forests

Review

Managing Forests for Water in the Anthropocene—The Best Kept Secret Services of Forest Ecosystems

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Abstract: Water and forests are inextricably linked. Pressures on forests from population growth and climate change are increasing risks to forests and their aquatic ecosystem services (AES). There is a need to incorporate AES in forest management but there is considerable uncertainty about how to do so. Approaches that manage forest ecosystem services such as fiber, water and carbon sequestration independently ignore the inherent complexities of ecosystem services and their responses to management actions, with the potential for unintended consequences that are difficult to predict. The ISO 31000 Risk Management Standard is a standardized framework to assess risks to forest AES and to prioritize management strategies to manage risks within tolerable ranges. The framework consists of five steps: establishing the management context, identifying, analyzing, evaluating and treating the risks. Challenges to implementing the framework include the need for novel models and indicators to assess forest change and resilience, quantification of linkages between forest practice and AES, and the need for an integrated systems approach to assess cumulative effects and stressors on forest ecosystems and AES. In the face of recent international agreements to protect forests, there are emerging opportunities for international leadership to address these challenges in order to protect both forests and AES.

Keywords: forest management; aquatic ecosystem services; cumulative effects; risk management; scenario analysis; bowtie analysis

1. Introduction

We believe that forests are important for the water supply of humanity—Statement by participants of the Kunming Expert Meeting on forests and water, March 2014.

Forests are critical to human well-being, yet the loss of forest to other land uses has been extensive and much of the world's remaining forest is unprotected or degraded [1]. Globally, forest health continues to be at risk due to unrelenting pressures from growing populations for food, fiber and energy [2]. There have been substantial changes to forest management and other land use practices over the past 25 years that have had positive effects on forest ecosystems. Generally, the conversion of forested land to other land uses has decreased, but in some parts of the world, particularly in developing countries, conversion of forests to agriculture continues to be a problem (Figure 1; [3,4]). Where forest conversion is not an issue, fragmentation from forest harvest in combination with other temporary land uses is occurring under the overarching effect of climate change, leading to increased frequency and intensity of other natural stressors such as fire and pest outbreaks (e.g., [4–8]). Together, the effects of natural and anthropogenic stressors place the sustainability of forest ecosystems at risk (e.g., [9–11]).

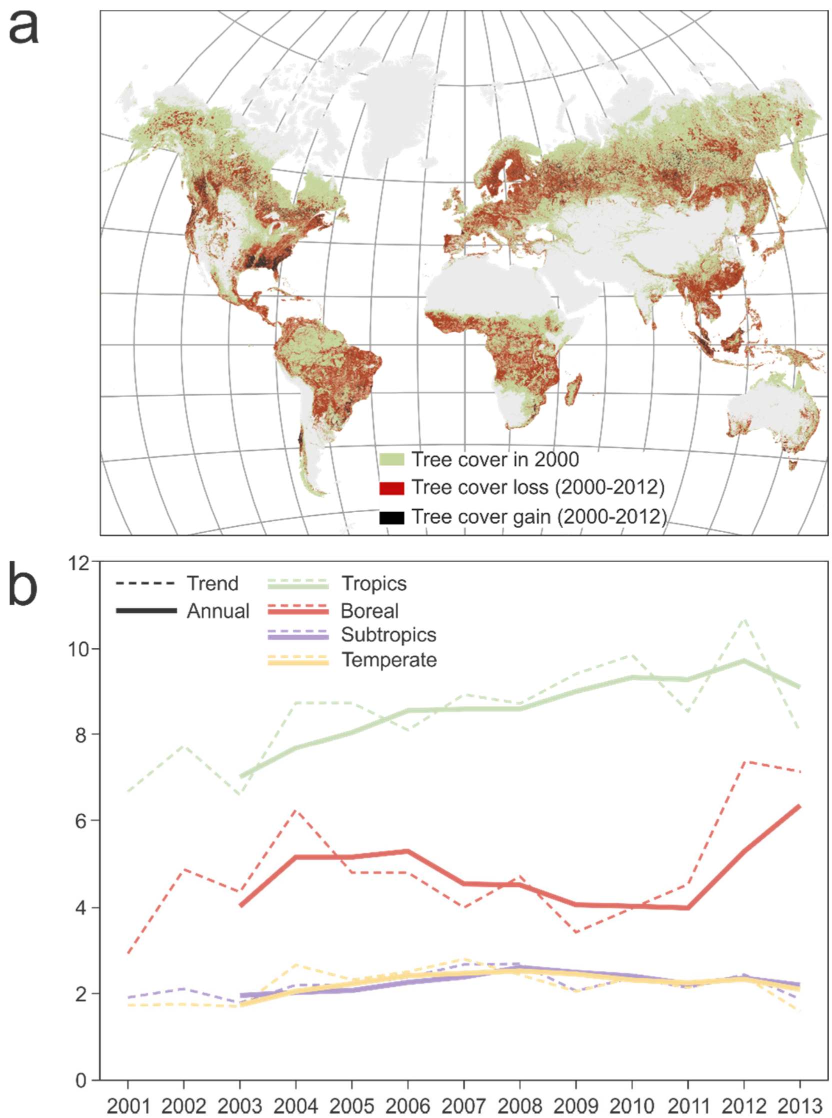

Figure 1. (**a**) Global forest loss; and (**b**) biome specific rates of forest loss (modified from [3]). Data for both (**a**) and (**b**) from [4].

Ecosystem services (ES) are the benefits to people from healthy functioning ecosystems. The Millennium Ecosystem Assessment (MEA) [12] classifies ES as: provisioning (the products obtained from ecosystems such as food, fiber and fresh water); regulating (the benefits obtained from the regulation of ecosystem processes such as climate and nutrient cycling); cultural (the non-material benefits people obtain from ecosystems such as recreation and aesthetic experiences); and supporting (the indirect benefits that facilitate all other ES such as biodiversity). Over 25% of the total global forest area is managed for ES, with only minor variations over the last 25 years [13].

Forests provide a wide array of ES [14–16]. Among the most valuable services produced by forests are aquatic ecosystem services (AES). Forests are source areas for clean water. In the U.S., national forests are the largest source of drinking water [17]. Forests regulate flow patterns and maintain water quality by filtering sediments, nutrients and other contaminants from runoff, reducing the need for water treatment infrastructure [8,18–20]. Forests also provide water for irrigation, hydropower, recreation and fisheries [21,22]. Forest vegetation absorbs snowmelt and rainfall, controlling runoff and erosion and regulating groundwater recharge and discharge [23,24]. These processes maintain human and natural assets by reducing the frequency and intensity of flooding and drought [25]. Forest vegetation is also important for maintaining high quality aquatic habitat for biodiversity. In 2008, the U.S. Chief Forester remarked that AES are among the most valuable products produced by forests, largely due to the high costs of flood damage and the need to replace forest ecosystems with human infrastructure [26]. More recently, the U.S. Deputy Chief Forester stated that the U.S. Forest Service is the "nation's largest water company" [27].

Since the release of the MEA, there have been numerous efforts to mainstream AES in public policy, both in Europe [28] and North America [29,30]. In spite of these initiatives and the growing public awareness of the importance of forests for AES, a systematic integration of AES in forest resource assessment and management is lacking in both science and policy. As the interconnections between forests and the hydrologic cycle become more apparent, the urgent need to understand the role of forests and water has emerged as an international priority. Of particular note is the 2002 *Shiga Declaration on Forests and Water*, stating that governments and stakeholders should adopt holistic, multidisciplinary and multi-stakeholder approaches to improve understanding of forest and water relationships and effective implementation of policies, planning and management initiatives worldwide related to forests and water (Table 1; [31]).

Table 1. Principles for forest and water management in the Anthropocene (Recommendations for decision makers stated in the Shiga Declaration (Final): Adopted on 22 November 2002, Shiga, Japan [31]).

Principle	Description
Principle 1	Move from a sectoral to an integrated cross-sectoral approach to economic, social and environmental planning at local, national and international levels.
Principle 2	Capture the total economic value of forest and water resources and evaluate trade-offs and distributional and equity effects of policies to maintain AES.
Principle 3	Put in place appropriate incentives to support the sustainable management of forest and water services to ensure that those who use resources pay the full cost of their exploitation and those who bear the costs of conservation are equitably compensated.
Principle 4	Promote effective and equitable collaborative arrangements and partnerships among governments and stakeholders to develop new tools for managing AES.

Since the Shiga Declaration, many events on forests and water have been organized by the Food and Agricultural Organization (FAO) of the United Nations (UN) and other institutions to provide insight into the topic as well as important recommendations for moving forward. The FAO synthesized the main outcomes and recommendations resulting from these processes to develop a comprehensive and practical international *Forests and Water Agenda* [32] to guide future action. The Agenda is a 20-point program to advocate for the "recognition of forest-water interactions and the role trees and forests play in maintaining resilient landscapes and providing high-quality water resources, taking into account forest-water interactions for different climatic zones, forest ecosystems and at different landscape scales." The FAO then launched a five-year *Forests and Water Action Plan* at the World Forestry Congress that was held in September 2015 in Durban, South Africa. The Action Plan aims to balance trade-offs and maximize synergies between forests and water management [33]. Coinciding with the launch of the Action Plan was the release of the *UN Sustainable Development Goals* [2], where the status of forests and their benefits were given prominent consideration. In particular, Goals 6 (recognizing the role of forests in ensuring sustainable and secure water supplies) and 15 (protecting, restoring and promoting sustainable use of forests and ecosystems and their services) highlight the importance of managing forests for water and other ES to promote resilient landscapes and communities [2].

Despite these initiatives, a systematic integration of forest AES into management decisions remains lacking. A key barrier to managing AES is that we have not developed the scientific basis, nor the policy and finance mechanisms, to systematically incorporate AES into forest management decisions. Specifically, we need a better understanding of: (1) how human activities affect the ecosystem and the production of AES; (2) how the supply and demand for AES interact at different scales and how this information can be integrated into decision-making; (3) how to quantify the magnitude of AES benefits so that the trade-offs of alternative forest management strategies can be understood and ranked; and (4) how to turn AES values into effective incentive and finance mechanisms at a large enough scale to have an impact [34].

To overcome this barrier, we need a paradigm shift. The concept of ES was originally introduced as a metaphor to illustrate the dependence of humans on healthy functioning ecosystems; however, the risks to global atmospheric and hydrologic cycles from forest degradation and deforestation illustrate the peril of viewing forests as simply a stream of human benefits that can be unbundled and severed from each other in the design of policies and incentives (e.g., [35]). Ecosystems are characterized by complexity that operates at multiple scales, resulting in unavoidable trade-offs and risks in the face of changing human behavior and preferences. Our limited understanding about how particular forest management strategies affect AES means that policies to enhance particular services can have unintended consequences. We need to consider the connection between forests and people more holistically to reflect a broader set of values in forest management decisions [36]. We must move from an optimization approach that treats AES as a suite of independent benefit streams that can be unbundled from landscapes and maximized across human endpoints, to a risk-based approach that maintains the regulating and supporting services that underpin all other services, and develop policies and incentives that reconcile social and economic behaviors within these ecological constraints.

Now is the time to act to ensure that we develop appropriate strategies and supporting science to integrate AES in forest management policies and practices. The formal integration of AES into forest management would benefit from an internationally recognized standard and credible framework that addresses the risks inherent in uncertain and complex systems. The International Organization for Standardization (ISO) 31000 Risk Management Standard [37] is an internationally recognized standard used across sectors to analyze policy effectiveness and manage risks of management actions. The purpose of this paper is to present the ISO framework and show how it could be used to analyze the main characteristics of the integrated forest-AES system. We also identify conceptual challenges associated with developing management goals for AES and propose new approaches to reduce risk and ensure sustainable forest management for AES.

2. Managing Forests to Reduce Risk

The ISO 31000 [37] and its Bowtie analysis tool [38] provide a credible framework and approach to reduce complexity and can enable the integration of desired ES into management systems (Figure 2). The standard can be used to address the uncertainties associated with ecosystem processes and with human and ecological responses to management interventions. Complexities include non-linear responses, interactive effects, and feedbacks that operate at multiple scales, resulting in unavoidable trade-offs and risks in the face of changing human behavior and preferences.

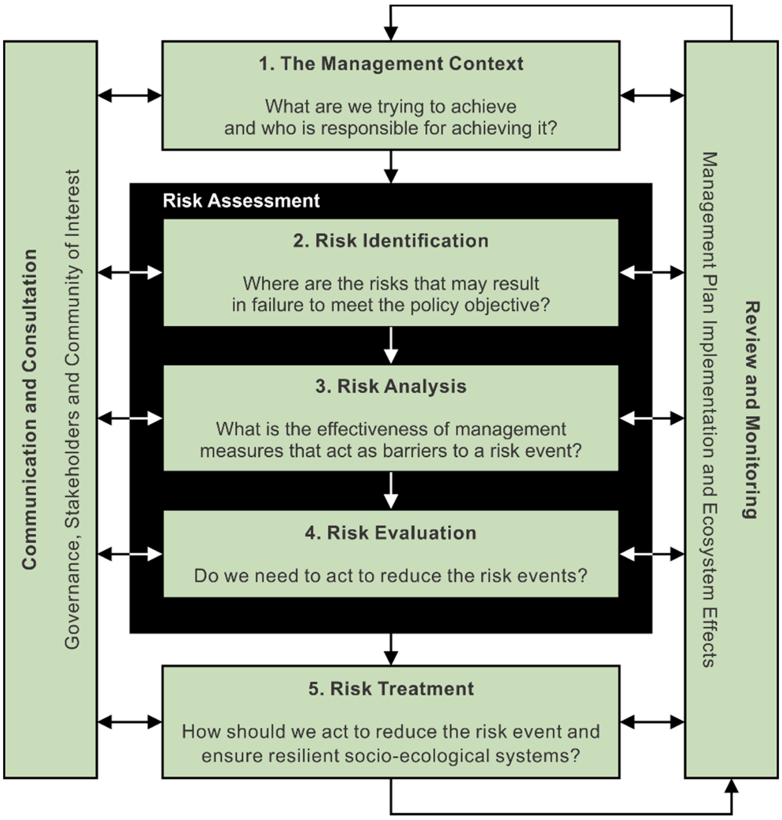

Figure 2. International Organization for Standardization (ISO) 31000 Risk Management Framework for the management of forest-ecosystem risk. Modified from [39,40].

Applying the ISO 31000 risk management framework to forest ecosystems and their AES simplifies and streamlines the analysis of the risks of alternative management strategies in the following ways: it helps identify the most relevant characteristics of the system that make it susceptible to risk; it helps identify the main risks rising from failing to meet management goals; and it informs new and innovative solutions. The ISO 31000 risk management framework in our context consists of five steps (Figure 2): (1) defining forest AES management objectives (goals) and context (boundaries); (2) identifying risk; (3) analyzing risks by looking at pressures-effects-impacts within the system; (4) evaluating the severity and distribution of risk and identifying risk limits to avoid strategies that lead to intolerable or catastrophic outcomes; and (5) developing and implementing management strategies to treat the risk.

In the remainder of this paper, we outline the steps and explore conceptual considerations and challenges in applying the ISO 31000 risk management framework to managing forest-derived AES. We conclude by suggesting a plan of action to develop tools and the capacity to enable governments to address these challenges.

2.1. Step 1. The Management Context: What Are We Trying to Achieve, and Who Is Responsible for Achieving It?

The first step requires defining a realistic boundary for describing the management context for AES. Forests and AES are part of a broader system in which the social and the ecological components are strongly interrelated as in Figure 3 [41,42]. The characteristics of forest ecological and social systems are defined by larger scale external ecological drivers, such as climate, disturbance and succession regimes, and social drivers, such as value systems and legal institutions, which lie outside the management context for AES. The management context is defined by forest ecosystem and social system characteristics as well the forest management context, which translates forest characteristics into

AES and their relationship to people. The forest ecosystem is defined by forest structures (e.g., nutrient pools) and functions (e.g., nutrient cycling) which individually or in combination produce AES (e.g., clean water supply). The forest social system is similarly defined by structures (e.g., decision makers, communities, property rights) and processes (e.g., consultation, legal). Together these systems combine to set up the rules for forest management and determine how forest management decisions (*i.e.*, forest plans, harvest rates and locations) based on tenures, forest regulations, and market conditions translate into forest AES and human benefits.

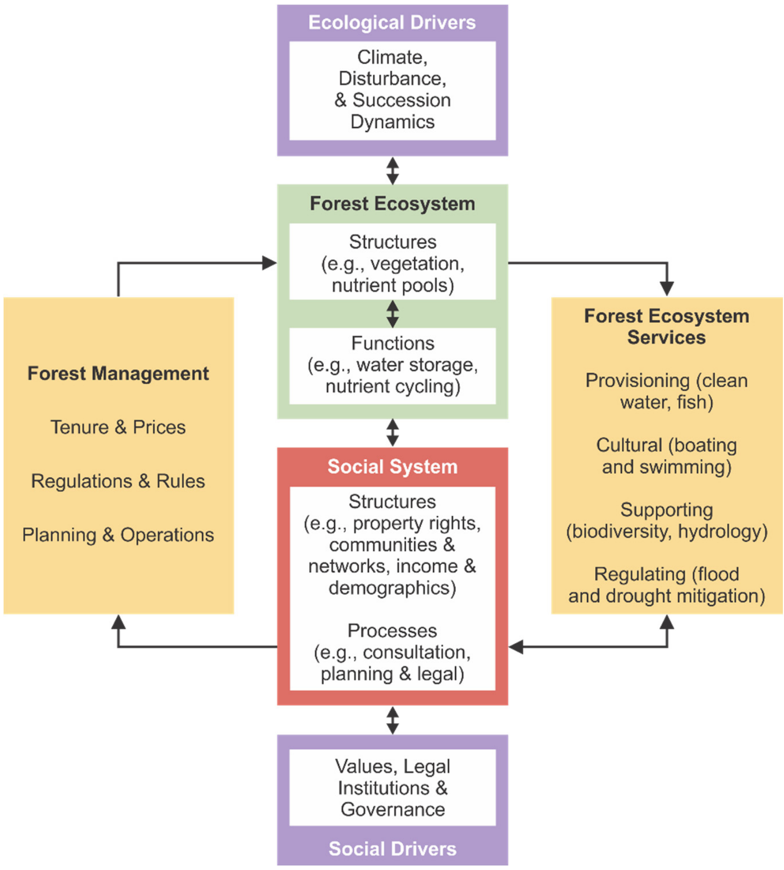

Figure 3. Forest aquatic ecosystem services are part of a socio-ecological system. Modified from [41].

The boundary of the management context is fuzzy, due to the dynamics and feedbacks within and between the ecological and social systems [43]. There are multiple pathways from forest ecosystems to AES and their beneficiaries that are contingent on cross-scale interactions. Therefore, forest management decisions can have consequences far from and long after the fact (Figure 4; [44]). For example, there are numerous relationships between AES supply areas and beneficiary areas [45]. Services can be produced and consumed at the same location, or benefits can be detached from service areas, either with distinct directional patterns (e.g., downstream or downwind from service areas) or multiple directional patterns. This means that for some AES, the management context can extend across regional, national and transnational boundaries and that forest management decisions can have time lags that affect benefits of future generations. The choice of which benefits and beneficiaries to include in the risk management assessment is critical since choices can lead to a biased evaluation of the risks and have a significant effect on whether or not an intervention is beneficial (e.g., [46]). Limiting the scope of benefit assessment to the supply area can significantly underestimate the value of AES (e.g., [18,47,48]). This is particularly important for countries such as Canada and Russia where populations benefitting from forest AES largely reside outside of forest areas.

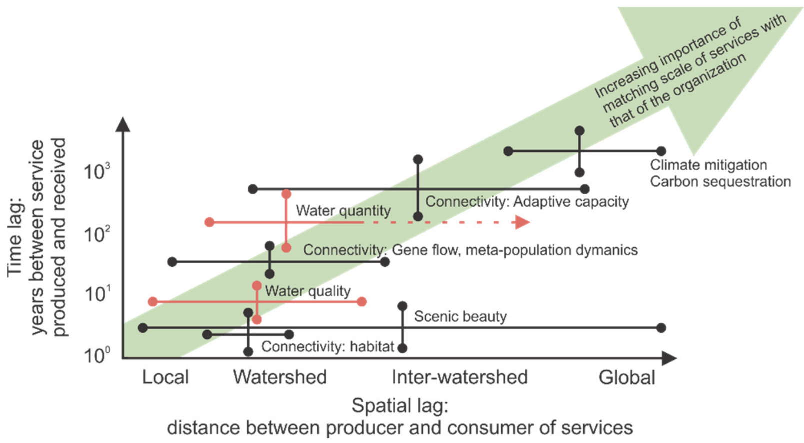

Figure 4. Forest aquatic ecosystem services affect people long after and far from where forest management decisions are made. The vertical axis shows the time lag in terms of multi-decadal recovery, and scale of impacts ranging from local to national and global. Modified from [44].

The impacts of forest management decisions on beneficiaries and their values can create feedbacks within the social system, resulting in changes in regulations and planning processes governing forest management, which over time may drive a redistribution of AES. A realistic boundary for the management context must, therefore, include multiple interacting spatial and temporal scales and feedbacks between the distribution of AES and forest management rules.

Challenges

1. Decision makers need to identify the linkages between the forest AES and people and be cognizant of the spatial and temporal mismatches between ecosystem functions, services, and beneficiaries. Mapping service areas helps us understand who the decision makers are that affect services and where management interventions should be concentrated while beneficiary mapping helps us understand who is affected by decisions, and from a financing perspective who might be willing to pay or need to be compensated for practice changes.
2. We need to understand the full scope for trade-offs and externalities. Ecosystems are multi-functional with ecosystem functions that contribute to multiple AES in potentially conflicting ways. To avoid inconsistencies, we need to develop a conceptual map that shows the causal chain from forest management decisions to ecosystem services and benefits (e.g., [49]).
3. We need to understand what incentives currently link AES to people and where there are policy gaps and opportunities. For commodities such as timber, the demand is global with supply linked to demand through global commodity markets [50]. In contrast, the demand for flood protection/water purification or other AES is local or regional and linked to supply through forest watershed management or water treatment facilities. We need to identify where current incentives create vulnerabilities and feedbacks between beneficiaries and the capacity of ecosystems to supply AES.

2.2. Step 2. Risk Identification: Where Are the Risks That May Result in Failure to Meet the Policy Objective?

The period since the 1950s has been termed the Great Acceleration, or the Anthropocene. It is characterized by accelerated demographic, industrial and technological changes caused by an unprecedented growth in population, which is expected to surpass 8 billion by 2030 [51]. These accelerated changes are reflected in numerous ecological and socio-economic indicators that suggest that ecological systems may have moved outside of the natural range of variation, a concept that has traditionally been used to identify limits of acceptable change [52]. By moving beyond the historical range of natural variation we are in uncharted territory with increased risk of passing a threshold or tipping point resulting in regime shift [53] and irreversible consequences for forest water resources (e.g., [54,55]).

Cumulative effects are changes to the environment that are caused by the combination of past, present and future human actions, which individually are insignificant but collectively have large and potentially destabilizing effects [56]. For example, cumulative effects of even minor modifications to forest management practices distributed across numerous headwater reaches might be significant for key downstream AES at the scale of regional drainage basins (e.g., [57–59]). Furthermore, legacy cumulative effects may be exacerbated by emerging forest management practices like those based on emulating natural disturbance regimes [60,61], increasing industrial encroachment on previously unmanaged landscapes [7], and a growing forest biomass removal industry to provide biofuel feedstock [62].

Forest managers need standardized methods for quantifying and predicting cumulative effects of forest management strategies (e.g., [55]). The methods need to include interactions and feedbacks and distinguish the effects of management from the underlying consequences of climate change. Furthermore, the methods must be robust enough to capture not only the range of natural variability but also thresholds, tipping points and regime shifts (Figure 5). Scenario analyses can be used to identify and address the risks from cumulative effects. The merit of future scenario analysis is recognized globally; the users of the Global Forest Resources Assessment indicated interest in scenario analysis to better understand the drivers and pressures affecting future forests, and to gain an understanding of forest dynamics in the face of predicted stressors, in order to design more effective policies [63]. Scenarios, together with models and indicators of the cumulative effects associated with these land use/land cover scenarios, are necessary to explore alternative assumptions of socioeconomic and environmental conditions that can be used to communicate key risks and uncertainties to the public and decision makers (e.g., [64]).

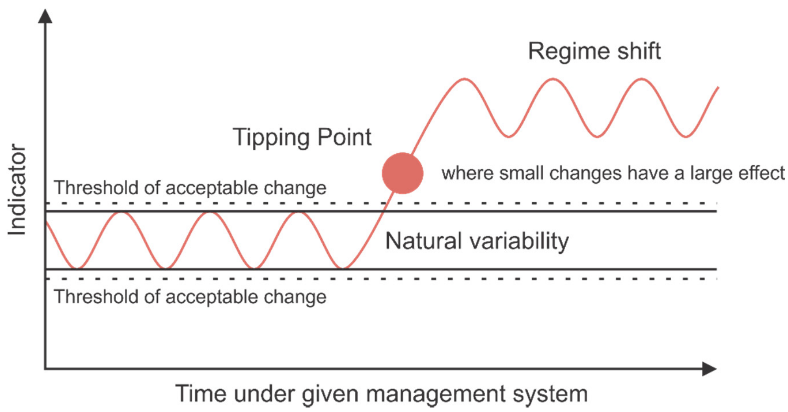

Figure 5. Concepts of thresholds, tipping points and regimes shifts into forest management strategies.

In conducting scenario analyses, either quantitative or qualitative approaches can be used (Figure 6). For quantitative scenario analysis, high quality modeling of future forest land use/land cover changes needs to be coupled with spatial databases of socio-economic and biophysical variables linking underlying drivers and pressures to forest loss and gain (e.g., [49]). The models provide a starting point for informing a future vision of the forest. Underlying assumptions can be drawn from a set of internally consistent global narratives of future social and ecological drivers to assess land use and land cover change and implications for forest AES (e.g., [63]). Land use/land cover scenarios are key to exploring scientific uncertainties related to interacting changes in the carbon cycle, hydrologic processes, and climate (e.g., [65]), or those prepared for the MEA [64,66]. Multi-scale (national, regional and spatially explicit) land use/land cover scenarios are used to link projections of future climate and socio-economic changes to regional and local decision-making (e.g., [64]). Downscaled and spatially explicit scenarios are particularly important for understanding forest AES since place matters both in terms of forest management as well as the spatial and temporal relationships between the supply and demand for AES. For example, the relative amounts of precipitation, forest evapotranspiration, runoff and streamflow at a particular site can be used by forest managers to decide if a forested landscape could be used for source water, forest products or soil water conservation [67]. The physical, chemical and biological properties of water flowing through forested landscapes will be influenced by the balance between precipitation *versus* evaporation and surface *versus* subsurface flow paths, and the contributions of local, intermediate and regional flow systems to the surface waters. Therefore, indicators that are used to monitor AES must reflect the ecological and hydrological diversity at local, watershed, region and inter-regional scales.

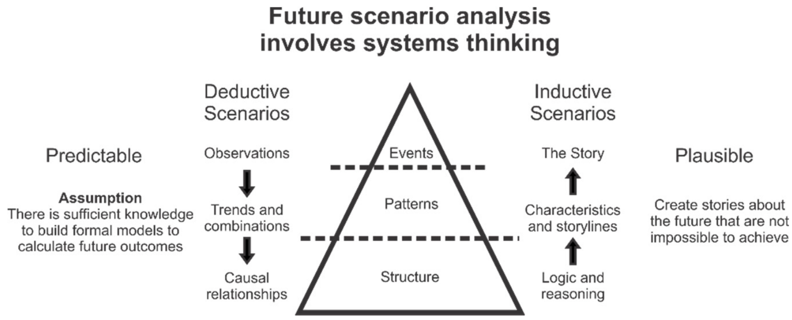

Figure 6. Quantitative (deductive) *versus* qualitative (inductive) scenario analyses.

Qualitative scenario analysis is an alternative approach to quantitative analysis, which can reveal hidden assumptions, risks and uncertainties in our understanding of a system's behavior [68]. Qualitative approaches use logic and intuition to build internally consistent and flexible scenarios free from the restrictions of mathematical algorithms, creating a space where alternative futures as a function of known uncertainties can be considered [69–71]. By engaging diverse sets of stakeholders (including experts, decision makers, and others with valuable perspectives and backgrounds) and considering system drivers of change across disciplines, qualitative approaches can foster interdisciplinary, integrative and innovative problem solving for complex environmental challenges [72,73]. By embracing uncertainty, qualitative scenario analysis can build strategic decision-making capacity rather than cripple it, because participants learn to anticipate perceived uncertainty [73,74]. Furthermore, this approach fosters genuine conversations about the future captured by the scenario narratives [73,75]. Important qualitative factors can be revealed and incorporated into the process when scenarios are developed as narratives, including values, behaviors and institutions, all of which encourage broad thinking and add depth to future scenario narratives when compared to those generated by mathematical modelling alone [76].

Challenges

1. We need spatial and temporal data that are consistent and comparable at different scales. Both traditional but also contemporary data-capture methods such as airborne and satellite imagery will be vital.
2. We need multi-temporal and multi-spatial scale models to understand better the risks to AES from drivers of changing forest landscapes (both retrospectively and prospectively) and to create narratives for exploring management options under different scenarios.
3. We need models that can represent interacting pressures on forest ecosystems that are poorly understood but may further threaten the sustainability of AES and that link forest and social system behaviors.
4. We need to represent uncertainties at national, regional and local scales.

2.3. Step 3. Risk Analysis: What Is the Effectiveness of Management Measures That Act as Barriers to a Risk Event?

Risk analysis is based on the following logic: "*if* cumulative effects are the result of the residual pressures after implementing existing management measures, *then* we need to enhance the system of management measures to reduce pressures below detectable effects (prevention), or reduce the effects to minimize impacts (mitigation)" [40].

Step 3 begins with identifying risk drivers (human activities that are considered the sources of pressures) that influence the pressures-effects-impacts cycle. *Pressures* are the physical, chemical or biological agents that are introduced to the ecosystem as the result of the risk drivers that trigger an undesirable effect, and *impacts* are the result of the undesirable effect (Figure 7). The risk analysis step analyzes the performance of the management system that is put in place to reduce pressures. The management system includes hard controls, which are actions or structures that prevent or reduce the pressure. These hard controls are based on design criteria (set by science and engineering) that *contribute to the effectiveness* of the management measure. The management system also includes soft controls, which are enabling, facilitating and tracking activities that *contribute to the compliance* of the management measure. The performance of the management system is analyzed in terms of the effectiveness of the management controls, as well as their compliance (regulatory) or adoption (voluntary), and must consider both preventive (pressures-to-effects) and mitigation (effects-to-impacts) measures (Table 2).

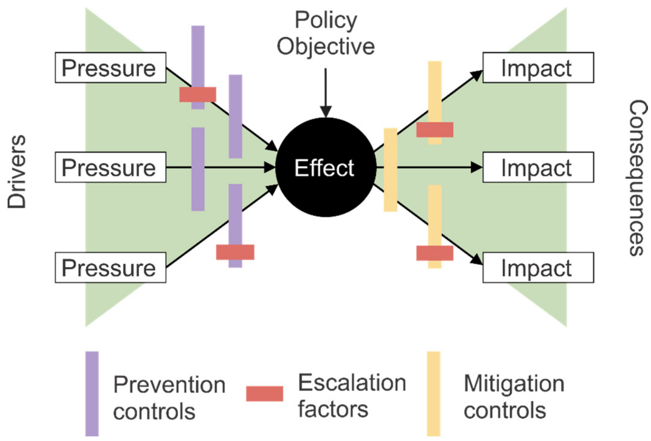

Figure 7. ISO 31010 Bowtie Analysis Tool to analyze the performance of the management system. *Prevention controls* act to reduce the effect. *Mitigation controls* act to decrease the severity of the impacts as a result of the effect. *Escalation factors* are outside influences (e.g., climate change) that undermine the performance of prevention or mitigation controls. Modified from [77].

Table 2. System of management measures (adapted from [78] and illustrated in [40]).

Management Measures		
Hard Controls	Avoid	Where and when is the human activity allowed to occur?
	Prevent	What is the amount of human activity permitted?
	Mitigate	What is the degree of impact?
Soft Controls	Enable	What is the allocation and coordination of authority?
	Facilitate	How can we make the public care that we can meet the policy objectives?
	Track	What is the target, and how can we track compliance and conformity to reach the target?

The way we evaluate the performance of the forest management system is a product of our forest management philosophy. Over the past century, forest management paradigms have shifted from the principle of maximum sustained yield (mid-1900s to 1980s), to ecosystem-based management (1980s to present). Ecosystem-based management is largely focused on the emulation of natural disturbance and uses the natural range of variation in ecosystem attributes as a reference condition against which to evaluate the performance of the management system [79].

To track the performance of the management system we need indicators and models that provide information on changing "baseline" conditions as well as the human activities that cause deviations from baseline conditions. Models enable us to answer "what-if" questions and different model scenarios provide an estimate of the risks of effects arising from the adoption of different management measures. Linking models with management in this manner allows governments to identify potential weaknesses and strengths in the performance of the management system, as well as to identify threats and opportunities for enhancing the performance. A system in baseline condition expresses attributes within the range of natural variation in the absence of human activity. However, as climate change intensifies and systems evolve beyond historic analogues, the concepts of baseline condition and natural range of variation are no longer useful or even desirable as management objectives (e.g., [80,81]). With accelerated anthropogenic and global stressors, we are increasingly moving our ecosystems outside of the range of natural variation. Equilibrium-based modeling approaches are not very good at predicting outcomes in natural systems that exhibit non-linear dynamics. Similarly, parametric approaches may fit well to existing data but lack out-of-sample predictive skill and misidentify key driving variables in nonlinear systems [82].

We need new ways to evaluate performance and bring the concepts of resilience including resistance, recovery, thresholds and regime shift into forest management [83–85]. Resilience is often suggested as a policy goal and a performance measure for the stability of social and ecological systems; however, there is significant debate on what resilience means and how to measure and manage for it [86]. Ecological definitions focus on concepts of *resistance* (related to the risk and severity of impact from exposure to disturbance), *recovery* (ability to return to the prior functioning state) and *proximity to thresholds or tipping points* [83,85,86]. While some efforts to measure resilience are underway, the development of modeling approaches and indicators to assess resilience remains a challenging field of research.

We also need ways to evaluate the complexity of interacting stressors that lead to changes in ecosystem states. For example, models have been developed that use changes in variance as a basis for predicting impending changes in ecosystems (e.g., regime shifts) due to anthropogenic stress [87–89]. The approach is based on the premise that ecosystem dynamics may become more variable before a regime shift and that this variance can be used as an indicator of the impending change [87]. An interesting characteristic of this approach from a management standpoint is that variance can be modeled even when there is no clear understanding of the underlying (typically non-linear) mechanisms of the impending change in ecosystem state. This suggests that detection may be possible using only routine monitoring data [87,89]. These measures of resilience are primarily used to measure how close systems are to thresholds and regime shift—the regime shift itself is seen as neither good nor bad, which makes a focus on measuring resistance, recovery and regime shift *per se* incomplete and unsatisfying for understanding resilience.

New approaches are being developed to understand the stability of systems and feedbacks between multiple systems. The best analogy for these indicators is that they are related to concepts of redundancy and adaptation/mutation. One promising approach focuses on entropy indicators [90]. Entropy indicators are based on the assumption that the more processes, interactions, and feedbacks that are present in a system, the more likely the system is to persist and adapt to changes [91,92]. Similarly, indicators based on information theory express the degree of predictability and self-organization of a system [90,93]. For evaluating these indicators, the feedbacks in the socio-ecological system must be carefully identified at multiple scales and across different components [93].

Challenges

1. We need to build and share databases of regulatory and voluntary management measures.
2. We need to evaluate the performance of the system of management measures that are put in place to reduce the risk of cumulative effects in the face of changing global conditions, including their effectiveness as well as the compliance of regulatory measures and the adoption of voluntary measures.
3. We need to bring the concepts of thresholds, tipping points and regimes shifts, and their appropriate indicators, into forest management strategies.
4. We need to create new indicators and methods for modeling resilience that reveal the pathways between pressures-effects-impacts, and that incorporate synergistic/antagonistic interactions and feedbacks within the managed system.

2.4. Step 4. Risk Evaluation: Do We Need to Act to Reduce the Risk Events?

Where Step 3 identifies deficiencies in the management system, either through inadequate effectiveness, compliance or adoption, Step 4 evaluates the likelihood of undesired consequences and assesses them in terms of exceeding risk tolerance levels or acceptable bounds. Risk evaluation is a normative process that matches the severity of ecological, social and economic impacts under different scenarios to tolerances expressed by stakeholders in order to define a safe operating space. The application of the concept of AES can assist in this process because it links consequences of forest management that affect AES to human benefits, thereby framing risks from forest-water interactions in terms that people can understand.

Risk evaluation may be based on probability impact graphs developed either qualitatively or quantitatively [94,95]. Risk tolerance curves (e.g., Figure 8) show that limits of acceptable and tolerable risk are based on underlying assumptions about: (1) adaptive capacity including the ability and limits of current technologies to mitigate risk; (2) feasibility of adaptation which is determined in part by social context and financial capacity; and (3) societal preferences about the amount and distribution of risk across different assets and communities [96]. Framing risk tolerance regarding adaptation incorporates institutional and social responses in defining limits [94]. Risks are then delineated according to whether they are tolerable (impacts that can be avoided and mitigated with adaptation), or intolerable (impacts that are unacceptable and unavoidable through adaptation). Tolerable risks would include adapting to soil moisture deficits through irrigation. Intolerable risks would include those that have a low probability but catastrophic consequences, such as the cascading effects of drought and famine from changes in atmospheric moisture patterns, as well as those that have a relatively low impact but are sufficiently frequent to be disruptive and impose unacceptable cost over time, such as recurring extreme flood events.

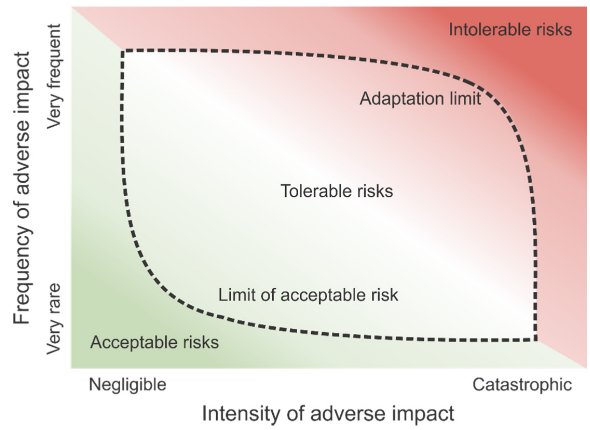

Figure 8. Risk tolerance curve is based on acceptable risks (there is no need to act), tolerable risks (risks can be managed by adaptation), and intolerable risks (risks that cannot be managed with adaptation). Modified from [94] based on [95].

Risk perceptions are subjective and individuals have different tolerances for risk. Therefore, the process for deriving societal risk tolerances must be transparent (Figure 9; [77]). It is important to ensure that all affected communities are involved in evaluating risks and in developing adaptation strategies. Typically, forest planning and operation take place at watershed or sub-watershed scales where stakeholder representation is limited to local and regional interests. This can result in a biased prioritization of risks, focusing on those that are local and decisions that have short-term payoffs with relatively certain costs and benefits. This leaves a gap in representation of potential broader risks to AES, which are more uncertain but may underpin the productivity of the system overall. To address risks to AES at an appropriate scale, it will be necessary to increase the scope of forest planning processes and tools to broader regional strategic assessment that can represent cross-sector (e.g., agricultural) impacts and longer-term perspectives.

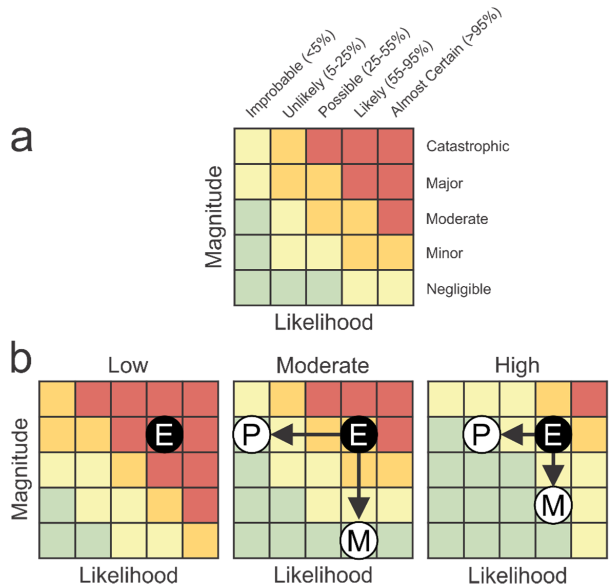

Figure 9. (**A**) Risk criteria and (**B**) risk tolerance matrices to evaluate if a management system should be changed (effects (**E**) are managed through mitigating (**M**) or preventative (**P**) measures). Coloration within the matrices denotes the necessary course of management action (**Green**: No management measures required; **Yellow**: Existing management measures adequate; **Orange**: Existing management measures need enhancement, and **Red**: Additional management measures needed). Modified from [40,77].

Probability impact diagrams can facilitate discussion, highlighting critical areas of uncertainty and win-win or no-regret strategies. However, they are less helpful when there are trade-offs between risks. For example, some strategies to support climate regulation may come at the expense of water availability and biodiversity. Similarly, maximizing fiber production may reduce water availability [97]. In such cases, evaluating the costs and benefits of risks under alternative scenarios may be desirable. Quantitative assessment of risk to AES is complicated by the ecological uncertainties described in previous sections that make it difficult to quantify probabilities. Similarly, the public good nature of AES such as clean water and aquatic biodiversity make a monetary valuation of costs and benefits challenging. The MEA [12] classification of ES as supporting, regulating, provisional, and cultural services is not amenable to valuation because the intermediate nature of supporting and regulating services and feedbacks between services can lead to double counting of benefits [98,99]. Both the EU Forest Action Plan [100] and the Biodiversity Strategy [101] call for the development of a standard framework for valuing forest ES.

Equity is an important component of adaptive capacity. In the case of forest AES, the poorest of the poor may be dependent on forest clearing for subsistence needs and have very little capacity to adapt to changes in water availability outside of further clearing of forest [21,102]. Understanding the distributional impacts of policies can help target resources to ensure that communities have the finances and capacity to adapt in ways that reduce risk and avoid negative cascading consequences.

There are challenging intra- and inter-generational equity issues to address in determining risk tolerances and the need for management action. Equity implies weighting costs and benefits more for the poor and accounting for impacts on future generations in risk management. The burden of forest protection will fall on those who rely on forest products to maintain livelihoods while AES benefits will accrue downstream and to future generations. Indices of relative poverty can be used to weight impacts of wide spread environmental risks (e.g., [103]), and discount rates are used to reduce the relative weight of future to current costs [104]. Since costs and benefits are not borne equally between different communities, weighting schemes have both inter- and intra-generational equity trade-offs (e.g., [105]). One justification for discounting is that growth will ensure that future generations will be wealthier. However, this assumption is false with irreversible loss of natural capital suggesting that discounting may not be suitable for some types of risks that exhibit thresholds and tipping points [106,107]. The choice of weights is probably the most contentious and influential variable in determining the need to act to reduce ecosystem risk as illustrated by the debate on the Stern 2007 Intergovernmental Panel on Climate Change report and the role of discounting [108,109]. Scenarios should be evaluated in terms of the sensitivity of results to different weighting schemes.

Decisions must be made in the face of a lack of knowledge on system behavior and prior probability distributions that describe system dynamics. Strategies for making decisions should involve identifying key sources of uncertainty, and identifying policies that are more forgiving in the event of negative surprise. In other words, costs in terms of system efficiency may have to be traded for reduced vulnerability and risk. This approach is particularly important when there are strong disagreements about assumptions and when decision-making is being done outside of historical context (e.g., [110]).

Effective decision-making strategies are those that perform well over the broadest range of alternative assumptions. A key source of uncertainty is related to interactions between social and ecological systems as humans adapt and respond to new policies that change forest condition. Often these interactions are too complicated to treat analytically and there is a need for multi-scale approaches to understand how the effects of these interactions cascade from individual decisions to communities and regions [111]. One way to deal with this uncertainty is to use agent-based models that are capable of representing individual behaviors and non-linear responses, while incorporating spatial and temporal heterogeneity [112]. Geographic Information Systems can be linked to agent-based models so that it is possible to have a spatial and temporal description of the distribution of risks and vulnerabilities, and reduce unanticipated consequences both locally and globally [113].

Challenges

1. We must develop standardized methods for valuing ES. There is increasing evidence that AES are linked regionally, nationally and internationally; thus there is a need for consistent and transparent methodologies to compare and aggregate benefits and values of AES at different scales. Both the EU Forest Action Plan [100] and the Biodiversity Strategy [101] call for the development of a standard framework for valuing forest ES.
2. We must standardize approaches for distinguishing intermediate services and final benefits. The MEA [12] classification of ES as supporting, regulating, provisional and cultural services is not amenable to valuation [98]. Challenges include distinguishing intermediate services from final benefits to ensure there is no double counting, and addressing spatial and temporal dimensions [98,99].
3. We must choose appropriate discount rates to account for intra- and inter-generational equity. Equity problems are prominent in dealing with AES, because benefits are usually downstream from where management actions take place and costs are incurred. Some benefits have long time lags before they are realized after a management action, whereas most costs are immediate.

2.5. Step 5. Risk Treatment: What Policies and Strategies Can Reduce Risk and Increase the Resilience of Forest Ecosystems and Their Services?

Though forest AES provide large benefits, they are not being adequately protected from the risks of cumulative effects. There is a need to strengthen and develop new policies to protect the valuable regulating and supporting (in addition to the provisioning and cultural) AES, which currently fall outside of markets, on behalf of downstream beneficiaries and future generations. The scale and jurisdiction of forest ownership and management are not typically aligned with management of forests for AES. Forest policy and management decisions are made either at too small a scale (e.g., forest management unit or stand) or too large a scale (national or international), whereas many regulatory and supporting AES require management actions at a watershed scale because that is the scale in which hydrologic processes and other AES typically express themselves.

Protection of AES requires a range of policy approaches from formal protection to incentives for beneficial practices by forest industry and private landowners [114]. Protection policies that emphasize exclusionary zoning are critical for the protection of AES. However, on their own they may be insufficient. Without additional incentives, protective measures may be unsupported and eroded by non-compliance and illegal encroachments, particularly if they reduce livelihood opportunities for those who cannot adapt. Effective forest management will benefit from policies that focus on individual behaviors and responses to price signals and other incentives embedded in tenures and institutions. Protection policies and incentivized approaches are complementary; protected areas act as refugia and perform an insurance role, whereas incentives allow for more adaptive behavior on the ground as conditions change. Unfortunately, these strategies are typically considered separately even though there are feedbacks between the two.

Incentives and payments for ES (PES) are an increasingly common way to internalize the benefits of AES in forest management decisions, particularly in developing countries where they often provide a substantial portion of rural income [115–118]. Getting the prices right is a critical aspect in the design of PES programs. However, the public-good nature of many of the regulating or supporting AES makes it difficult to determine how much the public is willing to pay, leading to budget shortfalls [118]. Water supply utilities, irrigation systems, and power companies are the most frequent buyers of AES (e.g., [118]). However, there is a gap in financing payments for AES that provide purely public benefits such as aquifer recharge. Government PES are particularly important for regulating and supporting AES where traditional private sector options are limited. An example of a successful government PES program is Mexico's Payment for Hydrological Environmental Services Program where the government pays forest landowners for watershed protection and aquifer recharge and collects revenues for the program from water supply charges [119]. However, sustainable financing of PES programs is an ongoing problem.

Multilateral initiatives have provided more than $1 billion in financing for forest carbon investments over the past decade. Commitments to forest conservation were top of the agenda at the Conference of the Parties (COP) 21 climate talks in Paris, particularly for tropical forests where illegal clearing, encroachment, and agricultural pressures continue to be a leading cause of global deforestation. The COP 21 discussions followed on the 2014 New York Declaration on Forests where world leaders committed to reducing natural forest loss by 50% by 2020 and end it altogether by 2030. Britain, Germany and Norway pledged $5 billion for forest conservation in poor countries through 2020 under the New York Declaration. Estimates are that as much as $10 billion a year flow into forest conservation, but this is about half of the funding required to reduce global deforestation by 50% [120].

If these measures are adopted in the COP 21 agreements, then significant investment in forest ecosystems worldwide can be expected, with promising benefits for AES. To date the impetus for forest conservation has been driven by carbon sequestration benefits; however, such a focus could lead to some of the same pitfalls and unanticipated consequences as the previous focus on forests for fiber and fuel. While the New York Declaration mentions the importance of forests for provisioning services including food and water, the ecological functions emphasized in the agreement focus only on biodiversity and carbon. Water regulating functions are not mentioned as a policy priority or objective anywhere in the document. Forests can only take up carbon if they take up water, and part of the price of carbon sequestration is paid in water uptake [32]. To manage forests for water in the 21st century, we need to ensure that carbon and biodiversity policies emphasize the linkages with AES.

Challenges

1. Dealing with complexity means we need to design forest management strategies that reflect feedbacks between forest AES and future landscape conditions, and that signal appropriate scarcities and risks. Regulatory and voluntary (*i.e.*, incentive) strategies must be considered jointly to account for perverse incentives and feedbacks.
2. We must develop incentives that can protect hydrologic regimes that underpin forest AES across multiple boundaries from sub-watersheds to large multi-basin drainage areas. Similarly, we must incorporate signals about future ecological scarcity into current incentives to address lag times in forest restoration.
3. Market mechanisms and PES are important anti-poverty programs. Often PES and anti-poverty programs are linked, but it is important to ensure that these programs are properly targeted and generate beneficial AES outcomes to avoid just becoming income redistribution programs [115,121].
4. The unprecedented level of forest investment under new carbon agreements provides opportunities for new investments in AES. These investments should be undertaken as experiments in order to better understand the relationship between forest management practices and AES at multiple scales. These types of experiments could help us to improve how we manage forests in the face of increasing demands for food, fiber and energy, and to ensure that we avoid some of the unanticipated consequences that have arisen from past carbon-focused policies.

3. Conclusions

Humans are altering the world's remaining natural landscapes at an unprecedented rate. As pressures move ecosystems outside of the natural range of variation, ES from forests are at increasing risk. Governments and companies have committed to reducing deforestation by half by 2020 and ending it altogether by 2030. To accommodate these ambitious targets in the face of growing populations, both forest and non-forest lands will have to be managed more intensively, making a focus on ecological thresholds and protection of AES even more critical.

There is currently a gap in our scientific knowledge about the impacts of various forest management policies on AES. In spite of the enormous progress made in slowing forest loss and fragmentation, international agreements and action plans still tend to operate within "silos" (single-issue oriented policies), even if the silos now include other ES such as carbon. A single-issue focus in policies can create the potential for unintended feedbacks and consequences. An AES approach that considers multiple water-related benefits allows us to explicitly include a broader range of values in forest management decisions, and in particular to recognize the contribution of regulating and supporting AES in maintaining forest and agricultural productivity.

Effective tools will be required to improve the prediction and management of risks to forest AES. We show how the ISO 31000 Risk Management framework can be adapted to forest management risk assessment, and we highlight a suite of challenges that need to be overcome to achieve the five-step implementation of the framework. The forest community should come together to help "customize" tools that will achieve the following:

1. Define a realistic boundary for the forest AES management context that specifies how spatial and temporal scales and lags should be represented in the boundary condition.
2. Develop models and indicators that reveal the pathways (including interactions and feedbacks) among pressures-effects-impacts and that incorporate concepts of complexity, thresholds, tipping points and regime shifts into forest ecosystem monitoring and assessment programs.
3. Develop standardized methods for assessing the cumulative effects on forest AES from multiple stressors and build databases of regulatory/voluntary management measures to assess and monitor management effectiveness and compliance.
4. Develop next generation models and indicators to analyze the adaptability of socio-ecological systems to changing conditions and indicators to track the resilience and robustness of policies operating within these systems.
5. Develop incentives (e.g., payments for ES) that will mitigate impacts of forest management, loss, or degradation of hydrologic function and other AES, and that will overcome some of the complexity highlighted above.

We call for a concerted effort to build these tools as part of the *UN Forest and Water Agenda* announced at the World Forestry Congress in Durban, South Africa. Global leadership and experience are needed to bring together a community of experts, including knowledge developers and users, who can develop effective solutions promptly. Research and advocacy by civil society organizations have improved scientific understanding and helped build public support for forest conservation and restoration. Now we need to focus on not just carbon, but water as the common center of the energy, fiber and food nexus for forest management.

We call for a strengthening of forest governance for water-related values by explicitly identifying the protection of AES in international agreements and policy statements. Furthermore, indicators for crediting the protection of AES should be incorporated in international funds and agreements such as REDD+ (Reducing Emissions from Deforestation and Forest Degradation) transactions. This will enable the development and financing of incentives for AES within existing financial mechanisms such as the Carbon Fund and the Forest Carbon Partnership Facility. It is important to ensure that a substantial share of revenues from these funds goes not just to individual or private tenure holders but also to local communities and governments since the sustainability of AES depends not only on what happens in a single forest stand but cumulatively at watershed levels.

National and international level assessments of risks to AES from forest management, degradation, or loss are required. However, the new "future forests" guide published by the FAO [63] does not assess water. To address risks to whole forest ecosystems and their services, we recommend that AES be specified directly in the objectives of all future international forest agreements and action strategies. If forests are the lungs and sweat glands of the earth, then water is the venous system. The focus on forests for trees without equal consideration of water and AES is akin to providing resuscitation while letting the patient bleed to death. We need to use investments to protect forests under new international commitments as living laboratories in which opportunities for natural and designed experimentation and evaluation of innovative forest management can occur. We further recommend principles from adaptive management to refine hypotheses and assimilate new information to sustain the services provided by forests for future generations.

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