7	50	-	-	3	100	-	-	-	-
	size increment	14	5	4	86	100	86	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	successional stage	6	2	1	50	17	0	-	-	17	0	17	100	17	100	33	100	33	50	-	-	-	-	17	1	-	-
	aboveground biomass	3	1	0	33	-	-	-	-	33	0	33	0	-	-	33	0	-	-	-	-	33	100	-	-	-	-
management	management intensity	19	6	4	58	63	50	5	0	5	100	-	-	-	-	5	100	21	75	11	50	-	-	-	-	-	-
	management treatment	55	18	13	69	29	69	15	75	11	67	13	71	9	60	15	75	27	60	13	86	4	100	7	1	-	-
	time since treatment	13	4	2	46	38	40	-	-	-	-	-	-	-	-	-	-	62	50	-	-	-	-	-	-	-	-
	provenance	8	3	3	100	100	100	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
land use	land use	14	5	2	50	29	50	0	-	-	-	-	-	7	100	7	100	43	33	7	0	7	100	-	-	-	-
	landscape vegetation cover	15	5	4	87	27	75	7	100	40	83	7	100	7	100	7	100	7	100	-	-	13	100	-	-	-	-
	vegetation type	15	5	3	60	27	50	13	100	40	67	-	-	-	-	-	-	27	50	-	-	-	-	-	-	-	-
herbivory	herbivore pressure	11	4	2	45	18	0	18	50	-	-	9	0	27	33	45	40	9	100	18	50	9	0	-	-	-	-

*NOTES: **Calculations for resilience predictors: N^1** number of studies for a given resilience predictor; **N^2** percentage of studies for a given resilience predictor in relation to the 303 assessed studies; **N^3** percentage of studies with a significant relationship for a given resilience predictor in relation to the 303 assessed studies; **N^4** percentage of studies with a significant relationship for a given resilience predictor in relation to the number of studies in which such predictor is present. **Calculations for the relationship between resilience predictor(s) and system variable(s): $\%^1$** percentage of studies in which a given resilience predictor is present for a particular disturbance category out of the total number of studies in which that predictor is present (N^1) **$\%^2$** percentage of studies in which a given resilience predictor significantly explained a system variable under a given disturbance category out of the total number of studies in which such relationship of predictor and system variable is present.*

Table 7. Relationship between ecological resilience predictors and biomes. See text in 2.1.1 for further details.

Resilience predictor \ Biome					boreal		mediterranean / semi-arid		temperate		tropical-subtropical		not included	
	N¹	N²	N³	N⁴	%¹	%²	%¹	%²	%¹	%²	%¹	%²	%¹	%²
biodiversity	non-plant functional diversity	5	2	2	100	-	-	-	-	40	100	60	100	-	-
	plant functional diversity	17	6	3	59	-	-	24	75	35	50	12	100	29	40
	plant functional traits	20	7	4	55	-	-	25	80	35	29	20	50	20	75
	taxonomic diversity	39	13	7	56	10	50	10	100	46	44	18	57	15	67
	type of admixture	4	1	1	75	-	-	-	-	75	67	-	-	25	100
composition	forest type	42	14	8	55	7	67	31	62	43	50	-	-	19	50
	species identity	88	29	18	64	6	40	25	73	56	65	8	57	6	40
forest structure and functioning	tree/stand age	45	15	9	62	16	29	29	69	31	71	7	100	18	50
	canopy characteristics	6	2	1	67	-	-	17	0	67	75	17	100	-	-
	competition	11	4	2	64	9	100	18	50	64	57	-	-	9	100
	non-canopy stand structure	52	17	10	56	17	56	13	71	46	67	15	25	8	25
	tree size	60	20	15	75	8	40	25	93	50	70	10	83	7	75
	stand density	29	10	5	55	14	50	17	60	52	67	7	0	10	33
	size increment	14	5	4	86	-	-	29	75	57	88	7	100	7	100
	successional stage	6	2	1	50	-	-	-	-	50	67	33	50	17	0
	aboveground biomass	3	1	0	33	-	-	-	-	100	33	-	-	-	-
management	management intensity	19	6	4	58	-	-	16	67	63	50	11	50	11	100
	management treatment	55	18	13	69	11	67	20	73	55	70	5	67	9	60
	time since treatment	13	4	2	46	15	50	-	-	54	43	8	0	23	67
	provenance	8	3	3	100	13	100	25	100	50	100	-	-	13	100
land use	land use	14	5	2	50	-	-	7	100	43	17	50	71	-	-
	landscape vegetation cover	15	5	4	87	7	100	27	75	60	89	-	-	7	100
	vegetation type	15	5	3	60	7	0	27	75	27	75	20	33	27	50
herbivory	herbivore pressure	11	4	2	45	18	100	18	0	55	50	9	0	-	-

*NOTES: **Calculations for resilience predictors: N¹** number of studies for a given resilience predictor; **N²** percentage of studies for a given resilience predictor in relation to the 303 assessed studies; **N³** percentage of studies with a significant relationship for a given resilience predictor in relation to the 303 assessed studies; **N⁴** percentage of studies with a significant relationship for a given resilience predictor in relation to the number of studies in which such predictor is present. **Calculations for the relationship between resilience predictor(s) and system variable(s): %¹** percentage of studies in which a given relationship is found out of the total number of studies in which that predictor is present (N¹) **%²** percentage of studies in which a given resilience predictor significantly explained a system variable under a given biome category out of the total number of studies in which such relationship of predictor and system variable is present.*

Metrics and methodologies

The literature review reveals the more common metrics used in studies focusing on ecological indicators (as said before, in studies focused on the socio-economic aspect, the quantitative approach is scarcer and therefore is not considered in this assessment of metrics), grouped in categories (Figure 2A). Note that a single study may involve more than one type of measuring resilience. For instance, indices are commonly tested by statistical modelling procedures, and recovery estimations are done together with the evaluation of resistance or other resilience indices.

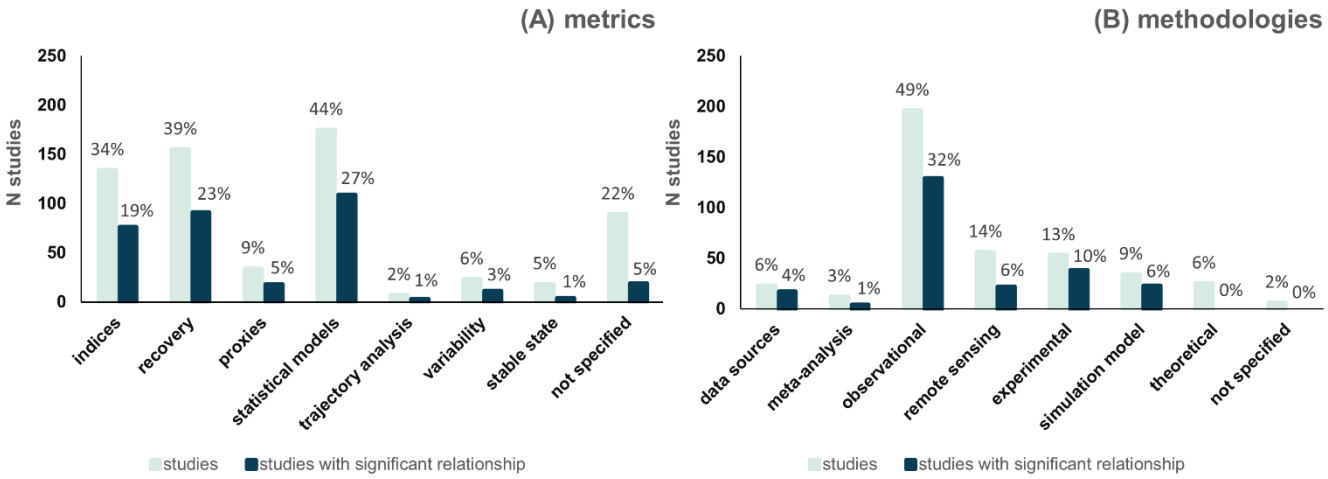

Figure 2. Number of studies (light blue) and number of studies with a significant relationship (dark blue; see 2.1.2) in which a broad category of (A) metrics and (B) methodologies is present. The percentage of studies was calculated over 399 total studies.

The following paragraphs describe the results for each metric and methodology:

Indices: They allow evaluating different phases of resilience (e.g., resistance, recovery) and integrating them into the analysis. The use of indices implies the comparison between the variables of the disturbed system and those of the reference system by means of algorithms that usually involve differences or ratios. The influence of predictors and covariates on the behavior of these indices is commonly analysed using statistical models. Indices are widely used (34% out of 399 reviewed studies) and they commonly appear in studies with a significant relationship between resilience predictors and system variables (19% out of 399 studies), particularly in engineering resilience approaches.

Recovery: This metric may correspond to different descriptors of recovery, such as recovery rate (Meng et al 2020) or the time to full recovery (Thum et al. 2016), and it may also relate recovery to resistance by biplot analysis (Ingrisch and Bahn 2018). This metric assumes that the system variables eventually achieve the values exhibited before the disturbance, so it is assuming a dynamic equilibrium without the potential of thresholds leading to alternative states. These dynamics are particularly likely to occur in variables with fast, asymptotic behavior, such as tree rings or remote sensing measures of vegetation cover (e.g., NDVI). This metric is the second most used in literature (39% out of 399 studies, 23% in significant), often together other indices.

Proxies: These parameters are applied in the absence of direct measures of the behavior of system variables. Its use is limited (9% out of 399 studies, 5% with statistical significance) and does not allow a straight application of the approach "resilience of what to what" (Carpenter et al. 2001).

Statistical models: Notably, they allow including different factors that determine the behavior of the indices (e.g., Waltz et al. 2014). This metric is the most used in literature (44% out of 399 studies, 29% with statistical significance) and permits a clear application of the "resilience of what to what" model and a solid identification and evaluation of predictors and co-drivers.

Trajectory analyses: Despite their usefulness in addressing the multiplicity of variables that make up the forest system resilience, the development and use of these techniques have been very limited up to now (2% out of 399 studies, 1% with statistical significance) (Sánchez-Pinillos et al. 2019; Sommerfeld et al. 2020).

Variability: This metric addresses ecological resilience and considers that a high variability, or consistent trends leading to cross the boundaries that describe the reference system, indicates a loss of resilience. So, the measures include time series trends, which can consider resilience indices (Gazol et al. 2016), variability estimations (Jourdan et al 2022), and autocorrelation and covariation analysis (Pappas et al. 2020). In spite of the great potential that this metric offers to analyse long-term performance of the system, particularly in a context of climate change, its use has been relatively scarce (6% out of 399 studies, 3% with statistical significance). This is probably because of the high weight of disturbances in the study of resilience in forests ecosystems and the need of enough long-time series of data.

Stable state analysis: This metric addresses ecological resilience and it may correspond to transition rates, residence time or early warning signals (critical slowing down, autocorrelation and synchrony analysis, return time after small disturbances, Dakos et al. 2014), indicating the proximity of thresholds conducting to alternative states, such as tree mortality (Cailleret et al 2019). The number of studies using this metric is relatively small (5% out of 399 studies, 1% with statistical significance), likely due to the need of long-time series of data and its strong theoretical component.

Regarding the **methodology** (Figure 2B), in most cases, it relies on observational data obtained by each study (49% out of 399 reviewed studies, 32% with statistical significance) or from other data sources (6% out of 399 studies, 4% with statistical significance). In contrast, experimental studies on resilience are quite rare (13% out of 399 studies, 10% with statistical significance). Studies using remote sensing is another remarkable source of information on forest resilience (14% out of 399 studies, 6% with statistical significance), particularly at the landscape level. The use of model simulations for studying forest resilience is not very common (9% out of 399 studies, 6% with statistical significance), while the number of studies based on meta-analysis is also low (3% out of 399 studies, 1% with statistical significance). Finally, the number of theoretical publications is appreciable (6% out of 399 studies).

3.1.2 Stakeholder assessment

Resilience predictors scoring

From the stakeholders involved in Exercise 2, we obtained 12 filled tables in which they scored each selected ecological resilience predictor from 1 to 10 (1: worst, 10: best) based on the criteria of representativeness, comprehensiveness, measurability and applicability. The mean and standard deviation obtained for each criterion and resilience predictor are shown in Table 8.

The scoring reveals that the best-scored ecological resilience predictors by stakeholders are **forest structure**, **tree species identity** and **protection status** (average values >7.5). These predictors are followed by basal area, management strategy, forest managed for conservation, tree age structure, forest biomass, land use intensity and tree functional diversity, all of them with mean values between 7.0 and 7.5. On the contrary, fire treatment and deadwood are the worst scored and with more variability among replies (average values 5.8±2.1 and 5.7±2.7, respectively).

Regarding the number of replies obtained for each resilience predictor, **protection status** shows the highest number (92% out of 48 replies) and management strategy has the lowest number (73% out of 48 replies). In the case of replies obtained for each criterion, **measurability** presents the highest number (95% out of 144 replies) followed by representativeness, comprehensiveness and applicability (83%, 81% and 81% out of 144 replies, respectively).

Table 8. Results of the scoring a set of criteria for each ecological resilience predictors. Mean and standard deviation are shown (N=12). The number of replies is shown in brackets.

	Resilience predictor	Representativeness (1 to 10)	Comprehensiveness (1 to 10)	Measurability (1 to 10)	Applicability (1 to 10)	Average
ECOLOGICAL	Basal area (m^2/ha)	6.1±2.9 (11)	5.9±1.8 (10)	9.1±1.2 (12)	7.2±1.5 (10)	7.4±1.7
	Tree age structure (*yr*)	7.0±2.0 (11)	6.6±1.3 (10)	8.3±1.5 (12)	6.6±2.3 (10)	7.2±1.0
	Forest biomass (m^3/ha)	7.5±1.7 (11)	6.1±1.9 (10)	8.1±1.5 (12)	6.6±0.7 (10)	7.2±1.0
	Forest structure (*vegetation type*)	8.0±1.8 (10)	7.5±1.6 (10)	7.6±1.6 (12)	7.3±1.9 (10)	7.7±1.3
	Management strategy (*category*)	8.1±1.4 (9)	7.6±1.8 (8)	6.7±1.5 (10)	7.3±1.8 (8)	7.3±1.3
	Forest managed for conservation / protection of soil, water, and other ecosystem functions (*ha*)	8.5±1.3 (10)	7.1±1.6 (10)	7.2±1.9 (12)	6.8±1.4 (10)	7.3±1.2
	Fire treatment (*category*)	6.0±2.5 (10)	5.0±2.5 (10)	5.5±2.2 (12)	6.2±2.3 (10)	5.8±2.1
	Deadwood (m^3/ha)	7.6±2.1 (10)	5.8±3.1 (10)	5.7±3.1 (12)	6.1±2.4 (10)	5.7±2.7
	Tree functional diversity (*groups*)	7.8±1.2 (9)	7.5±1.8 (10)	6.1±1.8 (10)	6.6±2.2 (9)	7.1±1.0
	Tree species identity (*category*)	8.1±1.1 (9)	7.7±1.0 (9)	7.8±1.1 (11)	7.0±1.7 (9)	7.6±0.9
	Land use intensity (*levels*)	7.5±1.3 (9)	7.0±1.9 (9)	7.4±1.8 (10)	7.4±1.9 (9)	7.2±1.6
	Protection status (*category*)	7.3±1.8 (10)	6.3±2.2 (11)	8.7±1.4 (12)	7.5±1.5 (11)	7.6±1.1

*NOTES. Description of each criterion: **Representativeness** is the capacity of the forest socio-ecological system to the properties described by predictors (i.e., explanatory capacity); **Comprehensiveness** is the ability of the predictor to resume and integrate the mechanisms involved in the resilience of ecosystem services and value chains ((i.e., a resilience predictor that is linked to different system variables describing different forest ecosystem services or components of the value chains); **Measurability** is the ability to be measured (e.g., existence of available information); and **Applicability** is the possibility of being managed, likely to promote resilience.*

3.2 Socio-economic resilience indicators (system variables and predictors)

3.2.1 Literature review

Prevalence of system variables and predictors

For socio-economic indicators, the literature review shows that the most frequently used system variables belong to the broad categories of economics, social features, land use, forest features and management, followed by value chains and trade and biodiversity (Figure 3A). For resilience predictors, the most common categories are management, regulation and institutions, economics, social features and land use, followed by value chains and trade, adaptation, education, recreational activities and working force (Figure 3B). Importantly, there is a high percentage of studies where the system variable(s) or resilience predictor(s) are not specified (44% and 29% out of 55 studies, respectively). Note that a single study may involve more than one category of system variable and resilience predictor.

The following paragraphs describe the results for each category of socio-economic indicators:

Adaptation: This category is used only for resilience predictors in 7% out of 55 reviewed studies, in which a significant relationship (significant, hereafter) between predictors of resilience and system variables was found in 2% of the cases. It includes predictors such as adaptive capacity, alternatives, creativity and innovations (e.g., Dessalegn, 2016; Moen et al., 2010; Nightingale et al., 2014; Schoennagel et al., 2017).

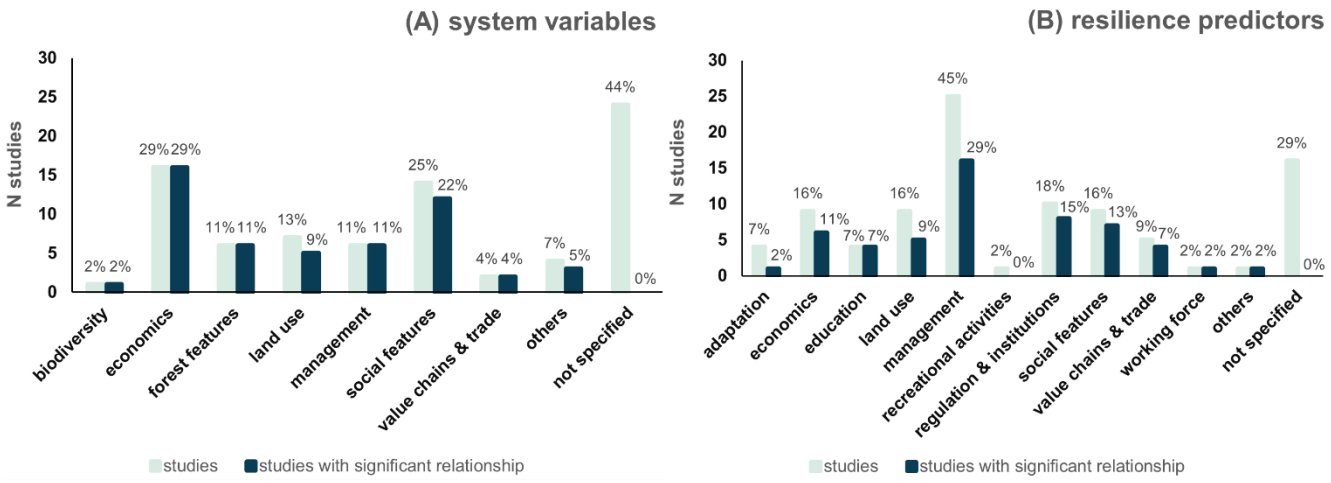

Figure 3. Number of studies (light blue) and number of studies with a significant relationship (dark blue; see 2.1.1) in which a broad category of (A) system variables and (B) socio-economic resilience predictors are present. The percentage of studies was calculated over 55 total studies.

Biodiversity: From the reviewed studies, only plant taxonomic diversity belonging to this category has been found (Ticktin et al., 2018) which is present in 2% out of 55 studies, with a significant relationship between resilience predictor and system variables.

Economics: It is the most used category of system variables in literature (29% out of 55 studies) and shows the most frequent significant relationships with predictors (also 29% out of 55 studies). For resilience predictors, this category is represented in 16% out of 55 studies, 11% significants. In this category are included activity, finances and livelihood (e.g., Hahn et al., 2021; Harris et al., 2000; Ticktin et al., 2016).

Education: Resilience predictors such as learning and local knowledge (Ballard et al., 2010; Ticktin et al., 2018) are included in this category. It is used in 7% out of 55 studies with significant relationship with system variables.

Forest features: This category includes system variables related to forest composition and forest structure (Dymond et al., 2014; Knoot et al., 2010). It is used in 11% out of 55 studies with significant relationship with resilience predictors.

Land use: It is commonly used on literature, both for system variables and resilience predictors (13% and 16% out of 55 studies, respectively), but with few studies showing significant relationships (9% out of 55 studies for both). Some examples are land covers, agriculture and urban (Dessalegn 2016; García-Jácome et al., 2020; Knoot et al., 2010).

Management: This category includes system variables and resilience predictors related to development actions, forest management strategy, networking and traditional practices (Akamani et al., 2015; Dymond et al., 2015; Knoot et al., 2010; Singer et al., 2015). It is the most used category for resilience predictors (45% out of 55 studies) and the most frequent predictor in studies with a significant relationship with system variables (29% out of 55 studies). As system variable, this category is used in 11% out of 55 studies with significant relationships.

Recreational activities: This category is only represented as resilience predictor, particularly as tourism in literature (Kim et al, 2017), being one of the least used (2% out of 55 studies) without significant statistical results.

Regulation and institutions: In this category resilience predictors such as autonomy of the town, legislative framework and political will are included (Harris et al., 2000; Kelly et al., 2015; Twidwell et al., 2019). It is the second most used on literature for resilience predictors (18% out of 55 studies), showing significant relationship with system variables in 15% of cases.

Social features: This category is the second most used in literature for system variables (25% out of 55 studies), with 22% of studies showing a significant relationship with predictors. For resilience predictors, this category represents 16% out of 55 studies with significant results in 13% of cases. It includes community resources, household capabilities and natural resource dependence (Akamani et al., 2015; Smith et al., 2012).

Value chains and trade: Resilience predictors such as the use of wood for energy production, infrastructures and wood products and trade are considered in this category (Beeton et al. 2017, Cooper et al., 2018; Kelly et al., 2015). It is the second most used category in literature for resilience predictors (9% out of 55 studies), with 7% of studies showing significant results.

Working force: From literature review, this category is only represented for resilience predictors, particularly as employment (Pinkerton et al., 2013) and being one of the least used in 2% out of 55 studies, with a significant relationship.

Prevalence and statistical significance of relationships between system variables and predictors

Regarding the relationship between resilience predictors and system variables, the literature review reveals that 7 resilience predictors belonging to 5 broad categories (economics, land use, management, regulation and institutions and social features) are present in more than 5% out of 55 reviewed studies and they significantly explain at least one system variable in more than the 49% of the cases (Table 9).

For **economics**, **activity** is the most commonly resilience predictor (7% out of 55 studies), explaining 5 system variables (100% significantly). All the combinations with system variables **activity**, **attractiveness**, **leadership**, **livelihood** and **social organization**, are equally frequent (25% of cases in which the resilience predictor is present) and the relationship is statistically significant in 100% of the cases.

For **land use**, **agriculture** is the most common resilience predictor (7% out of 55 studies), explaining 2 system variables (75% significantly). This predictor category is related to **plant taxonomic diversity** and **land covers** system variables in 25% of the cases in which this predictor is present and it explains them significantly in 100% of the cases.

For **management**, the most common resilience predictors are **development actions**, **networking** and **forest management strategy** (16%, 16% and 11% out of 55 studies, respectively), explaining between 6 and 12 system variables (in 100% of studies significantly). For **development actions**, all 12 combinations with system variables are equally frequent (11% of the cases in which this predictor is present) and 100% show significant results. Most of the system variables combined with these predictors belong to the broad categories of **economics** (activity, finances and incomes) and **social features** (attractiveness, demography, household capabilities, leadership and social organization). In the case of **networking**, the 7 combinations with system variables are equally common (11% of the cases), and 100% show significant results, being most of the system variables in the broad category of **social features** (demography and leadership). **Forest management strategy**, related to 6 system variables, being **forest composition** and **forest structure** (33% of the cases for both) the more common of them. This predictor significantly explained these system variables in 100% of the cases.

Table 9. Relationship between socio-economic resilience predictors and system variables explained by them. See text in 2.1.1 for further details.

	Resilience predictor \ System variables					biodiversity		economics								forest features				land use				management					
						plant taxonomic diversity		activity		capital		finances		incomes		livelihood		forest composition		forest structure		land cover		management land		development actions		networking		traditional practices	
		N^1	N^2	N^3	N^4	$\%^1$	$\%^2$	$\%^1$	$\%^2$	$\%^1$	$\%^2$	$\%^1$	$\%^2$	$\%^1$	$\%^2$	$\%^1$	$\%^2$	$\%^1$	$\%^2$	$\%^1$	$\%^2$	$\%^1$	$\%^2$	$\%^1$	$\%^2$	$\%^1$	$\%^2$	$\%^1$	$\%^2$	$\%^1$	$\%^2$
adaptation	adaptative capacity	1	2	2	100	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	alternatives	1	2	2	100	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	100	0
	creativity	1	2	0	0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	innovations	1	2	2	100	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
economics	activity	4	7	7	100	-	-	25	100	-	-	-	-	-	-	-	-	25	100	-	-	-	-	-	-	-	-	-	-	-	-
	credits	1	2	2	100	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	finances	1	2	2	100	-	-	-	-	-	-	100	0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	livelihood	2	4	4	100	50	100	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	50	100
	management costs	1	2	2	100	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
education	learning	2	4	4	100	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	local knowledge	2	4	4	100	50	100	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
land use	agriculture	4	7	5	75	25	100	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	25	100
	geographic isolation	1	2	2	100	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	land covers	2	4	4	100	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	50	100	-	-
	urban	2	4	4	100	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	50	100	50	100
management	development actions	9	16	16	100	-	-	11	100	11	100	11	100	11	100	-	-	-	-	11	100	11	100	11	100	-	-	-	-	-	-
	forest management strategy	6	11	11	100	-	-	-	-	17	100	-	-	-	-	-	-	-	-	17	100	-	-	17	100	33	100	33	100	17	100
	networking	9	16	16	100	11	100	-	-	-	-	-	-	-	-	-	-	11	100	-	-	-	-	-	-	-	-	11	100	11	100
	traditional practices	1	2	2	100	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
recreational activities	tourism	1	2	0	0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	100	0
regulations & institutions	autonomy of the town	2	4	4	100	-	-	50	100	-	-	-	-	-	-	-	-	50	100	-	-	-	-	-	-	-	-	-	-	-	-
	legislative framework	6	11	9	83	-	-	17	100	-	-	-	-	-	-	17	100	-	-	-	-	-	-	-	-	-	-	-	-	33	100
	local institutions	1	2	2	100	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	political will	1	2	0	0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
social features	community resources	4	7	5	75	-	-	-	-	-	-	-	-	-	-	50	100	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	health problems	1	2	0	0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	household capabilities	1	2	0	0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	migration	1	2	2	100	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	100	100
	natural resource dependence	1	2	2	100	-	-	-	-	-	-	-	-	-	-	100	100	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	public values	1	2	2	100	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	100	100
	social quality of life	1	2	2	100	-	-	100	100	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
value chains & trade	energetic wood use	1	2	2	100	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	infrastructures	2	4	2	50	-	-	-	-	-	-	-	-	-	-	-	-	50	100	-	-	-	-	-	-	-	-	-	-	-	-
	wood products and trade	2	4	4	100	-	-	50	100	-	-	50	100	-	-	-	-	-	-	-	-	-	-	50	100	-	-	-	-	-	-
working force	employment	1	2	2	100	-	-	100	100	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
others	multifunctionality	1	2	2	100	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

*NOTES: **Calculations for resilience predictors: N^1** number of studies for a given resilience predictor; **N^2** percentage of studies for a given resilience predictor in relation to the 55 assessed studies; **N^3** percentage of studies with a significant relationship for a given resilience predictor in relation to the 55 assessed studies; **N^4** percentage of studies with a significant relationship for a given resilience predictor in relation to the number of studies in which such predictor is present. **Calculations for the relationship between resilience predictor(s) and system variable(s): $\%^1$** percentage of studies in which a given relationship is found out of the total number of studies in which that predictor is present (N^1) **$\%^2$** percentage of studies in which a given relationship is significant out of the total number of studies in which such relationship is present. Those resilience predictors for which the type of predicted system variable is not specified in the literature are not included in this table.*

Table 9 (continuation). Relationship between socio-economic resilience predictors and system variables explained by them. See text in 2.1.1 for further details.

	System variables / Resilience predictor					social features												value chains & trade				others					
						attractiveness		community resources		demography		household capabilities		leadership		natural resource dependence		self-development		social organization		energetic wood use		non-timber products production		ecosystem services		multifunctionality		soil characteristics	
		N^1	N^2	N^3	N^4	$\%^1$	$\%^2$	$\%^1$	$\%^2$	$\%^1$	$\%^2$	$\%^1$	$\%^2$	$\%^1$	$\%^2$	$\%^1$	$\%^2$	$\%^1$	$\%^2$	$\%^1$	$\%^2$	$\%^1$	$\%^2$	$\%^1$	$\%^2$	$\%^1$	$\%^2$	$\%^1$	$\%^2$	$\%^1$	$\%^2$
adaptation	adaptative capacity	1	2	0	0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	alternatives	1	2	2	100	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	creativity	1	2	0	0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	innovations	1	2	2	100	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
economics	activity	4	7	4	50	25	100	-	-	-	-	-	-	25	100	-	-	-	-	25	100	-	-	-	-	-	-	-	-	-	-
	credits	1	2	2	100	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	finances	1	2	2	100	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	livelihood	2	4	4	100	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	management costs	1	2	0	0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
education	learning	2	4	4	100	-	-	50	100	50	100	-	-	-	-	-	-	50	100	-	-	-	-	50	100	-	-	-	-	-	-
	local knowledge	2	4	4	100	-	-	50	100	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
land use	agriculture	4	7	4	50	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	geographic isolation	1	2	0	0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	land covers	2	4	2	50	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	50	100
	urban	2	4	2	50	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
management	development actions	9	16	9	56	11	100	-	-	11	100	11	100	11	100	-	-	-	-	11	100	-	-	-	-	-	-	-	-	-	-
	networking	9	16	11	67	-	-	-	-	11	100	-	-	11	100	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	traditional practices	1	2	2	100	-	-	100	100	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
recreational activities	tourism	1	2	0	0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
regulations & institutions	autonomy of the town	2	4	4	100	50	100	-	-	-	-	-	-	50	100	-	-	-	-	50	100	-	-	-	-	-	-	-	-	-	-
	legislative framework	6	11	9	83	17	100	-	-	-	-	-	-	17	100	-	-	-	-	17	100	-	-	-	-	-	-	-	-	-	-
	local institutions	1	2	2	100	-	-	-	-	100	100	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	political will	1	2	0	0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
social features	community resources	4	7	5	75	-	-	50	100	-	-	-	-	-	-	25	100	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	health problems	1	2	0	0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	household capabilities	1	2	0	0	-	-	-	-	100	0	100	0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	migration	1	2	2	100	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	natural resource dependence	1	2	2	100	-	-	100	100	-	-	-	-	-	-	100	100	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	public values	1	2	2	100	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	social quality of life	1	2	2	100	100	100	-	-	-	-	-	-	100	100	-	-	-	-	100	100	-	-	-	-	-	-	-	-	-	-
value chains & trade	energetic wood use	1	2	2	100	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	100	100	-	-	-	-	-	-	-	-
	forest management strategy	6	11	7	67	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	infrastructures	2	4	2	50	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	wood products and trade	2	4	4	100	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	50	100	-	-	-	-
working force	employment	1	2	2	100	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
others	multifunctionality	1	2	2	100	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	100	100	-	-

*NOTES: **Calculations for resilience predictors: N^1** number of studies for a given resilience predictor; **N^2** percentage of studies for a given resilience predictor in relation to the 55 assessed studies; **N^3** percentage of studies with a significant relationship for a given resilience predictor in relation to the 55 assessed studies; **N^4** percentage of studies with a significant relationship for a given resilience predictor in relation to the number of studies in which such predictor is present. **Calculations for the relationship between resilience predictor(s) and system variable(s): $\%^1$** percentage of studies in which a given relationship is found out of the total number of studies in which that predictor is present (N^1) **$\%^2$** percentage of studies in which a given relationship is significant out of the total number of studies in which such relationship is present. Those resilience predictors for which the type of predicted system variable is not specified in the literature are not included in this table.*

For **regulation and institutions**, the most common resilience predictor is **legislative framework** (11% out of 55 studies) explaining 7 system variables (in 83% of studies significantly). This predictor is usually related with **land cover** (33%) and explains it significantly in 100% of the cases.

For **social features**, the most common resilience predictor is **community resources** (7% out of 55 studies), explaining 4 system variables (in 75% of studies significantly). The most common relationships are with **incomes** and **community resources** (50% of the cases in which the predictor is present) and it explains them significantly in 100% of the cases.

3.2.2 Stakeholder assessment

Resilience indicators identification

From the 12 stakeholders participating in Exercise 1, we obtained 6 filled tables in which they established the links among potential socio-economic predictors and system variables describing different components of the forest value chain (Figure 4). The result of this exercise reveals that, according to the expertise and perception of the participants, the most common resilience predictors are deforestation, investment in forestry, naturalness, forest expansion, protection status and salvage logging. For system variables, they are volume of wood production, employment in forestry, forest products value and area for recreational activities.

According to the pattern of links established among resilience predictors and system variables, the more prevalent links with more than four replies are (1) **deforestation** related to **volume of wood production**, **employment in forestry**, **forest products value** and **growing stock**; (2) **investment in forestry** with **volume of wood production**, **employment in forestry** and **quality of wood production** (3) **naturalness** with **volume of wood production** and **area for recreational activities**; (4) **forest expansion** with **growing stock** and **volume of wood production**; (5) **protection status** with **volume of wood production, employment in forestry** and **area for recreational activities**; and (6) **salvage logging** with **volume of wood production**, **forest products value** and **quality of wood production**. Note that resilience predictors and system variables differ from literature review (see 2.2.1 for more details).

Resilience predictors scoring

From Exercise 2, we obtained 12 filled tables in which the 12 stakeholders scored from 1 to 10 (1: worst, 10: best) on the criteria of representativeness, comprehensiveness, measurability and applicability for each socio-economic resilience predictors. The mean and standard deviation obtained for each criterion in each resilience predictor are shown in Table 10.

For socio-economic predictors, the scoring reveals that the best ones scored by stakeholders are **naturalness**, **forest expansion,** and **deforestation** (average values >7.0). However, deforestation, together with wood products import/export, are the predictors with the most variable replies (±2.0). Other predictors with high scoring are protection status, forest road network, investment in forestry, salvage logging, forest area under verified forest management certification, fellings in forest available for wood supply and forest ownership, all of them with average between 7.0 and 6.5. On the contrary, forest connectivity index, wood products import/export and education in forestry are the worst scored (average between 5.7 and 5.5).

Regarding the number of replies for each resilience predictor, **education in forestry** obtained the highest number (96% out of 48 replies) and forest ownership the lowest number (88% out of 48 replies). In the case of replies obtained for each criterion, **measurability** presents the highest number (99% out of 156 replies) followed by representativeness, applicability and comprehensiveness (98%, 97% and 85% out of 156 replies, respectively).

Figure 4. Links established by the stakeholders among potential socio-economic resilience predictors and system variables explained.

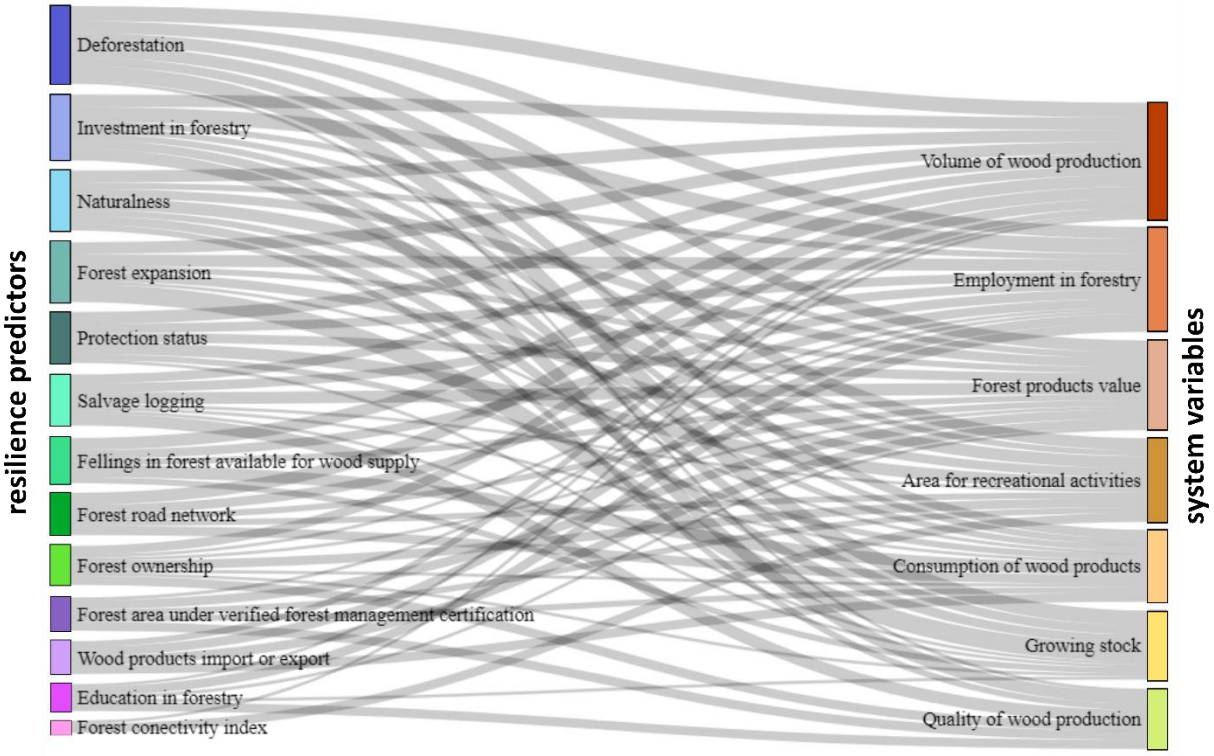

Table 10. Results of the scoring a set of criteria for each socio-economic resilience predictors. Mean and standard deviation are shown (N=12). The number of replies is shown in brackets.

	Resilience predictor	Representativeness (1 to 10)	Comprehensiveness (1 to 10)	Measurability (1 to 10)	Applicability (1 to 10)	Average
SOCIAL-ECONOMICAL	Deforestation (*ha*)	6.9±3.2 (12)	6.3±3.0 (11)	8.8±1.3 (12)	7.0±3.2 (12)	7.2±2.0
	Forest expansion (*ha*)	6.6±2.5 (12)	6.1±2.5 (10)	8.6±1.2 (12)	7.8±1.8 (12)	7.3±1.4
	Naturalness (*ha of plantations or man-undisturbed*)	8.0±1.3 (12)	6.7±2.4 (10)	7.8±1.3 (12)	6.9±1.8 (11)	7.4±1.2
	Forest connectivity index (*unitless*)	5.2±2.4 (12)	5.6±2.0 (10)	7.1±2.2 (12)	5.2±2.2 (11)	5.7±1.7
	Protection status (*category*)	6.5±2.1 (12)	5.9±2.1 (10)	8.5±1.5 (12)	7.1±2.3 (12)	7.1±1.2
	Forest area under verified forest management certification (*ha*)	5.3±2.6 (12)	6.0±1.6 (10)	8.3±1.4 (12)	7.6±2.0 (12)	6.9±1.6
	Fellings in forest available for wood supply (m^3/ha)	6.1±2.7 (11)	5.8±2.3 (10)	7.5±2.1 (12)	6.5±2.4 (12)	6.6±1.9
	Salvage logging (m^3)	6.1±2.8 (12)	5.7±2.1 (11)	7.5±2.1 (12)	6.9±2.2 (12)	6.7±1.7
	Wood products import or export (*million EUR*)	4.5±2.7 (11)	4.2±2.6 (10)	8.6±1.1 (12)	4.0±2.8 (11)	5.6±2.0
	Investment in forestry (*million EUR*)	6.0±2.0 (12)	5.9±1.9 (10)	8.8±1.1 (12)	7.1±2.2 (12)	7.0±1.2
	Education in forestry (*number of graduated students*)	3.6±2.5 (12)	4.3±2.0 (11)	8.1±2.2 (12)	5.7±2.9 (12)	5.5±1.5
	Forest road network (*m/ha*)	6.0±2.3 (12)	6.4±2.1 (10)	8.6±1.1 (12)	6.8±1.6 (12)	7.0±1.1
	Forest ownership (*ha of public or private area*)	6.0±2.9 (11)	5.6±1.5 (9)	8.3±2.3 (11)	5.5±2.9 (11)	6.5±1.8

*NOTES. Description of each criterion: **Representativeness** is the capacity of the forest socio-ecological system to the properties described by predictors (i.e., explanatory capacity); **Comprehensiveness** is the ability of the predictor to resume and integrate the mechanisms involved in the resilience of ecosystem services and value chains ((i.e., a resilience predictor that is linked to different system variables describing different forest ecosystem services or components of the value chains); **Measurability** is the ability to be measured (e.g., existence of available information); and **Applicability** is the possibility of being managed, likely to promote resilience.*

4 Discussion

4.1 Resilience indicators

4.1.1 Ecological resilience indicators (system variables and predictors)

The last decades of scientific evidence reveal an increasing interest in investigating the factors that determine the resilience of forests and the forest value chain. This large information has generated an important background that allows identifying contrasted predictors of the resilience of system variables, which in turn are directly or indirectly related to forest ecosystem services. Based on the scientific evidence provided by the **literature review** from 2000-2022, we can extract several general considerations about the most relevant predictors of resilience of the main forest variables. These considerations particularly apply to temperate forests which broadly correspond to a great part of European forests, and to a context of climate change, particularly under drought conditions. Importantly, these general considerations should be refined according to the specificities determined by local, national, and regional contexts, including biophysical (e.g., topography, soils, herbivory) and socio-economic (e.g., demand of forest goods, number of sawmills, market features, regulations) characteristics. Also, the identification of the most relevant resilience indicators should consider the effect (positive or negative) of predictors on the resilience of system variables under different disturbances/ stressors and biomes. This effect may follow complex non-lineral patterns which should be accounted, as well as trade-offs and synergies, when applying this information to decision-making processes (Nikinmaa et al. 2023) This would improve the selection of concrete resilience indicators to enhance the resilience of forest social-ecological systems in different contexts.

Overall, we can recognise that the main ecosystem properties for which resilience has been assessed in the literature, refer to forest **structure** (tree size, age, stand basal area), **functioning** (primary production, carbon stocks, and less commonly biogeochemical cycling), and **biodiversity** (both in terms of species composition and abundance), although there is a noticeable variability in the specific system variables evaluated. On the other side, the most important predictors of the resilience of the above-mentioned forest properties also correspond to **structural** and **biodiversity** forest features, which in turn are modified by **forestry planning and silvicultural practices**.

For instance, the resilience of tree growth appears highly dependent of structural properties, such as tree size and age, and neighbours (stand structure), and also by biodiversity-related parameters, such as species identity. When growth (in terms of demographic rates and biomass) is scaled-up to stand level, its resilience also appears predicted by structural (basal area, density or size classes) and biodiversity (plant taxonomic or functional diversity) features. Importantly, a consensus emerges from the literature on the importance of plant taxonomic diversity on the resilience of stand primary production, while the relevance if functional diversity is increasingly recognised. As said above, these structural and biodiversity-based predictors are tightly related to forest management (silvicultural practices). In turn, the resilience of forest diversity is also highly determined by management. Therefore, the integrative assessment and promotion of forest ecosystem resilience should address all these three groups of system variables (structural, functioning, and biodiversity), according to the specificities and context of each case. Although the mutual relationships between predictors and system variables may appear rather complex at first glance, a general rule for enhancing ecosystem resilience in forests points to management practices promoting irregular (ensuring

regeneration and avoiding adverse effects of intense competence), and diverse (with well-adapted species) stands.

More particularly and according to the literature review:

- forest composition parameters such as **species identity** and **forest type** - which often correspond to a scaling-up from species to community levels - can be considered important predictors of **tree growth**. The mechanisms underlying this relationship are well-known ecological principles of species habitat selection and community assembly, which involve species interactions through the different life-history stages. The relevance of these composition-based predictors highlights the importance of selecting species appropriate for the new climate change context to promote the resilience of European forests.
- forest biodiversity such as **plant taxonomic diversity** also appears as an important predictor of both **tree and stand production**. This relationship is also well-based in mechanisms related to species functional complementarity, species interactions such as facilitation, and species selection, which have been documented to determine forest ecosystem functioning (e.g., Grossiord 2019). The use of this predictor is consistent with current trends to enhance mixed forests as a sound strategy to promote the resilience of forest ecosystem services.
- forest structure parameters - often associated with **management plans and silvicultural practices** - are important predictors of the resilience of **tree growth**, and likely of **stand-level production**. This is consistent with the well-known principle of stand structure determining its functioning (i.e., primary production), being this relationship dynamics through time by responding to the interaction between density-dependent processes and changing availability of resources, thus, it often exhibits complex patterns (Jump et al 2017). The management of forest structures, thus, emerges as a relevant procedure to enhance forest resilience in front of climate change, but it merits an important local contextualization. In fact, forest structural features are also relevant predictors for the resilience of forest biodiversity, reflecting the existence of an important and complex trade-off between forest goods provisioning - particularly, timber harvest - and biodiversity-related services.

The **stakeholder assessment** supports the value of vegetation and species composition and identity as predictors of forest resilience, and at lesser extent stand biomass and tree age. Interestingly, the increasing interest in academic literature about the importance of functional diversity, does not yet seem translated to stakeholders. It is also noticeable the value of protection status for forest resilience is recognised by stakeholders, which appears under-evaluated in academic studies. Overall, this preliminary stakeholders' perception tends to recognise the **protection status** of forests as a sound operational way to enhance forest resilience, even more than silvicultural practices by themselves.

4.1.2 Socio-economic resilience indicators (system variables and predictors)

The scientific evidence obtained from the **literature review** for resilience indicators under a socio-economic context is very limited. In most cases, the robustness of the relationships between socio-economic resilience predictors and system variables explained or predicted is based on a single case in each study. Virtually, no specific indicators (both predictors and system variables) have been consistently found to be used in the different studies (such is the case of tree growth for ecological indicators). In addition, some parameters considered in the literature are quite general and not related to the forest/wood value chain (e.g., demography, community resources and other social features) and its effect would be indirect.

Despite the lack of enough evidence, some predictors have been suggested to explain the resilience of several variables describing the forest socio-ecological systems:

- **Economic activity** can act as a predictor of the resilience of system variables related to **livelihood** and **social features**, such as **attractiveness**, **demography**, **leadership** and **social organization**.
- **Development actions** can contribute to the resilience of **economic activity** and **incomes**, which are also favoured by enhancing community resources, and also to the resilience of **social features**, such as **attractiveness**, **demography**, **leadership** and **social organization**, which are also explained by networking.
- **Forest management strategy** is also a predictor of the resilience of system variables related to **forest features**, such as **forest composition and structure**, in correspondence with the above-discussed ecological resilience indicators.
- **Land use** (particularly, the weight of agricultural land) can act as a predictor of the resilience of system variables related to **biodiversity** (**plant taxonomic diversity**).
- The **legislative framework** appears as a relevant predictor of the resilience of landscape-level system variables, such as **land cover**.

Note that many of these predictors refer to building contextual conditions which should promote at different scales social adaptability and well-being, integrated with natural values. Differently from ecological indicators (which are largely focused on stand level), socio-economic ones tend to cover larger spatial and decision-making scales (from landscape to national).

According to the **stakeholder assessment**, it has been established a set of potential relationships between socio-economic resilience predictors and system variables to explain the resilience of the forest value chain in the current scenario of climate change. Overall, the most robust predictors of the resilience of forest socio-economic variables correspond to land-based processes, including land use patterns (protection status, naturalness) and dynamics (deforestation, forest expansion, salvage logging), and investment in forestry. More particularly, the relevant relationships between predictors and system variables are the following:

- To explain the resilience of economic **activity,** estimated by the system variable **employment in forestry**:
  - Resilience predictors related to economics → **investment in forestry**.
  - Resilience predictors related to forest regulation → **protection status**.
  - Resilience predictors related to management → **deforestation**.
- To explain the resilience of system variables related to **biomass**:
  - **Growing stock**
    - Resilience predictors related to management → **deforestation** and **forest expansion**.
  - **Quality of wood production**
    - Resilience predictors related to economics → **investment in forestry**.
    - Resilience predictors related to management → **salvage logging**.
  - **Volume of wood production**
    - Resilience predictors related to economics → **investment in forestry**.
    - Resilience predictors related to management → **deforestation**, **forest expansion** and **naturalness**.
- To explain the resilience of **cultural** with the system variable **area for recreational activities**:
  - Resilience predictors related to management → **naturalness**.
  - Resilience predictors related to forest regulation → **protection status**.

- To explain the resilience of **economics** with the system variable **forest products value**:
  - Resilience predictors related to management → **deforestation** and **salvage logging**.

Likewise, the scoring of socio-economic resilience predictors supports the stakeholders' perception by establishing potential relationships between predictors and system variables. Particularly, the best-scored predictors correspond to land-based processes related to the dynamics (**deforestation**, **forest expansion**) and land use patterns (**naturalness**).

However, the information obtained from stakeholders should be taken with caution. Firstly, because the established links are based on a small sample of replies, reducing their reliability, and highlighting the need to extend the exercises to a larger number of participants in order to obtain contrasting key-stakeholders views from different socio-ecological systems. This would improve the process of hierarchization of resilience predictors to be applied in management and decision-making to enhance the resilience of forest systems. Secondly, the understanding some predictors was difficult, as realised by the replies and post-exercises discussions with participants. In general, the complexity in understanding corresponded with predictors with lower scorings or a lower number of replies (e.g., fire treatment and forest connectivity index). This also applies to some criteria, such as representativeness and comprehensiveness. Moreover, stakeholders underlined that spatial and temporal scales are relevant for scoring each resilience predictor.

4.2 Metrics and methodologies

There is a lack of uniformity in the metrics used to estimate resilience in the literature, and not rarely there is no explicit reference to the comparison to a reference state, or to the search of predictors aiming to improve resilience. This can be explained by the context-dependence of resilience assessment, which impedes giving unique recommended metrics. However, the analysis of the metrics used, allows to identify the existence of implicit criteria that we have systematised as follows, in order to help the selection in each case of the specific procedures for measuring resilience:

(i) focus of the analysis on disturbances (engineering resilience approach), variability around a dynamic equilibrium, or ecological thresholds leading to alternative states (ecological resilience approach).
(ii) analysis of single or multiple system variables.
(iii) temporal recording of system variables providing discrete or continuous sets of data.
(iv) acquisition of data following a diachronic or synchronic procedure, in relation to disturbances or events.

Then, we propose a guide for the use of the different possibilities of measuring resilience (**metrics**) based on these criteria:

Well-defined disturbances, comparison of system variables to a pre-disturbance or undisturbed reference state

- Single system variable (univariate approach)
  - Diachronic recording following disturbance (comparison to pre-disturbance situation)
    - Discrete records through time
      - No particular relevance of recovery → **indices** and **statistical models**.

        - Relevance of recovery → **recovery** (e.g., rate, time to full recovery, resistance/recovery biplots)
      - Continuous records through time → **variability** (e.g., time series analysis)
    - Synchronic recording (comparison to undisturbed systems)
      - Discrete records → **indices** and **statistical models**.
      - Continuous records → **variability** (e.g., time series analysis).
- Multiple system variables (multivariate approach) → **trajectory analysis** (e.g., multivariate analyses and distances between observed variables and reference state).
- Gradual change of system variables due to stress (single or multiple system variables)
    - Focus on temporal variability under equilibrium dynamics → **variability** (e.g., variance/mean and time series analysis).
    - Focus on potential tipping points → **recovery** and **stable state analysis** (e.g., early warning signals and critical slowing down).

No availability of estimations or system variables; resilience is inferred from associated parameters → **proxies**.

About the **methodologies** applied to study forest resilience, empirical data obtained from field observations or experimental settings done by the own studies is the rule in most cases, highlighting the specific scope of much of the available information. Remote sensing is also becoming a regular source of information to cover large territories, but with a limited capacity to evaluate stand-level predictors, since high-resolution methodologies (i.e., LIDAR) have not been yet regularly applied to study forest resilience. Noticeably, experimental studies on resilience are also quite rare, likely due to the difficulties to carry on manipulations at the forest stand level, although common garden experiments at tree level have usually been performed. Quite surprisingly, the use of model simulations has been underused until now, though its suitability to assess future resilience under scenarios of climate change or management regimes. The scarce number of meta-analysis can be explained by its dependence on a minimal number of empirical studies. Lastly, theoretical studies are not rare, but they do not provide quantitative assessments involving direct measures of the resilience of system variables.

5 Conclusion

The main ecological variables of forests for which resilience has been investigated refer to forest structure, functioning, and biodiversity properties, which in turn can be related to ecosystem services. Thus, integrative assessments of the resilience of forest socio-ecological systems should address them, selecting specific parameters according to the characteristics and interests of each situation. In turn, the most relevant predictors, potentially suitable to be managed in order to enhance resilience, correspond to forest composition and forest management properties. Particularly, forest biodiversity and structure parameters - often associated with management - appear as important predictors of both tree and stand production resilience.

This set of resilience indicators, corresponding to system variables related to predictors, has been particularly documented in temperate forests - which broadly correspond to a great part of European forests -, considering the resilience to the climate change trends and associated disturbances, particularly those related with drought.

Stakeholders' perception supports the relevance of forest composition as a predictor of the resilience of forest systems. The protection status of forests is also recognized as a sound

operational way of enhancing forest resilience. Interestingly, this perception does not acknowledge silvicultural practices per se as a guarantee of forest resilience.

Currently, the scientific evidence of factors determining the resilience of forest systems in a socio-economic context (e.g., the forest value chain) is scarcer. The available information in literature points to economic activity, development actions, forest management strategy, land use, and regulations as predictors of the resilience of socio-economic variables. However, specific indicators (system variables and resilience predictors) have not been found to be used consistently across studies, and in many cases, they have not been related to the forest value chain. This highlights the need to reinforce quantitative research on the resilience of forest socio-economic aspects, following a similar framework than that for ecological variables.

In contrast, the stakeholders' perceptions provide relevant insights about potential indicators to enhance forest resilience. Particularly, the most robust predictors recognised by stakeholders were those related to land-based processes, including land use patterns and dynamics (deforestation, forest development, naturalness) and investment in forestry. Feedback and inputs obtained from key stakeholders appear as a valuable tool to assess the resilience of forest socio-ecological systems and to implement measures to enhance it, and merits further development by enlarging the number of stakeholders and the inclusion of other views and expertise not represented in the initial group of stakeholders consulted.

Finally, the scientific evidence reveals a great variety of procedures - methodologies and metrics - to estimate the resilience of forest social-ecological systems. This variety obeys to the objectives and the context specificities of the studies. Nevertheless, some sources of information such as remote sensing, experimental settings, and analytical procedures - based on model simulations - merits further application. The elaboration of guidelines based on criteria related with the type of disturbance, number of system variables and temporality can help to select the most suitable metrics among the great availability of procedures available to measure resilience

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