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Perspective

Roadmap to develop a stress test for forest ecosystem services supply

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SUMMARY

Forests play a key role in a bio-based economy by providing renewable materials, mitigating climate change, and accommodating biodiversity. However, forests experience massive increases in stresses in their ecological and socioeconomic environments, threatening forest ecosystem services supply. Alleviating those stresses is hampered by conflicting and disconnected governance arrangements, competing interests and claims, and rapid changes in technology and social demands. Identifying which stresses threaten forest ecosystem services supply and which factors hamper their alleviation requires stakeholders' perceptions. Stakeholder-oriented stress tests for the supply of forest ecosystem services are therefore necessary but are not yet available. This perspective presents a roadmap to develop a stress test tailored to multiple stakeholders' needs and demands across spatial scales. We provide the *Cascade* and *Resilience Rosetta*, with accompanying performance- and resilience indicators, as tools to facilitate development of the stress test. The application of the stress test will facilitate the transition toward a bio-based economy in which healthy and diverse forests provide sustainable and resilient ecosystem services.

INTRODUCTION

In the transition from a fossil-based to a more sustainable bio-based economy,[1] forests play a critical role as they provide a broad range of renewable resources such as building materials, raw materials for the textile and paper industries, bio-energy, and many more.[2,3] However, the supply of services from forests such as timber, carbon sequestration, soil protection, and recreational use is increasingly under pressure from a "perfect storm" of "wicked problems" including climate change, land-use change, biodiversity loss, invasive species, enhanced atmospheric ozone exposure, and deposition of acidic compounds.[4–6]

Competition from other land uses and land-use changes result in deforestation and degradation, accelerating the loss of forest ecosystem service supply.[5] It is particularly important to ensure that these pressures do not irreversibly damage forest systems, as about 80% of the world's poor live in rural areas where they depend directly on forest ecosystems for providing food, clean water, energy, shelter, medicine, and cash incomes.[7–9] Not only those living near forests but also millions worldwide benefit directly and indirectly from services provided by forests.[10]

The increasing extraction of forest resources has undesirable repercussions for the future supply of services and ecological integrity, such as declining biodiversity or soil degradation.[11,12]

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The many, often competing, claims upon natural resources have spawned controversy and debate. The ensuing conflicts are exacerbated by a lack of anticipation since, in the coming decades, forests' physical and natural environments will likely change far beyond the experiences of current forest owners, managers, policy makers, and of society at large.[13,14] Importantly, socio-economic changes and changes in governance affect the supply of services from forests at different operational scales.[15] At the level of the forest management unit, changes in the natural and physical environments affect forest functioning: owners and managers (individuals, private sector organizations, communities, or the state) may respond by opting for alternative tree species and species mixtures and genetic diversity in the forest. These management units are embedded in social-economic contexts that are both rural and urban. That socio-economic context determines the financial means of the forest owners and managers, the availability of qualified workers, and the traditions and cultural functions the forest has for owners, managers, and various users and forest-related interest groups.

Whether a local-forest-based sector is economically profitable and sustainable depends on technological and economic developments and on the changing demand for intermediate and final forest value-chain products.[16,17] At the macro level, forest value chains from a national to an international level are embedded in society's demand for forest ecosystem services.[18] Because a national-forest-based sector supplies multiple products—such as the raw materials for energy, pulp, and paper but also ecological services, attractive landscapes, and touristic opportunities—it usually comprises several forest value chains and is often related to other sectors, such as energy, manufacturing, and tourism. A sector's economic development is affected by consumer–citizen–science–policy discourses ranging from the local to the global level.[19] At this interface, decisions are made—or postponed or avoided—on, for example, the role of forests in climate change mitigation or protecting terrestrial biodiversity.[20]

Cross-scale interactions as well as interactions between stresses can have top-down or bottom-up cascading effects. For example, the establishment of new international, national, and subnational policies to combat climate change, such as the 2016 Paris Agreement building on the United Nations Framework Convention on Climate Change, has a top-down effect on the forest supply chain, e.g., through harnessing forests to achieve national targets in emission reductions.[21] Simultaneously, changes in forested environments have bottom-up cascading impacts on supply chains.[22] For example, atmospheric nitrogen deposition affects soil processes and thereby forest growth, which influences forests' susceptibility to drought and consequently to pests and diseases.[23]

Currently, supply-chain governance, social demands on forests, and the market economics for forest products are often not aligned with each other.[24,25] For example, the United Nations Framework Convention on Climate Change (UNFCCC) accounting system is organized such that carbon credits for timber that replaces carbon-intensive building materials are assigned to the timber merchant rather than to the forest owners or managers producing the timber. Producers of bio-energy and bio-materials increasingly compete for means of production, and meanwhile, the Bonn Challenge aims to restore 150 million hectares (ha) of degraded land by 2020 and 350 million ha by 2030,[26] and the Paris Climate Agreement[27] calls for more carbon sequestration in forests. Moreover, the expanding transnational markets for forest products are affected by national political decisions. For instance, China's decision to phase out logging in all of its natural forests and to decrease the overall harvesting quota has increased the pressure on forests elsewhere; forests that are often already being exploited heavily.[28] When social demands cut across policy sectors and governance levels, considerable governance challenges can occur as a result of competition between goals and trade-offs between the supply of services. For example, polices promoting biodiversity versus bioeconomy and zero deforestation commitments versus bioeconomy strategy and within individual policies such as the EU forest strategy.[29–31]

The additional demand on forests is to contribute to the transition from the current, fossil-based economy toward a bio-based economy. This demand strengthens the need for a decision-making process that: (1) addresses trade-offs and synergies between supporting, provisioning, regulating, and cultural ecosystem services[32] (Figure 1); (2) balances benefits and costs for different users and beneficiaries; (3) integrates fragmented governance arrangements for forest supply chains; and (5) manages conflicting demands on land-use sectors from the food, fibre, and energy domains. A holistic approach is necessary, given that political, societal, economic, and technological developments occur at a much shorter temporal scale than changes in forest structure, composition, biodiversity, and associated ecosystem services. The sustainability of forest characteristics and the supply of forest ecosystem services is at risk if differences in the temporal scale between the human and environmental domains are not incorporated into decision-making processes.

In our opinion, a multi-stakeholder and multi-scale stress test covering the full forest supply chain is necessary for decision-making on the role of forests in the transition from a fossil-based to a bio-based economy. The stress test should provide insight into the resilience to stresses of each individual stakeholder, as well as the resilience of the entire chain due to cascading effects of the stresses between stakeholders across scales and domains. The development and application of such a stress test could be initiated by governments or private organizations, for example, when allocating funding for large-scale investments in afforestation and reforestation such as the European Green Deal,[33] by incorporating community organizations, local forest owners, institutions, and companies. To our knowledge, a methodology to develop such a stress test does not yet exist.

Here, we present a 10-step roadmap for the development and application of a stress test of forest ecosystem service supply. This roadmap includes selecting performance and resilience indicators and setting target values for multiple ecosystem services in what we call the *Forest Ecosystem Service Supply Cascade* (*FESSC*). We feel that the resilience of the FESSC to stresses from a stakeholder's point of view deserves particular attention, as each stakeholder can oversee and influence only part of the FESSC. Therefore, we propose a stakeholder-oriented tool that we call the *Resilience Rosetta*. In the following sections, we describe how the FESSC can be made resilient and how the components involved in that process can be visualized by the Cascade and from a stakeholder point of view by the Resilience Rosetta. Subsequently, we present general categories of indicators of the performance and resilience of the

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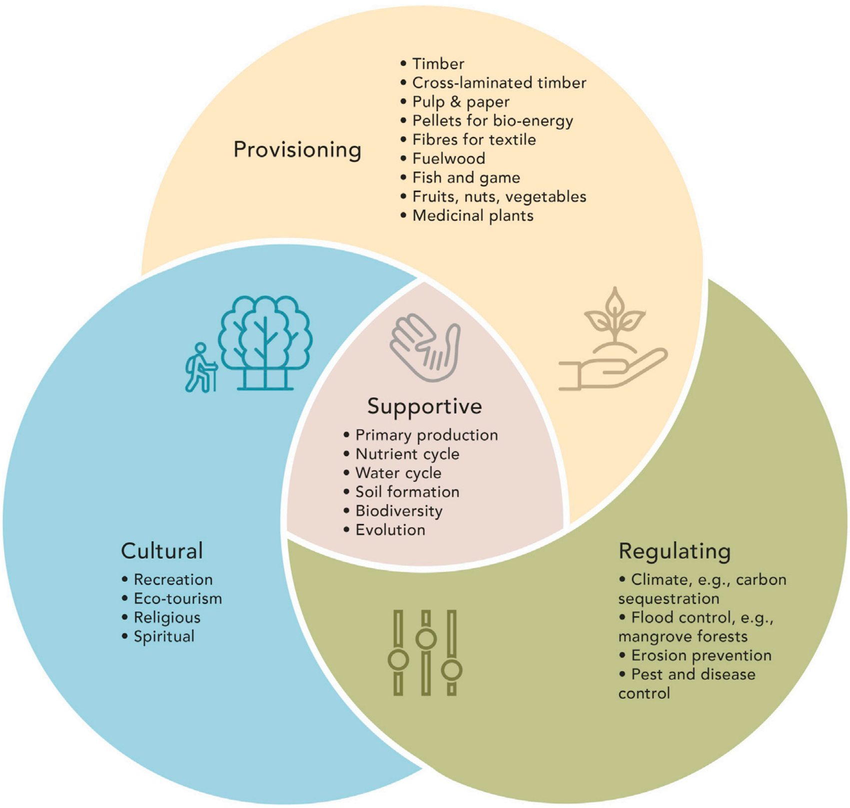

Figure 1. General categories of forest ecosystem services following the classification of the Millennium Assessment, with examples

FSSC and the steps that can be taken to develop and apply the stress test as a collaborative multi-stakeholder and multi-scale process, supported by the Cascade and Resilience Rosetta. Finally, we discuss ways forward and opportunities and challenges for parties that would initiate the development and application of such a test.

RESILIENT FOREST ECOSYSTEM SERVICE SUPPLY CASCADE

The challenge in making the FESSC resilient is to understand how the system responds to stresses that affect its performance in terms of the forest ecosystem services provided. These stresses can be disaggregated into stresses resulting from changes in human domains (such as changes in governance, technological innovations, or socio-economic developments) and in the ecological domain (such as changes in climate, air pollution, or land use).[34] The interactions across hierarchical scales (i.e., forest ecosystems, rural and urban communities, forest value chains, and the forest sector including end-users and governance structures and interactions with other domains) may trigger cascading effects on the performance of the FESSC.[35] Building the forest sector's resilience as the primary (but not sole) sector associated with forest ecosystems requires policy and management interventions to accompany the demand for ecosystem services both upstream in the value chain and downstream (from global markets to owners and communities and forest stands). Efforts to increase resilience are needed at all hierarchical scales of the Cascade and depend on the activities of stakeholders at each scale. For example, it is not enough for stakeholders in a community surrounding a forest management unit, such as residents, managers, workers, visitors, and local businesses, to be aware of the impact of certain stresses of change on "their" forest and its ecosystem service potential; only when they process information on the stresses, know about appropriate responses, and have the necessary capacities, skills, and assets[17] will they be able to adapt forest structure and dynamics to make the forest more resilient.[36] Building resilience in the forest sector at all hierarchical scales along the FESSC requires an upstream effort along the value chain so that resilience thinking and actions permeate the entire cascade. Figure 2 visualizes the downstream and upstream cascading effects on the supply of the ecosystem service, here referred to as the Cascade. The Cascade is inspired by the stakeholder-oriented conceptualization of the relationship between biodiversity, ecosystem function, and human wellbeing proposed by Haines-Young and Potschin.[35] Their conceptualization follows the key questions related to the use of ecosystem services, i.e.: (1) who makes the choices regarding use, (2) which values are included or highlighted and which are excluded or obscured, and (3) who is impacted (positively or negatively) by choices regarding ecosystem service use.[37] Consequently, they distinguish *Biophysical Structure or Process*, *Function*, *Service*, and *Benefit (Value)*, which we further differentiate in the components presented in the Cascade (Figure 2) and the associated indicators (see below).

There are manifold interdependences and interactions between and across scales: actions at larger spatial and political scales may be in vain if they are not implemented locally for reasons such as a lack of capacity, belief, incentives, or commitment. Equally, initiatives by locals may fail if they are not facilitated by information and support, for example, from government agencies, companies, or the scientific community. Not only are hierarchical scales interlinked, but so are domains. Although ecosystem services such as timber and non-timber forest products originate in the forest ecosystem, they do not necessarily remain in the conventional forest sector in a narrow definition; instead, they may enter into cultural and social systems and value chains concerning food, water, agriculture, energy, medicine and health, culture, leisure, and tourism. Recognizing and bridging the nexus between sector-based approaches[38] and embracing a holistic approach are inherent to taking a social-ecological systems approach.[39] Figure 3 visualizes interdependence and interaction

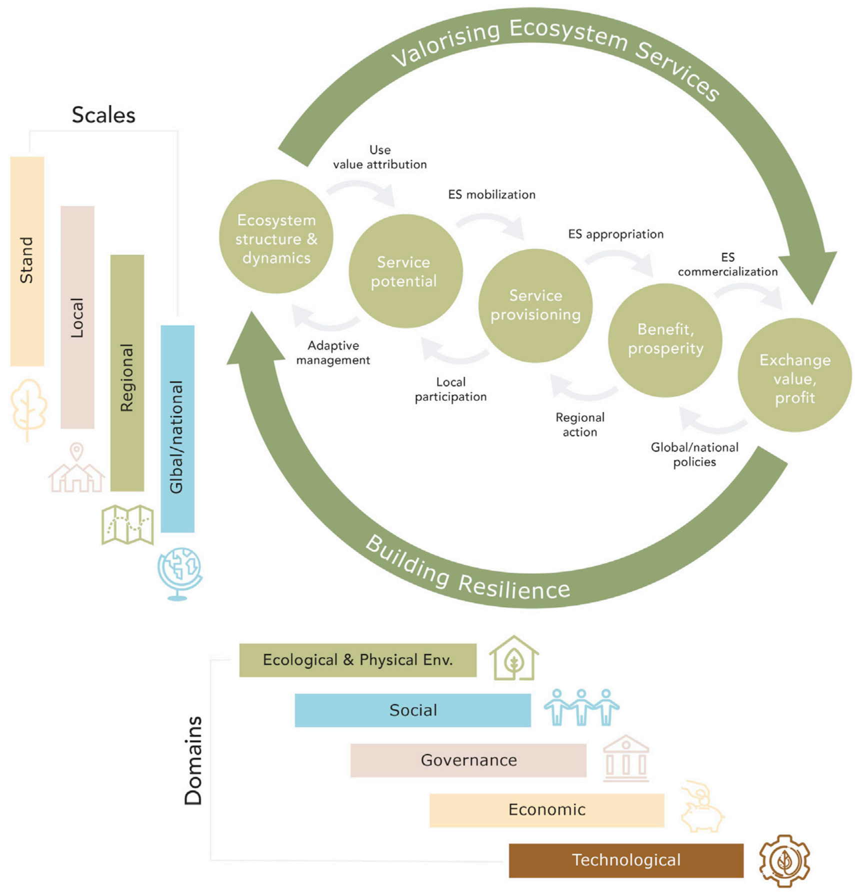

Figure 2. Forest Ecosystem Service Supply Cascade
The green circles represent different components of the Cascade, quantified or qualified by performance indicators for each ecosystem service. The horizontal axis represents, downwards, the ecosystem service supply from a forest ecosystem to societal domains and, upwards, the transfer of impacts of stakeholders and societal domains on the functioning of the forest ecosystem and the resilience of its ecosystem service supply. The vertical axis illustrates the spatial and hierarchical structure of the cascade, with numerous stands in many forest management units contributing to a flow of ecosystem services to the surrounding human communities and further on to global markets. ES, ecosystem service.

between scales and domains from a stakeholder point of view (S). Nested rings represent overlapping scales within each domain. Note that the scales presented per domain are examples and should be specified with concrete representatives in a particular stress test (see below). Outer arrows indicate potential interactions between scales and domains. These are to be specified for interactions between particular domains and scales during the development of the stress test.

The Cascade (Figure 2) and the Resilience Rosetta (Figure 3) present complementary visualizations. The Cascade visualizes that along the FESSC, multiple stakeholders are involved in the value chain of ecosystem services, with each affecting the resilience of part of the FESSC. The Resilience Rosetta presents the multitude of interactions between scales and domains from the point of view of a particular stakeholder. That stakeholder is positioned somewhere along the Cascade and needs to be resilient as well as be aware of his or her role for the resilience elsewhere in the chain. In combination, the Cascade and the Resilience Rosetta allow us to zoom in and out and to map resilience over the entire FESSC as well as for individual stakeholders.

PERFORMANCE AND RESILIENCE INDICATORS

An operational stress test would specify indicators and set target indicator values for the desired levels of performance of selected components of the FESSC and analyze whether various stakeholders are affected—and, if so, how—if the cascade's performance is diminished through stresses, resulting in a reduced amount or quality of the forest ecosystem services supplied. The selection and analysis of the indicators and related target values can then be used to instigate a multi-stakeholder process.[17] To assess the effects of stakeholders' activities on the supply of services along of the FESSC, we suggest distinguishing *performance indicators* (Table 1) for the supply of ecosystem services along the FESSC and *resilience indicators* (Table 2) for the capacity of the system to maintain ecosystem services in the face of stress.

Along the FESSC, the performance indicators subsequently quantify or qualify the structure, composition, and functioning of the forest ecosystem, i.e., its supporting services; the potential and actual value of the provisioning, regulating, or cultural ecosystem services associated with those forest characteristics; the benefits and contributions to human wellbeing of the ecosystem services; and eventually their monetary value and marketing. Note that not all ecosystem services attain the ultimate component of the Cascade of monetary valorizing and are in that case called intermediate ecosystem services.[40] We distinguish these components of the Cascade because they can be connected to stakeholders associated with the value attribution, mobilization, appropriation, and commercialization of ecosystem services. These stakeholders take position along the Cascade and have an impact on the performance of the associated Cascade components through their use and demand of ecosystem services and through the influence they exert on decision-making.

Key concepts in resilience thinking are adaptability, transformability, and their interrelatedness across scales.[41,42] Adaptability is often expressed in terms of the redundancy and diversity of the elements of the system.[41–43] Redundancy here refers to alternatives that enable a certain function to be maintained, e.g., different tree species or vegetation types to maintain carbon sequestration. Redundancy from a governance perspective[40,44] refers to those aspects of an institution (e.g., sole decision-making by a director), which can be replaced with alternative

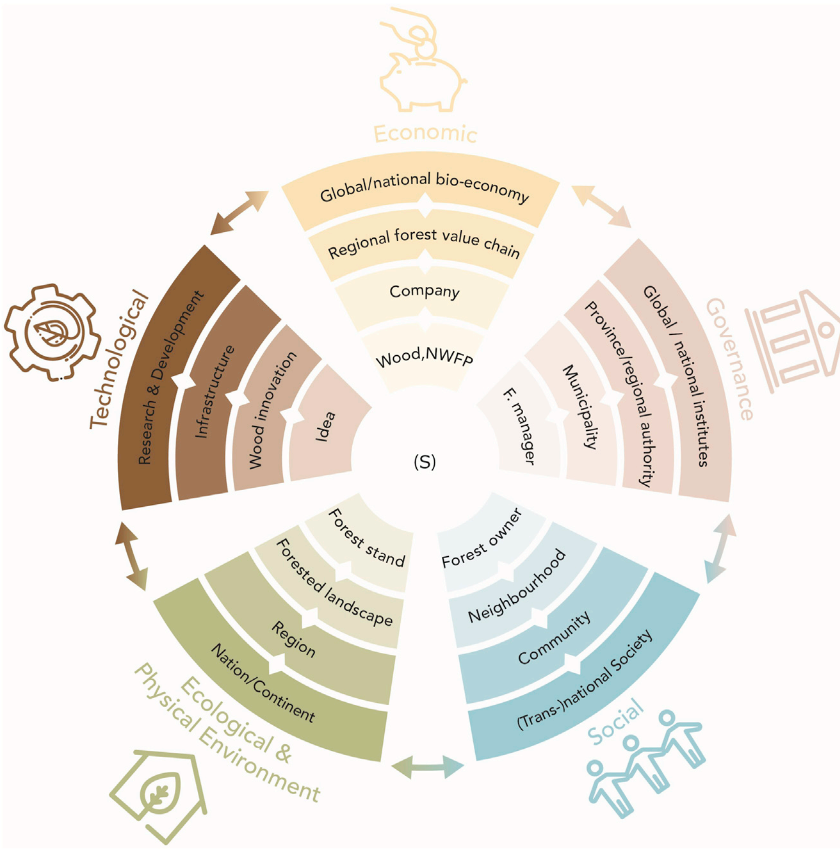

Figure 3. Resilience Rosetta
Overview of domains affecting the resilience of the Forest Ecosystem Service Supply Cascade. (S), stakeholder; NWFP, non-wood forest products.

mechanisms (such as a collegial decisions by a board), while institutional functioning and achievement of an institution's objectives is maintained. Diversity here refers to both the diversity of processes to maintain the ecosystem services and to alternative ecosystem services than those currently provisioned by the forest to enhance the adaptability of the FESSC to stresses. In the socio-technological domain, adaptability refers to the number of alternatives for production systems or for management and governance. Transformability is expressed in terms of novelties and innovation and connectivity across scales. The resilience indicators we propose therefore represent the redundancy, diversity, innovativeness, and connectivity of forest ecosystem services in relation to stresses. Domain- and scale-specific target values for both performance and resilience indicators must be determined through a combination of system analyses, stakeholder participation, and identifying existing and changing social-legal norms.

Operationally, selection and target setting of the performance and resilience indicators could be achieved in an iterative process in which stakeholders identify these indicators and targets for their own purposes and visualize them in a single-stakeholder-oriented Resilience Rosetta, e.g., by presenting the indicator relative to the target values in a color scheme. Multiple Resilience Rosettas can then be evaluated from the integrated point of view of the Cascade, allowing for the harmonization of indicators, the merging of multiple Resilience Rosettas (if possible), and the identification of gaps. Thus, both the Cascade and Resilience Rosetta can be used to facilitate the development, visualization, and evaluation of the performance and resilience indicators in a multi-stakeholder process. The Cascade presents a broad overview of the impacts of multiple interacting stakeholders along the whole FESSC with its down- and upstream cascading effects. In its simplest form, the Resilience Rosetta presents the indicator value for the supply of one forest ecosystem service under stress from the perspective of a specific stakeholder. This can be repeated for several stakeholders and multiple forest ecosystem services. A full stress test for a FESSC includes resilience indicators for all relevant provisioning, regulating, cultural, and supporting services (Figure 1) in response to different stresses for multiple stakeholders from multiple domains and scales. In a dynamic analysis, the Resilience Rosetta can be used to visualize future projections of scenarios (e.g., in climate, forest management, policy, governance, demography, market, technology) performed by domain- and stakeholder-specific models for selected resilience indicators. Thus, the comparison of Resilience Rosettas at different points in time, either monitored or simulated, reveals the consequence of human intervention to improve the performance and resilience of one or more forest ecosystem services at one scale and domain on the performance and resilience of another scale and domain and thereby trade-offs and synergies between services.

ROADMAP FOR THE DEVELOPMENT OF A STRESS TEST

We propose a 10-step roadmap for the development of a comprehensive multi-stakeholder and multi-scale stress test to identify and address vulnerabilities of the supply of forest ecosystem services to stresses. Such a test seeks to assess the two directions of the cascade: downstream the cascade—from the forest stand up to marketable products—in order to test cascading effects of stresses on forests and upstream the cascade—from global or national policymaking down to management decisions by forest owners—in order to test the cascading effects of fragmented governance arrangements and competing claims. For the upstream cascade, the stress test assesses the *performance* of components of the FESSC. For the downstream cascade, building *resilience* means strengthening the FESSC's adaptability and transformability.

The 10 steps to develop the stress test are as follows:

1. Identify FESSC-system-relevant *stakeholders* and the *groups most affected.* With these stakeholders, perform steps 2–10.

Table 1. Generic categories of performance indicators for the components of the *Forest Ecosystem Service Supply Cascade*

Ecosystem structure and dynamics	
	Stocks and fluxes of biomass and organic matter, biodiversity (e.g., genetic-, functional-, and species-diversity, fragmentation, threatened species), and intensity of functions (e.g., photosynthesis rate, litter decomposition rate).
Ecosystem service potential supply	
	Identification and quantification of any ecosystem structure or function that can be attributed to potential use- and option value for humans. Units are typically pools or flows of ecosystem structures and functions expressed as the potential direct and indirect use- and option value of a service. All of these indicators are expressed per unit of forest area over a given period of time.
Ecosystem service supply	
	Any quantity or quality of provisioning, regulating, or cultural services actually provided to people by the ecosystem. Units are typically quantities or frequencies of these services per unit of forest area and per unit of time.
Benefit and prosperity	
	Any quantification of contribution to prosperity or human well-being by a delivered ecosystem service. Contributions can be expressed in various quantitative and qualitative units, such as monetary value, contribution to gross domestic product (GDP), satisfaction with democratic deliberation on forest utilization alternatives, happiness indices, or any other measure of benefits, prosperity, and wellbeing per unit of forest area over a given period of time.
Ecosystem service exchange value and profit	
	Monetary quantification of the realized income or gain made from selling ecosystem services on a given market. The units used are always monetary, possibly expressed per unit of ecosystem services sold or per area of forest over a given period of time.

2. Describe the performance of the FESSC for one or more ecosystem service by selecting and setting *performance indicators* and *desired targets.*
3. Describe how a relevant domain functions and how that affects the supply of forest ecosystem services and identify *stress factors* in the ecological/physical environment domain. Determine the main stresses and identify their actual and potential impact on the performance indicators, either by monitoring or simulation.
4. Specify *resilience indicators* for relevant domains and scales of the Resilience Rosetta and their effect on one or more performance indicators within and between domains and scales and from the point of view of different stakeholders.
5. Identify *trends* and *uncertainties* in economic, governance, social system, and technology domains, as well as their effects on the resilience and performance indicators.
6. Quantify by data collection or simulation *performance indicators* and *map forest ecosystem functioning* and overall *supply of forest ecosystem services* in response to the stress factors in order to identify vulnerabilities and respective thresholds.
7. *Visualize* levels of performance on the FESSC by highlighting the impacts of the stress factors on the supply of forest ecosystem services.
8. Assess *inconsistencies* and *disconnects* in governance arrangements and *conflicts* among stakeholders and affected groups.
9. *Visualize* the resilience indicators and interactions in different domains and scales on the *Resilience Rosetta* from the view of individual stakeholders; merge multiple Resilience Rosettas, if possible.
10. Use *multi-stakeholder dialogue* to discuss implications for forest-sector policies, management plans, governance arrangements, and necessary actions.

SUMMARY AND POTENTIAL INITIATORS OF A STRESS TEST

In sum, we propose a roadmap for the development of a stress test to be applied to an entire FESSC. Important challenges to make the FESSC resilient are that: (1) the temporal scale of decision-making in the human domains (governance, societal, economic, technological) is not connected to the temporal scale of changes in the environmental and physical domain and is often much shorter, (2) no stakeholder can oversee and influence the entire FESSC, and (3) stakeholders most affected are not necessarily those with the most influence on a particular section of the FESSC. A stress test, identifying for which ecosystem services and where along the FESSC which stakeholders are affected, and which stakeholders are the most influential in response to different stresses, is in our opinion needed to ensure the sustainable functioning of forest ecosystems and the supply of forest ecosystem services to society. We maintain that a stress test covering the full FESSC is an essential tool for the transition towards a sustainable bio-based economy. Forests and their ecosystem services could play an important role in such an economy by supplying, for example, timber, fibre, and food and sequestering carbon while maintaining other ecosystem services in areas like biodiversity, water, and air purification. Based on indicators and related target values and monitoring how the indicators change over time, the stress test will evaluate the performance and resilience of the supply of forest ecosystem services to changes in the ecological and physical environments of forests as well as to socio-ecological, technological, and governmental changes. The test is a diagnostic instrument in which domain- and scale-specific target values are set in order to assess the performance of the entire FESCC under future stresses and its resilience to them. We have designed the *Resilience Rosetta* and the *Cascade* diagram as tools to support the dialogue between stakeholders from different domains and sectors in which the forest supply cascade serves as a framework to identify interdependencies, trade-offs, and synergies both between forest ecosystem services and between stakeholders. Co-developing a stress test in a multi-stakeholder dialogue strengthens the acceptance of resilience-enhancing measures. We envision an iterative movement through the steps of the roadmap to gradually refine the test, sharpen the indicators, agree on new target values, assess vulnerabilities, and identify priorities to ensure resilient forests, maintain forest ecosystem functions, and provide forest ecosystem services.

The development and application of a stress test could be initiated by different parties. Governments aspiring toward the transition to a bio-based economy could initiate the development of

Table 2. Generic categories of resilience indicators for each of the domains of the Resilience Rosetta and Cascade

Indicator	Domains: Ecological and physical environments	Social	Governance	Economic	Technological
Redundancy	• alternative pathways to provide a FES exist within the ecosystem	• multiple values are attributed by stakeholders to a FES • extent to which (social) roles are unique to specific stakeholders involved in providing the FES	• FM addresses diversity to maintain FESs to enhance resilience • alternative pathways are formulated for decision-making • decisions are made by more than one person and/or institution	• multiple economic activities are related to a particular FES • alternative economic activities can replace existing activities	• spread of risks and function of technological developments in risk management and adaptation • alternative future technological development pathways
Diversity	• diversity of FES	• inventories of stakeholder perspectives and objectives are conducted and known • different stakeholder objectives are taken into account in decision-making at different management and policy levels • type of appropriation rules and specification of benefit rights	• polices address ecological diversity and diversity in governance structures and ownership • governance arrangements cover the entire cascade • governance arrangements are coherent, complementary, and connected • decision-making by forest owner/manager is shared with users	• economic diversity in FES and products • multi-functional FM implementation/objectives in forest planning	• current and potential technological developments support maintenance and diversification of FES
Innovation	• forest can adapt and renew in response to stresses	• societal sectors are included in innovations • stakeholders' perceptions of the use of new technologies • social learning from management or policy experiments • community-based mechanisms of FM adaptation to changes	• FM and policies strengthen adaptive potential and innovative FM systems have been developed • existence of system(s) of learning from management or policy experiments • experiments and adaptive management occur	• economic innovations • length of supply chains/value added for main FES delivered	• technological development is driver of innovation and considered desirable across the range of societal actors

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Table 2. *Continued*

	Domains				
Indicator	Ecological and physical environments	Social	Governance	Economic	Technological
Connectivity	• physical corridors between forest tree populations are present • connectivity between populations	• social connectivity between domains and scales • political engagement in decision-making processes and advocacy • direct and indirect stakeholders in FM and use are connected	• connectivity of governance arrangements across scales • extent of interactions between local, regional, and (inter)national governance in decision-making • interactions are coherent, complementary, and connected	• spatial economic coherence regional clustering of economic activities and connections or transactions with other regions and countries • interaction between forest ES and products and other economic sectors	• technological developments focus on "smart connections" between FES, e.g., productivity, health, safety, recreation, climate adaptation

Each resilience indicator addresses the extend of/to which the bullet point mentioned is met (either qualitatively or quantitatively) at a particular spatial or operational scale. FM, forest management; FES, forest ecosystem service or services.

a stress test on the full FESSC by considering multiple forest ecosystem services and taking the interests of a broad range of stakeholders into account when developing governance frameworks and public policies that ensure the sustainable management of public and private forests, thereby moving towards better-balanced forest management solutions. The development and application of a stress test could also be initiated by other parties such as large private investors (e.g., investment banks, companies aiming to offset their CO_2 emission), exchange-traded funds on carbon credits, non-governmental organizations aiming to alleviate rural poverty and inequality, national or international trade unions of paper, pulp, and wood-building materials aiming to safeguard the sustainable supply of raw materials, global organizations aiming to protect biodiversity, unions of small forest owners aiming to access global markets, and many others. A challenge may be to achieve internal consistency, completeness, and comparability despite the independent development of multiple stress tests. The scientific community could have a key role in enabling consistency, completeness and comparability by providing standardized methods and databases, independent evaluation and assessment of the stress tests, and connecting initiatives.

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DECLARATION OF INTERESTS

The authors declare no competing interests.

REFERENCES

1. Smith, P., Beaumont, L., Bernacchi, C.J., Byrne, M., Cheung, W., Conant, R.T., Cotrufo, F., Feng, X., Janssens, I., and Jones, H. (2021). Essential outcomes for COP26. Glob. Change Biol. https://doi.org/10.1111/gcb.15926.
2. Eyvindson, K., Repo, A., and Mönkkönen, M. (2018). Mitigating forest biodiversity and ecosystem service losses in the era of bio-based economy. For. Policy Econ. *92*, 119–127.
3. Ingrao, C., Bacenetti, J., Bezama, A., Blok, V., Geldermann, J., Goglio, P., Koukios, E.G., Lindner, M., Nemecek, T., and Siracusa, V. (2016). Agricultural and forest biomass for food, materials and energy: bio-economy as the cornerstone to cleaner production and more sustainable consumption patterns for accelerating the transition towards equitable, sustainable, post fossil-carbon societies. J. Clean. Prod. *117*, 4–6.
4. Ferraro, P.J., Lawlor, K., Mullan, K.L., and Pattanayak, S.K. (2012). Forest figures: ecosystem services valuation and policy evaluation in developing countries. Rev. Environ. Econ. Policy *6*, 20–44.
5. U FAO (2020). The State of the World's Forests 2020: Forests, Biodiversity and People (FAO).
6. De Vries, W., Dobbertin, M., Solberg, S., Van Dobben, H., and Schaub, M. (2014). Impacts of acid deposition, ozone exposure and weather conditions on forest ecosystems in Europe: an overview. Plant Soil *380*, 1–45.
7. Schlager, E., and Ostrom, E. (1992). Property-rights regimes and natural resources: a conceptual analysis. Land Econ. 249–262.
8. Staffas, L., Gustavsson, M., and McCormick, K. (2013). Strategies and policies for the bioeconomy and bio-based economy: an analysis of official national approaches. Sustainability *5*, 2751–2769.
9. Campos, A.D.L.O., Villani, C., Davis, B., and Takagi, M. (2018). Ending Extreme Poverty in Rural Areas–Sustaining Livelihoods to Leave No One behind (FAO).
10. Louman, B., Fischlin, A., Glück, P., Innes, J., Lucier, A., Parrotta, J., et al. (2009). Forest ecosystem services: a cornerstone for human well-being, *22* (IUFRO World Series), pp. 15–27.
11. Betts, M.G., Wolf, C., Ripple, W.J., Phalan, B., Millers, K.A., Duarte, A., Butchart, S.H.M., and Levi, T. (2017). Global forest loss disproportionately erodes biodiversity in intact landscapes. Nature *547*, 441–444. https://doi.org/10.1038/nature23285.
12. Drake, T.W., Van Oost, K., Barthel, M., Bauters, M., Hoyt, A.M., Podgorski, D.C., Six, J., Boeckx, P., Trumbore, S.E., Ntaboba, L.C., and Spencer, R.G.M. (2019). Mobilization of aged and biolabile soil carbon by tropical deforestation. Nat. Geosci. *12*, 541–546. https://doi.org/10.1038/s41561-019-0384-9.
13. Lindner, M., Fitzgerald, J.B., Zimmermann, N.E., Reyer, C., Delzon, S., van der Maaten, E., Schelhaas, M.-J., Lasch, P., Eggers, J., and van der Maaten-Theunissen, M. (2014). Climate change and European forests: what do we know, what are the uncertainties, and what are the implications for forest management? J. Environ. Manag. *146*, 69–83.
14. Mátyás, C. (2010). Forecasts needed for retreating forests. Nature *464*, 1271.
15. Termeer, C.J.A.M., Feindt, P.H., Karpouzoglou, T., Poppe, K.J., Hofstede, G.J., Kramer, K., Ge, L., Mathijs, E., and Meuwissen, M.P.M. (2019). Institutions and the resilience of biobased production systems: the historical case of livestock intensification in The Netherlands. Ecol. Soc. *24*, 15. https://doi.org/10.5751/ES-11206-240415.
16. Kaplinsky, R., and Morris, M. (2000). A Handbook for Value Chain Research (University of Sussex, Institute of Development Studies).
17. Bhatia, G., and Lane, C. (2013). Builing Resilience in Supply Chains (World Economic Forum), p. 41pp.
18. Nichiforel, L., Keary, K., Deuffic, P., Weiss, G., Thorsen, B.J., Winkel, G., Avdibegović, M., Dobšinská, Z., Feliciano, D., and Gatto, P. (2018). How private are Europe's private forests? A comparative property rights analysis. Land Use Policy *76*, 535–552.
19. Young, O.R., Agrawal, A., King, L.A., Sand, P.H., Underal, A., and Wasson, M. (1999). Institutional Dimensions of Global Environmental Change. IHDP Report No. 9 *II*.
20. Yousefpour, R., Temperli, C., Jacobsen, J.B., Thorsen, B.J., Meilby, H., Lexer, M.J., Lindner, M., Bugmann, H., Borges, J.G., Palma, J.H.N., et al. (2017). A framework for modeling adaptive forest management and decision making under climate change. Ecol. Soc. *22*. https://doi.org/10.5751/es-09614-220440.
21. Grassi, G., House, J., Dentener, F., Federici, S., den Elzen, M., and Penman, J. (2017). The key role of forests in meeting climate targets requires science for credible mitigation. Nat. Clim. Change *7*, 220–226. https://doi.org/10.1038/nclimate3227.
22. Seidl, R., Schelhaas, M.J., Rammer, W., and Verkerk, P.J. (2014). Increasing forest disturbances in Europe and their impact on carbon storage. Nat. Clim. Chang *4*, 806–810. https://doi.org/10.1038/nclimate2318.
23. Reyer, C., Stephen, B., Kristina, B., Jose, G.B., Harald, B., Sylvain, D., Sonia, P.F., Jordi, G.-G., Barry, G., et al. (2017). Are forest disturbances amplifying or canceling out climate change-induced productivity changes in European forests? Environ. Res. Lett. *12*, 034027.
24. Ros-Tonen, M.A.F., Reed, J., and Sunderland, T. (2018). From synergy to complexity: the trend toward integrated value chain and landscape governance. Environ. Manage. *62*, 1–14. https://doi.org/10.1007/s00267-018-1055-0.
25. Levermann, A. (2014). Climate economics: make supply chains climate-smart. Nature *506*, 27–29.
26. Bonn-Challenge (2011). The Challenge: A Global Effort (Bonn-Challenge).
27. Paris-Agreement (2015). United Nations Framework Convention on Climate Change (Paris-Agreement).
28. Sun, X., Canby, K., and Liu, L. (2016). China's logging ban in natural forests: impacts of extended policy at home and abroad. For. Trends, 1–8.

29. Aggestam, F., and Giurca, A. (2021). The art of the "green" deal: policy pathways for the EU Forest Strategy. For. Policy Econ. *128*, 102456.

30. Ronzon, T., and Sanjuán, A.I. (2020). Friends or foes? A compatibility assessment of bioeconomy-related Sustainable Development Goals for European policy coherence. J. Clean. Prod. *254*, 119832.

31. Luhas, J., Mikkilä, M., Kylkilahti, E., Miettinen, J., Malkamäki, A., Pätäri, S., Korhonen, J., Pekkanen, T.-L., Tuppura, A., and Lähtinen, K. (2021). Pathways to a forest-based bioeconomy in 2060 within policy targets on climate change mitigation and biodiversity protection. For. Policy Econ. *131*, 102551.

32. Reid, W.V., Mooney, H.A., Cropper, A., Capistrano, D., Carpenter, S.R., Chopra, K., Dasgupta, P., Dietz, T., Duraiappah, A.K., and Hassan, R. (2005). Ecosystems and Human Well-Being-Synthesis: A Report of the Millennium Ecosystem Assessment (Island Press).

33. Samper, J.A., Schockling, A., and Islar, M. (2021). Climate politics in green deals: exposing the political frontiers of the European Green Deal. Polit. Governance *9*, 8–16.

34. Ge, L.A., Niels, P.R., van Dixhoorn, I.D.E., Feindt, P.H., Kramer, K., Leemans, R., Meuwissen, M.P.M., Spoolder, H., and Sukkel, W. (2016). Why we need resilience thinking to meet societal challenges in bio-based production systems. Curr. Opin. Environ. Sustain. *23*, 17–27. https://doi.org/10.1016/j.cosust.2016.11.009.

35. Haines-Young, R., and Potschin, M. (2010). The links between biodiversity, ecosystem services and human well-being. Ecosystem Ecol. *1*, 110–139.

36. FAO (2018). The State of the World's Forests 2018 - Forest Pathways to Sustainable Development (FAO).

37. Jax, K., Barton, D.N., Chan, K.M., De Groot, R., Doyle, U., Eser, U., Görg, C., Gómez-Baggethun, E., Griewald, Y., and Haber, W. (2013). Ecosystem services and ethics. Ecol. Econ. *93*, 260–268.

38. Ostrom, E. (2009). A general framework for analyzing sustainability of social-ecological systems. Science *325*, 419–422. https://doi.org/10.1126/science.1172133.

39. McGinnis, M.D., and Ostrom, E. (2014). Social-ecological system framework: initial changes and continuing challenges. Ecol. Soc. *19*. https://doi.org/10.5751/es-06387-190230.

40. Lamothe, K.A., and Sutherland, I.J. (2018). Intermediate ecosystem services: the origin and meanings behind an unsettled concept. Int. J. Biodiversity Sci. Ecosystem Serv. Manage. *14*, 179–187.

41. Folke, C., Carpenter, S.R., Walker, B., Scheffer, M., Chapin, T., and Rockstrom, J. (2010). Resilience thinking: integrating resilience, adaptability and transformability. Ecol. Soc. *15*.

42. Nikinmaa, L., Lindner, M., Cantarello, E., Jump, A.S., Seidl, R., Winkel, G., and Muys, B. (2020). Reviewing the use of resilience concepts in forest sciences. Curr. For. Rep. *6*, 61–80. https://doi.org/10.1007/s40725-020-00110-x.

43. Walker, B., and Salt, D. (2012). Resilience Thinking: Sustaining Ecosystems and People in a Changing World (Island press).

44. Ballard, H.L., and Belsky, J.M. (2010). Participatory action research and environmental learning: implications for resilient forests and communities. Environ. Educ. Res. *16*, 611–627. https://doi.org/10.1080/13504622.2010.505440.