

Review

The Role of Regional Ecological Assessment in Quantifying Ecosystem Services for Forest Management

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Abstract: Regional ecological assessments evaluate sustainability as an interaction among ecosystem services and stressors across changing landscapes. Using ecological assessments to inform ecosystem management activities relies on assessing functional linkages between ecosystem processes and ecosystem services, because ecosystem processes are the primary targets of ecosystem management. We undertook a review of regional ecological assessments in the Appalachian region of the United States to examine how forest-based ecosystem services, forest ecosystem processes, and their linkages are quantified. To provide context, we first give an overview of common ecological assessment frameworks, including risk, vulnerability, resilience, and indicator-based approaches. Assessments tended to target either ecosystem-level properties thought to be important for ecosystem service sustainability, or else to target specific ecosystem services or stressors. Forest ecosystem-level assessment most often relied on specific indicators for system properties such as integrity or health, but how those properties or their indicators were related to ecosystem services was typically not quantified. Individual ecosystem services were frequently assessed in terms of risk and vulnerability to specific external stressors, but linkages to ecosystem processes, and potential tradeoffs among ecosystem services, were infrequently quantified. Integrated system-level assessment and ecosystem service assessment can improve support for ecosystem management by advancing our understanding of dependencies on the ecosystem processes that are modified through management. Models that evaluate ecosystem services and underlying processes in a systems context offer one approach to do so.

Keywords: ecosystem management; ecosystem services; ecological assessment; resilience; regional assessment; vulnerability



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1. Introduction

Scientists produce regional ecological assessments to supply information about natural resource sustainability in a form that is accessible for policy, planning, and land management applications. Assessment practitioners seek to quantify how ecosystem services (ES) such as the provisioning of clean water, carbon storage, wildlife habitat, harvestable products, and outdoor recreation are supported by ecosystems and how they are compromised by stressors such as overuse, land use change, climate change, and invasive species. Assessments may have very large scale and scope, geared mainly towards informing policy—examples include the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services regional assessment report for the Americas [1] and the US Forest Service Resources Planning Act Assessment [2]. More limited assessments are common for specific regions, undertaken by a variety of organizations and typically geared towards informing land management planning and decision-making [3]. We refer to these as regional ecological assessments—assessments of this kind often provide the best available overview of ecological conditions, environmental stressors, and resource sustainability for a given region.

Regional ecological assessment has increasingly made use of the ES concept, wherein ecosystem functions are quantified in terms of benefits to people [4]. This perspective has clear relevance for assessing sustainability and informing ecosystem management, but it also raises practical questions about how ecological assessment is performed. A central issue is the ecological level of organization at which assessment is focused. The ES concept encourages a focus on narrow ecosystem components and functions that produce particular benefits such as harvested species or drinking water, but at the same time, it emphasizes societal dependence on whole ecosystems to supply a wide variety of ES, not all of which are readily quantified [5–7]. Assessment may therefore be focused on ecosystem components such as a single tree species, processes with broader implications such as ground water filtration, or at the level of whole ecosystems or landscapes.

A primary objective for regional ecological assessment is to meet information needs for ecosystem management, and land managers using ecosystem management approaches are among the most important stakeholders for ecological assessments. Ecosystem management emphasizes conserving broad ecosystem processes such as nutrient cycling, biomass production, and natural disturbance regimes, and espouses sustainability as a system-level, rather than a resource-level, objective [8–10]. In practice, land managers contend with whole ecosystems as well as individual, high-priority ES, resources, or species in a single decision space for the same landscapes—a reality recognized in ecosystem management. For example, in fire-adapted ecosystems, the broad impacts of prescribed fire on system structure, function, and composition are of central concern, while the need to improve habitats for specific species through prescribed burning may also influence decisions [11].

Ecosystem management stresses the need to understand particular resources and broader ecosystem properties not separately but integratively, recognizing that these linkages—how valued resources are generated and maintained by underlying system processes—are of fundamental management concern. Not coincidentally, understanding how various ES are sustained by ecosystem processes within a whole system context has been considered a priority for ES science [12,13]. In practice, quantifying these functional relationships has lagged behind the basic measuring and mapping of individual ES provisioning, because mapping may be perceived as more immediately relevant for resource protection or because it may be more achievable with less intensive research [7,14,15].

Our goals were (1) to examine how regional ecological assessments have approached the quantification of ES, their stressors, and the ecosystems that provide ES, and (2) to explore how these approaches might be advanced to improve the relevance of regional ecological assessment for informing ecosystem management. First, we provide context by reviewing dominant assessment frameworks—risk, vulnerability, and resilience assessment, as well as indicator-based approaches—highlighting their relevance for ES and their association with different levels of analysis. Specifically, we distinguish between ES-focused and ecosystem-focused analysis. Next, to understand the practice of regional ecological assessment in this context, we reviewed assessment documents for the Appalachian Landscape Conservation Cooperative (ALCC) region. The ALCC was a regional conservation partnership, active from 2010 through 2018 across an area including parts of 15 states in the eastern United States [16]. The assessments we included were not specific to the partnership, but were relevant for the region. We summarized the range of forest-based ES, ecosystem properties, and stressors given attention in assessments, and characterized the quantitative approaches taken to their analysis.

Last, in light of our review, we discuss differences that we found between assessment theory and practice, and ways that assessment practice can be advanced. We suggest that integrative assessment approaches can inform the management of complex forest landscapes that support a variety of ES. In particular, we overview systems-based approaches that can help to connect ES outputs to the ecosystem processes that are the main target of ecosystem management.

Our review was limited in several ways. We took a case study approach, limited to the ALCC region, and we focused on analyses of forest ecosystems, the dominant natural

vegetation in the region. We focused on biophysical assessment of these systems, i.e., quantifying the condition and functioning of ecosystems and landscapes that provide ES. While assessing ES may be considered an inherently social–ecological enterprise because the focus is on the societal benefits and uses of ecosystems, biophysical assessment is a crucial element of this enterprise, and it is the element most often targeted in ecological assessment [7,15,17]. Where appropriate, we illustrate connections with social–ecological analysis and situate findings within this context.

2. Ecological Assessment Frameworks

Distinctions among common assessment frameworks relate closely to choices about assessing ES and their stressors either individually or synthetically at broader ecosystem levels (Figure 1) [5]. An exhaustive review of assessment theory is beyond our scope, but to provide context for our case study, we describe risk, vulnerability, resilience, and indicator-based frameworks and point out advantages and challenges in implementing them for ES assessment.

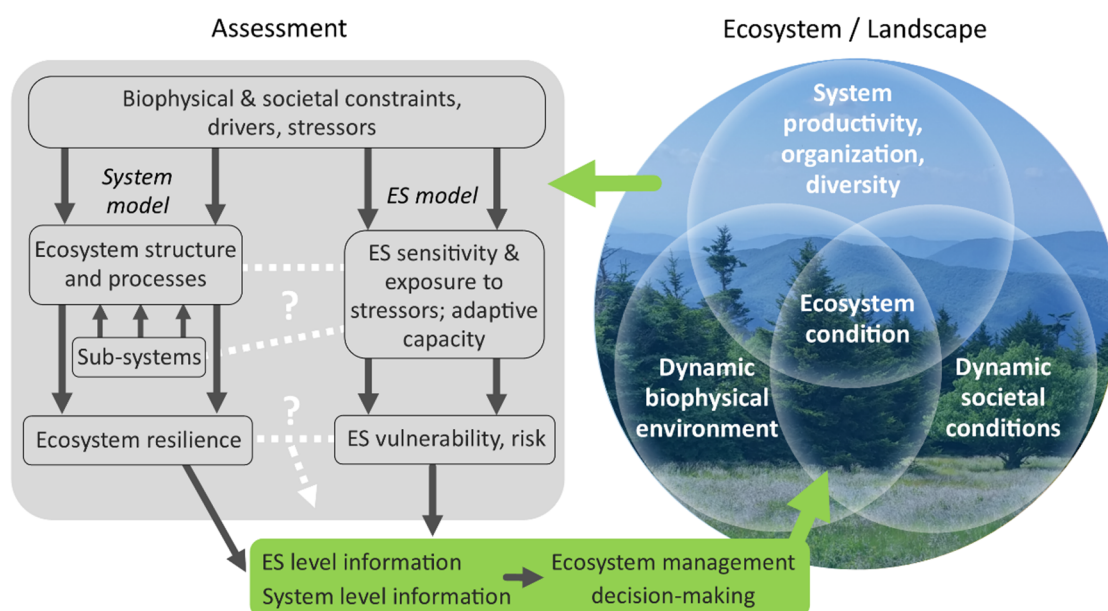


Figure 1. Representation of ecosystems and ecosystem services (ES) in ecological assessment frameworks. The capacities of ecosystems to support ES vary in response to environmental and societal conditions. These dynamics are represented in different ways by system-oriented assessment models and ES-oriented models. Assessments that quantify ecological effects, feedbacks, and other functional linkages between these different levels of organization, treating ES as integral system components, are uncommon (suggested by dashed white lines). Integrative assessments can aid ecosystem management by providing knowledge about dependencies in the ways various system processes and ES respond to environmental change and management actions.

2.1. Assessing Ecosystem Services Individually

Most efforts to incorporate ES in ecological assessment use risk or vulnerability frameworks, although risk or vulnerability language is not always used [18]. Risk and vulnerability are both measures of the susceptibility of a system, resource, process, or species to harm due to exposure to environmental stressors [19–21]. Risk and vulnerability assessment both accommodate the estimation of costs potentially resulting from this susceptibility, e.g., the likelihood of ES loss if no action is taken. This involves building conceptual and quantitative models to anticipate outcomes based on the exposure and sensitivity of ES to stressors (Figure 1). Sensitivity indicates the expected response to a given level of exposure [22]. Risk and vulnerability are chiefly distinguished by the former’s emphasis on estimating costs and benefits of likely outcomes to aid decision-

making (i.e., risk analysis), and the latter's emphasis on adaptive capacity, i.e., dynamic responses to stressors that reduce sensitivity or otherwise help to prevent loss [20,23].

Quantifying sensitivity and exposure to stressors can yield a mechanistic understanding of ES degradation with specific management implications for reducing stress, and predictive results mapped across landscapes can be integrated into planning efforts [24–26]. Active areas for ES risk and vulnerability model advancement include the development of process-based, spatiotemporal models; linking the production of ES with their flows to people; and accounting for adaptive capacities and feedbacks [14,27–29].

Risk and vulnerability frameworks are widely embraced for ES assessment, generally implemented at individual ES levels of analysis. This approach allows change in the provisioning of a given ES to be predicted, given the dynamics of various stressors, landscape conditions, and management activities [14,30,31]. Risk and vulnerability can also be framed as system-level properties, but, in practice, they are usually descriptors of the component(s) of an ecosystem or social–ecological system thought to be particularly susceptible to stress or having the highest management concern [22,32].

Challenges exist in linking such assessments to ecosystem management, an approach which assumes that ES arise from core ecosystem processes and are not independent from those processes or from one another [7,9,10]. One approach to leverage system-level information is to compile multiple independent vulnerability assessments for a group of complementary ES or collective 'bundles' of ES that occur together in the same landscapes [32–34]. However, decision support needs for ecosystem management are likely to require explicit consideration of interdependencies, including relationships to ecosystem processes. For example, an integrated framework may allow explicit analysis of tradeoffs among different ES gained or lost under management scenarios that affect whole systems and broad system processes [22,30].

2.2. Assessing Ecosystem Services at the System Level

Most assessments which characterize ES sustainability at the ecosystem level, or strive to be synthetic in the sense that they account for a spectrum of ES, use an indicator approach [35,36]. This typically involves indices that combine several measurable system traits, which are either demonstrated or assumed to collectively indicate an ecosystem property, such as integrity, health, or resilience [37,38]. Such indices have been compiled from measurements of biomass, species richness and composition, land use, land cover, habitat connectivity, topography, climate, geology, and other features—methods for combining and weighting different measurements into an index are highly variable among assessments [39–44].

Indicators provide a practical way to assess elusive system properties, while their utility depends on the reliability of the relationship between indicators and the properties of interest. This in turn depends on properties such as ecosystem health and integrity having clear operational definitions, credibly linked to observable characteristics [45]. An additional challenge involves uncertainty in the relationship between indicators and ES themselves—particularly when several indicator metrics are summarized as a single index [37,44,46]. Recommendations for enhancing indicator approaches have emphasized measuring processes and causal linkages among system components rather than isolated traits or static resource stocks, and explicitly defining any system-level endpoints such as health or integrity [38,44,47,48].

Resilience theory provides an alternative framework, rooted in systems ecology, that favors a system-level perspective and emphasizes quantifying ecosystem processes that underlie multiple ES [49,50]. In a systems framework, models for the functional relationships among internal system components as well as external influences are the basis for estimating system-level resilience (Figure 1). Recent definitions of resilience describe a multi-faceted property of systems wherein both an ability to recover from disturbance or stress and an adaptive capacity for more fundamental transformation contribute to the maintenance and renewal of system functioning [51–53]. This view was first applied

to social–ecological systems, but it can also describe the capacity of ecosystems to cope with multiple interacting stressors and to sustain fundamental ecological processes under environmental change [6,53,54].

For example, a forest’s species composition and structure change over time in response to multiple stressors, including fire, insect pathogens, and timber harvest. A resilient forest under these dynamics continues to develop and retains the adaptive capacity to provide a variety of ES, although specific ES may be diminished or enhanced over time [50,51]. This implies that the ES provided by future landscapes cannot be fully anticipated given uncertain societal and ecological change. Managing for resilience therefore entails sustaining robust ecosystem processes and guiding system change to support dynamic capacity for ES under a variety of possible future conditions—an approach with clear affinities to ecosystem management principles.

However, challenges exist for assessing ecosystem resilience with respect to ES. Doing so entails accounting for how system structures and dynamics respond to environmental change and stress, and how resulting pathways of system change enhance or compromise different ES [50,55,56]. Monitoring ecosystems in sufficient detail to quantify these complex dynamics at the spatial and temporal scales relevant to ecosystem management—usually, large landscape scales and decadal timescales—is daunting [46]. Further, communicating conceptually unfamiliar system analyses to stakeholders and decision-makers can be difficult, although this is improved when connections to ES-level concerns are explicit [15,57,58].

3. Appalachian Regional Ecological Assessment

3.1. Methods: Reviewing Assessments

The Appalachian region, with the Appalachian Mountains as its defining feature, includes a large but widely dispersed human population, high biological diversity on private and public lands, an extensive system of protected areas, and intensive natural resource extraction particularly in the energy sector—resulting in a complex intermixing of landscape types, uses, and values. We sought to examine how ecological assessments relevant for this region have quantified and evaluated ES, focusing on whether and how functional relationships between ES and their stressors, or ecosystems and their stressors, were quantified, as well as whether and how functional relationships between ES and ecosystem processes, or ecosystem-level properties represented by indicators, were quantified.

We searched for regional or national assessments that quantified the capacities of Appalachian forest ecosystems to supply ES or comparable natural resources, and/or regionally important stressors on those capacities. We included assessments covering the ALCC region or a major subregion (one or more states). Assessment documents ranged from online-only web pages to ‘gray’ literature not readily discoverable online. Our search therefore included bibliographic searches in the broader peer-reviewed literature, online searches, and queries made to scientists at agencies and NGOs with a presence in the study region.

Summarizing how ES have been analyzed required a way to identify and classify ES, a process that involves subjective judgement, whether classifying by ecological process, human use, or other criteria [5,59]. Terms encountered in assessments, such as ‘natural resources’, ‘natural assets’, or ecosystem ‘goods and services’, frequently referred to ecological outputs comparable to ES. Rather than attempting to match these to technical groupings such as provisioning, supporting, regulating, and cultural ES [12], we identified frequently recurring categories in the assessments themselves. These usually corresponded to ecological outputs whose relevance to human well-being is clear without technical explanation [59], such as water quality or nontimber forest products.

We first synthesized the broad findings of assessments with regard to ES sustainability, documenting analyses of individual ES and stressors, as well as landscape- or ecosystem-level properties that were connected either implicitly or explicitly to ES. We then examined assessment analytical approaches. Assessment documents typically included multiple

separate analyses, which we evaluated individually. We asked if relationships between ES and stressors, or ecosystems and stressors, were modeled analytically—e.g., using sensitivity and exposure models or ecological production functions [14,20]. For forest ecosystem-level properties, we asked whether these properties were examined using indicator or systemic approaches, and whether they were linked to ES explicitly (i.e., quantitatively). In all cases, we asked whether analysis was spatially explicit at the county level or finer.

3.2. Findings: Diverse Services and Stressors, Limited Assessment Tools

Appalachian assessments (Appendix A) quantified the biophysical provisioning of a variety of ES, corresponding to diverse and sometimes competing land and water uses. We identified 11 ES categories and eight stressor categories (Figure 2). We further grouped these into four and five categories, respectively, for a broad synthesis of assessment findings (Appendix B). Services included basic resources such as clean drinking water, bases of local economies such as nature-based tourism and harvested forest products, and forest carbon storage as a climate regulating service. They also included less tangible benefits such as rural landscape values—the sense of place that rural communities derive from landscapes dominated by natural features—and aesthetic appreciation of landscapes by visitors (Figure 3). Regionally important stressors included aspects of land use intensification, extensification, and landscape fragmentation—particularly including urbanization, energy resource extraction (e.g., surface mining), and infrastructure associated with energy development (e.g., hydraulic fracturing). Stressors also included forest pathogens, invasive species, and climate change (Figure 2, Appendix B). Many ES, landscape, ecosystem, and stressor variables were represented spatially, with approximately half of analyses including some form of spatially explicit evaluation and map product (Figures 2 and 4).

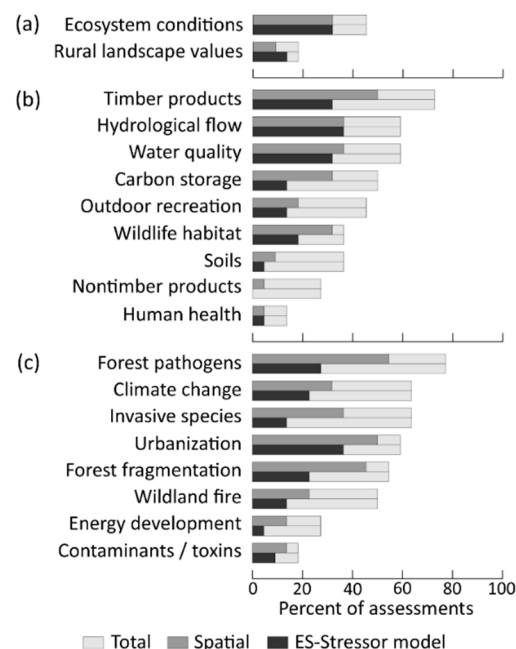


Figure 2. Categories of (a) ecosystem-level properties, (b) ecosystem services (ES), and (c) stressors quantified in 22 ecological assessment documents (Appendix A) that covered the Appalachian region or a significant subregion or state, and that focused on forest-based ES or resources. ‘Ecosystem conditions’ is used here to include ecosystem-level or forest-level properties encountered in assessment documents, including integrity, condition, health, and resilience. Specific definitions for these properties varied among documents. Total = percent of assessments in which the category was addressed quantitatively; Spatial = percent in which the category was quantified spatially at the county level or finer; ES-stressor model = percent in which a quantitative relationship expressed the effect of one or more stressor on an ES or system-level property.

Timber products

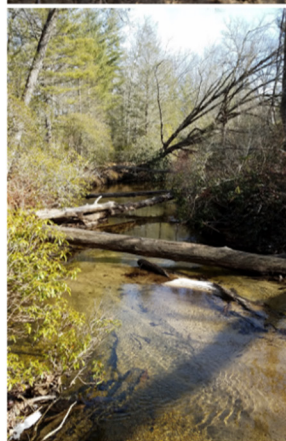
Hardwood production has been a key economic activity across the Appalachians, supporting rural livelihoods and supplying products at regional to global levels. Sustainable markets create an incentive to keep land forested, and working forests can support many other ES if appropriately managed. Timber stocks and production have been stable in recent decades, but are at risk of decline.

Nontimber forest products

Many products such as wild herbs are harvested in the region, and hunting and fishing are important recreational activities. Sustaining cultural and economic values associated with forest products can be compromised by overexploitation, as can occur in poorly regulated places and near population centers.

Water, hydrology, and soils

The Appalachians provide abundant clean water to populations within and beyond the region. Forests are important for drinking water, water-based recreation, and aquatic habitat quality. Forest conditions influence streamflows, which in turn affect flood risk, recreation and tourism, and habitat quality. Forest soils support many ES including clean water, stream-flow regulation, carbon storage, and forest products. Forest and wetland management and restoration can improve soils, water quality, and streamflow regulation.



Rural landscape values

Many of Appalachia's inhabitants value the sense of place associated with rural, largely forested places. They may also value the economic activity that development and industry bring. When these values compete, there may be an expectation that the quality of rural life need not be eroded as landscapes change. Development consistent with this expectation is challenging but possible.

Outdoor recreation

An abundance of natural areas, streams and rivers, and public lands make the Appalachians a prime destination for nature-based recreation and tourism. Associated economic activity creates incentives for forest and freshwater management that enhances a wide variety of compatible ES, but poorly managed recreation can also erode ES.

Forest carbon

Carbon sequestration and storage in forest plants and soils are components of climate change mitigation provided by Appalachian forests. Net carbon storage has increased over recent decades with growing forest age and extent. Rates of increase are declining, but old forests store massive amounts of carbon. Preventing these forests from becoming net carbon sources may involve urban development policy, restoration efforts on mined sites, and changes in energy markets and forest product markets.

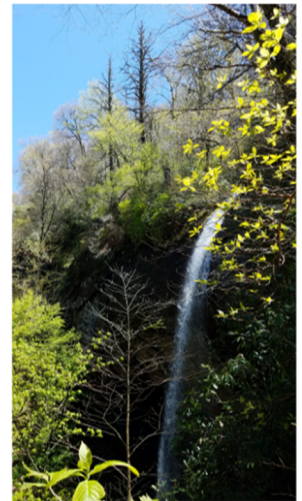


Figure 3. Ecosystem services provided by forested landscapes are abundant and diverse. Principles of ecosystem management highlight the importance of understanding these ES as integral components of entire ecosystems with dependencies on ecological processes at multiple scales and system organizational levels. Examples of ES described here were among those most frequently included in ecological assessment documents for the Appalachian region; statements regarding sustainability and management were synthesized from these documents (Appendices A and B—the ES shown here are further grouped into four categories in Appendix B). The flowering plant pictured at left is Bloodroot (*Sanguinaria canadensis*), a species harvested for use in the medicinal trade. Photos by the first author in western North Carolina.

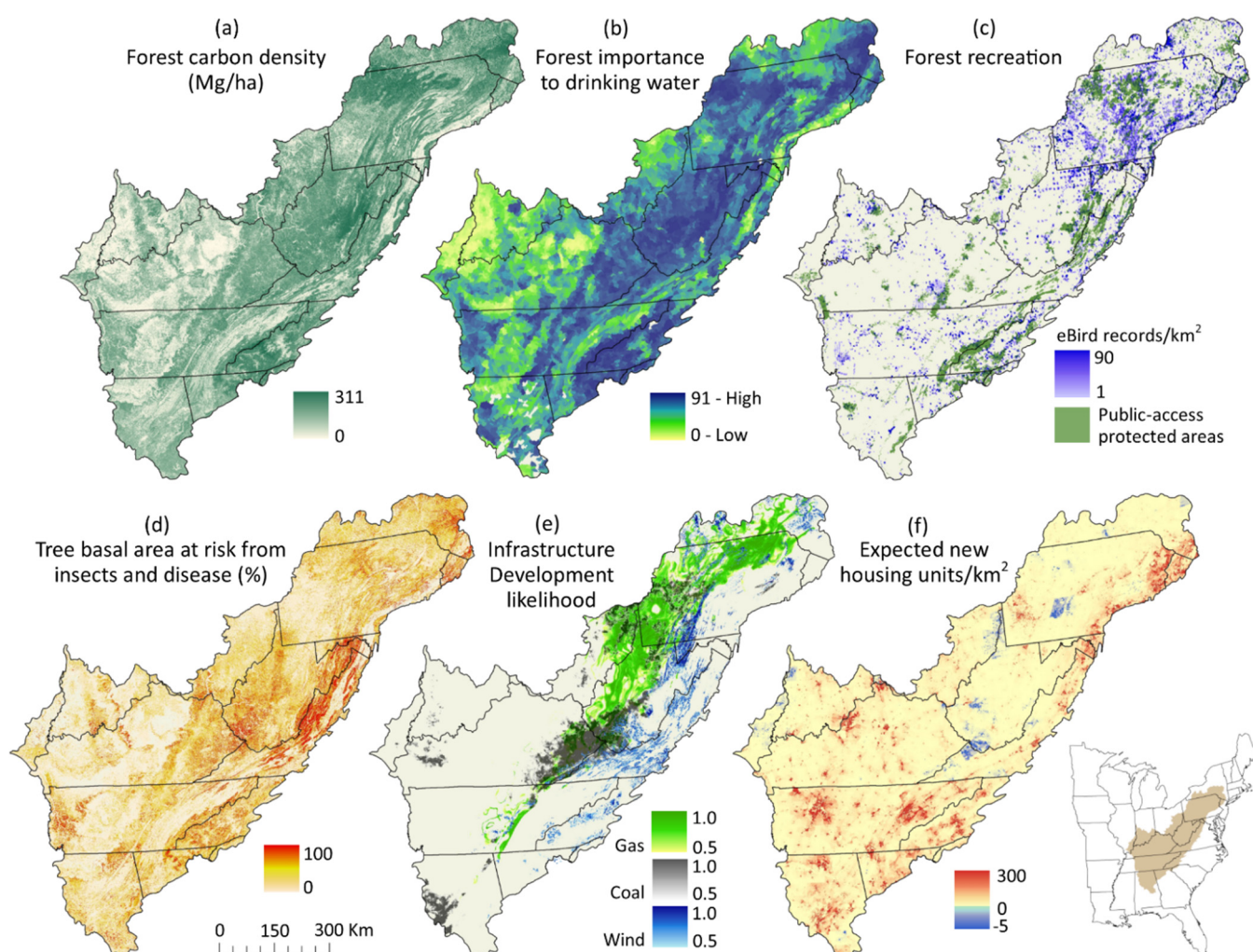


Figure 4. Examples of ecosystem service (a–c) and stressor (d–f) distributions across the ALCC region. Inset shows the ALCC location in the eastern United States. (a) Total forest stored carbon density (Mg/ha), 2000–2009 [60]. (b) Importance of forests for drinking water supply [61]. (c) Forest recreational uses: protected natural areas with public access, and density of citizen science observations of a common forest bird group (*Vireo* spp.) from 2003 to 2012 (observations/km²) [62,63]. (d) Expected composite risk of forest tree mortality from insects and disease, 2013–2027 (% of basal area) [64]. (e) Expected likelihood of infrastructure build-out for gas, coal, or wind energy extraction by 2035 [65,66]. (f) Expected change in housing density, 2010–2030 (units/km²) [67].

Analyses of system-level properties, described in assessment documents as the condition, integrity, health, or resilience of ecosystems, landscapes, or forests, occurred in around half of the assessment documents, but comprised a minority of analyses in any document (Figure 2). We included rural landscape values (Figure 3) as system-level properties when assessed at synthetic landscape levels rather than as a specific resource. In all cases, system-level analyses used indicator variables or composite indices to represent system properties. For example, low forest fragmentation was used in several analyses to indicate high system integrity [68].

Approximately half of quantitative assessments did not include any analysis of a functional or predictive relationship between stressors and ES, ecosystems, or ecosystem processes, beyond comparing their spatial distributions (Figure 2). In such cases, there was no explicit model for these relationships, such as an ecological production function or estimation of sensitivity, effect, or adaptive capacity. Those cases that did include some quantified or modeled stressor effect were dominated by assessments of individual ES, rather than ecosystems or system-level properties.

4. Discussion: Towards Integrative Assessment

Our case study review indicated that various analytical approaches have been applied unevenly across ALCC-relevant assessments. This may be due in part to uneven awareness of emerging science, but it may also reflect judgements of practitioners concerning the usability, fitness-to-purpose, or relevance of available frameworks and analytical tools. Our findings emphasize a need to better integrate between ecosystem and ES organizational levels, guided in part by theory linking ES outputs to ecosystem processes. We further suggest that adopting ES–ecosystem integrative approaches will facilitate science–management integration, by helping to clarify how ecosystem management decisions and activities can support ES sustainability.

4.1. Connecting Ecosystem Services to Ecosystems

In the Appalachian assessments that we reviewed, ecosystem-level analyses—all based on indicator or index approaches—were usually included side by side with ES-level analyses, often justified by implicit links between ES and ecosystem-level structure and process. This suggests that assessment practitioners recognize the importance of functional relationships across these different levels of organization. However, these links were seldom analyzed explicitly. For example, an assessment of forest resources for the Appalachian Regional Commission [69] included spatially explicit market and non-market valuation of forest-based ES including timber harvest, carbon stocks, wildlife habitat, recreational use, and watershed services. Separately, broader forest condition was quantified as a compilation of indicator metrics including tree growth and mortality rates, invasive species occurrence, risk of land use change and forest pathogens, and other disturbances. While these separate analyses have value in their own right, a premise of the assessment was that forests in good condition (as defined and measured therein) support greater ES value—but this relationship was not quantified or tested.

Quantifying functional relationships between ES and underlying ecosystem processes was rare in assessments, but this approach can improve analytical linkages among system properties such as resilience, vulnerabilities of specific ES, and risks associated with specific stressors. These relationships may not be straightforward—ecosystem capacities to provide particular ES are likely to be associated strongly with some system processes or components and weakly with others [14,17]. Stressors such as forest pathogens and fire likewise have variable impacts on different system processes and components, with variable consequences for different ES [50,70]. A forest's resilience to climate change, for example, may not directly predict an ES such as carbon storage, but this system's resilience and carbon storage capacity may shape one another in important ways.

No assessment that we reviewed used a system approach—e.g., based in systems theory or a process-oriented analysis—to quantify system-level properties, but we suggest that such approaches can advance understandings of ES–ecosystem linkages. For example, system properties such as resilience arise in system models from ecosystem component structures and the processes relating them to one another. Outputs such as quantified complexities, uncertainties, and organization of systems may be useful inputs in models for individual ES, where ES–stressor sensitivities are modulated by system properties [71]. An alternative systems approach to quantifying these relationships is to model the pathways through which multiple stressors influence multiple ecosystem components and processes, impacting multiple ES outputs (with possible interactions and feedbacks). This approach essentially incorporates ES as system components, processes, or outputs [5,7,54,72]. While beyond the scope of this review, system approaches have also been expanded to encompass social–ecological systems hierarchically. This can advance integration of the full ES cascade, which links ecological processes with flows of ES to society, in a systems framework [72].

System analyses and models take a variety of forms, which have not been fully explored in the context of assessment, but which should be useful. Assessment from a systems perspective contrasts with most indicator-based approaches in that system-level properties emerge from the dynamic functional relationships among system components, and so are

intrinsically process-based. For example, ecological network approaches have been used to examine how aspects of system complexity influence process stability in changing environments [73]. Network analysis can help to identify pathways and thresholds whereby stressors impact ecosystem components or push ecosystems outside their historical stability domains [56,70,73]. Information-theoretic measures, especially system entropy, have been used to quantify multiple dimensions of complexity linked to resilience observed in food webs, landscape structure and dynamics, and ecosystem processes [74–76]. Information-theoretic frameworks characterizing ecosystem development have been adapted to study ecological resilience and sustainability [55,77].

Identifying appropriate system structures and dynamics for measurement depends not only on the ES of interest, but also on the scales at which systems are delineated. This implies that properties quantified by resulting system models (e.g., complexity, adaptive capacity, resilience) are specific to these scales and ES scopes. Choices of scale for assessment connecting these system properties to ES include the scales at which people are strongly connected to ecosystems through interactions such as land and resource use and management, conservation, and recreation—the interactions around which ES are normally defined [7,53,78]. This suggests relatively broad landscape scales, and in the assessments that we reviewed, the frequent inclusion of spatially explicit analysis at broad landscape scales (Figure 4) also suggests that this general scale domain is of particular relevance.

These broad scales further suggest that system-level assessment requires a way to monitor ecosystem and landscape structures, processes, and change across large areas. Large-area monitoring should also maintain a capacity for ecologically nuanced evaluation of change at spatiotemporal scales commensurate with ES dynamics and management domains, a major challenge [38]. This is likely to rely in part on remote sensing technologies [79–81]. Historically, remote sensing-based change estimates have been limited to typologically and temporally coarse measures such as gross forest loss and gain at five- to ten-year intervals [14,27]. Richer characterization of vegetation productivity, disturbance, structure, phenology (the timing of biological changes), and other informative measures using remotely sensed data with frequent re-measurement intervals enhances ecosystem change modeling, but requires greater analytical investment [82,83]. Advances in this field are beyond the scope of this review, but we suggest that increasingly nuanced remote sensing-based observation of vegetation and land surface character, organization, and dynamics will continue to advance efforts to quantify ecosystem-level properties relevant for ES across large landscapes.

4.2. Connecting ES Science and Ecosystem Management

Ecosystem management strategies are often characterized by efforts to minimize risk while optimizing outcomes across multiple resources. When ES are analyzed individually, managers have the task of synthesizing varied assessments to evaluate management options (Figure 1), with little information about tradeoffs and interactions. Integrative assessment frameworks taking advantage of system and network analyses can help to cope with this complexity and to address ES and ecosystems together in an ecosystem management context.

In the assessments that we reviewed, discussions of forest ecosystem management activities such as prescribed burning, invasive species removal, and forest stand thinning were frequently framed around promoting system-level ecological properties such as resilience or ecological integrity. The importance of system-level properties was typically expressed in terms of their role in mitigating stressor impacts on a wide variety of specific ES. Often, these relationships with specific resources and stressors help to give definition to holistic ecosystem management goals which may otherwise appear vague [6,9].

Indeed, ecosystem management decisions are complex when a wide array of ES is at stake. Risk and vulnerability assessments for individual ES can be well-suited to inform single issue-focused management, but more complex decision-making involving multiple criteria can benefit from quantifying multiple ES as ecologically (or socio-ecologically)

linked phenomena [7,14,22]. For example, the Southern Forest Futures Project [84] undertook a variety of independent assessments of regionally important natural resources and ES, identified through stakeholder workshops. They used empirical models as well as forecasting under varied economic and ecological scenarios to provide context for future management options for particular ES. Continued work in this area could address how management options designed to promote one ES are likely to affect other ES, and how ecosystem management to promote system-level properties is likely to affect various ES.

Moreover, integrating management activities as drivers in system models provides a tool for adaptive management [3,10]. Management strategies may shift depending on continuous learning about the diverse responses of various ES to system change, including past management interventions. This is only possible when periodic assessment is geared towards detecting consequential system change, which implies that monitoring tools and system models with the appropriate sensitivities should be carefully matched to adaptive management goals [38,85].

Finally, analytical innovations that improve the management relevance of assessments are likely to succeed when they occur in the context of science–management engagement [15,86,87]. System models whose components are relevant and scaled to regional management priorities are unlikely to be arrived at without engagement from managers, and complex models are unlikely to be adopted as ecosystem management tools without engagement from researchers. The Landscape Conservation Cooperatives, including the ALCC, are an example of regional partnerships intended to create such dialogue [88]. The most significant achievement of the LCC Network may have been the development of research–management communities working across large landscapes and across institutional boundaries. Capacity for innovation in integrative assessment that is responsive to the needs of ecosystem management depends in part on the continued development of such communities.

5. Conclusions

We documented important differences between ES assessment theory and practice in our review of Appalachian ecological assessments. These differences suggest challenges and a future agenda for advancing regional ecological assessment for ecosystem management decision support. We found that the analysis of forest ecosystems and landscapes as complex, open systems affected by stressors and having functional links to all ES is well theorized, but also methodologically challenging and infrequently employed in regional ecological assessments. Linkages between ES and ecosystem processes, or indeed even explicit models for relationships among ES and stressors, were less common in assessments than expected, given their importance in risk and vulnerability analysis. Improving these analytical linkages will improve operational linkages between ecological assessment and ecosystem management. The relevance and impact of assessment also depends on science and management communities of practice working together to advance how ES sustainability is conceptualized and quantified. This will lead to an improved understanding of the capacity of ecosystems to adapt to novel conditions such as modern land use and climate change while continuing to provide valued benefits.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Regional environmental assessments included in our review for the Appalachian region.

Table A1. Regional and national assessments with direct relevance to the provisioning of forest-based ecosystem services and their stressors, even if explicit ecosystem service language was not used in assessment documents. Assessments encompassed either the Appalachian Landscape Conservation Cooperative (ALCC) region, which included significant parts of 15 states in the eastern United States, or at least one state within the ALCC. * Reports were available for 12 (state forest inventories) and 11 (state forest action plans) states partially or wholly in the ALCC region. We selected three representative states within each of these two assessment groups to include in our quantitative review of ecosystem service and stressor analyses (Figure 2). This reduced bias towards the approaches taken in these assessments, which were similar but not identical across states.

	Assessment Document	Institution/Agency	Regional Coverage	Reference
Federal agency	2013–2027 National Insect and Disease Forest Risk Assessment	USDA Forest Service	United States	[64]
	Assessment of Nontimber Forest Products in the United States Under Changing Conditions	USDA Forest Service	Coterminous US	[89]
	An Ecological Assessment of the US Mid-Atlantic Region: a Landscape Atlas	Environmental Protection Agency	Mid-Atlantic US	[39]
	Environmental Protection Agency's Report on the Environment	Environmental Protection Agency	Coterminous US	[90,91]
	Forests of the Northern United States (The Northern Forest Futures Project)	USDA Forest Service	Northeastern US	[92]
	Forests to Faucets	USDA Forest Service	Coterminous US	[61]
	Future of America's Forest and Rangelands: Forest Service Resources Planning Act Assessment	USDA Forest Service	United States	[2,93]
	National Report on Sustainable Forests (Montreal Process)	USDA Forest Service	United States	[68]
	The Southern Forest Futures Project	USDA Forest Service	Southeastern US	[84,94]
	State forest inventory: Individual reports for 12 Appalachian states. Pennsylvania, Indiana, and North Carolina included in quantitative review. *	USDA Forest Service	State-level, 12 states	[95–97]
State agency	State Forest Action Plans: Individual reports for 11 Appalachian states. Alabama, Ohio, and New York included in quantitative review. *	State forest resource agencies	State-level, 11 states	[98–100]
NGO	Assessing Future Energy Development Across the Appalachian Landscape Conservation Cooperative	The Nature Conservancy	Appalachian region	[65,66]
	Southern Forests for the Future	World Resources Institute	Southeastern US	[101]
Partnership: Federal, state, local agency, university, NGO	An Assessment of Natural Assets in the Appalachian Region: Forest Resources	Appalachian Regional Commission	Appalachian region	[69]
	An Assessment of Natural Assets in the Appalachian Region: Water Resources	Appalachian Regional Commission	Appalachian region	[102]
	Central Appalachians Forest Ecosystem Vulnerability Assessment and Synthesis: A Report from the Central Appalachians Climate Change Response Framework Project	Northern Institute of Applied Climate Science/USFS	Central Appalachians	[103]
	Central Hardwoods Ecosystem Vulnerability Assessment and Synthesis: A Report from the Central Hardwoods Climate Change Response Framework Project	Northern Institute of Applied Climate Science/USFS	US Central Hardwoods	[104]
	The Southern Appalachian Assessment	Southern Appalachian Man and the Biosphere	Southern Appalachians	[105]

Appendix B

Appalachian forest ecosystem services and large-scale stressors.

Table A2. The broad ES and stressor categories included here are not exhaustive but were represented in multiple regional assessments (Figure 2). The top half of the table intersects ES (columns) with stressors (rows); the bottom half of the table intersects additional ES with the same stressors. References include regional or national ecological assessments with findings specific to the region (Appendix A), supplemented by specific research within the Appalachian region.

Stressors	Ecosystem Services		References
	Water Quality, Hydrology, and Soils	Forest Carbon Storage	
Urbanization and fragmentation	Increasing urban land use coupled with forest and soil loss in landscapes with varied topography and steep slopes can exacerbate stream discharge rates, peak flow, and velocity. Increasing impervious surface and forest and soil loss typically result in reduced surface water availability for human use, and can increase stream sediment, nutrient, and pollutant concentrations.	Forest loss associated with urbanization results directly in reduced carbon storage capacity. These losses, together with similar effects of surface mining, may outstrip regional gains from forest growth, without significant changes in urban development policy, restoration efforts, timber markets, and other factors.	[2,39,90,92,94,106–113]
Energy development	Increased impervious surface cover and forest loss with gas well development can alter surface hydrology and reduce water availability and quality. Discharge from watersheds with mined sites commonly shows elevated dissolved solids and acidity, impairing aquatic biota. Negative effects can continue long after reclamation. Watersheds with mined land show elevated runoff, potentially elevating downstream flood peaks. Soil loss and compaction from surface mining and some reclamation practices can impede forest regeneration.	Forest losses associated with energy infrastructure development and surface mining are expected to result in reduced forest carbon storage. While the carbon storage potential of forest restoration on mined sites is high, successful forest restoration practices are not implemented on many to most sites, and some current practices may prevent significant new carbon sequestration. Carbon losses from future surface mining could outstrip regional carbon sequestration gains from existing forests.	[65,113–125]
Climate change	Impacts on water quality and availability vary sub-regionally, and depend on interactions with population growth and other factors. Mean temperature increases are likely to reduce water availability in some areas, with rural populations more affected than cities due to stronger reliance on ground water. Recent trends of increasing flood and drought frequency will likely continue. Effects of such events on streamflow depend on landscape vegetation composition and structure, soils, and impervious surface cover.	Impacts of climate change on forest carbon storage are likely to vary across landscapes, and interactions with other landscape dynamics add complexity. Rising temperatures can enhance forest growth and carbon storage, but this can be offset by drought impacts, and both of these effects depend on tree species composition. Changes in fire frequency due to temperature and precipitation changes will also modify carbon storage capacity, especially where wildland fire alters forest structure and cover.	[2,92,94,109,112,126–130]
Invasive species and forest pathogens	Species invasions and forest pathogen outbreaks can affect hydrology by changing forest vegetation structure and function. For example, widespread tree mortality in the Appalachians due to the invasive Hemlock wooly adelgid (<i>Adelges tsugae</i>) can temporarily increase stormflow peaks and cause long-term decline in total stream yield. Invasive plants can change soil properties, reduce nutrient and water availability for native plants, and negatively affect soil microbial communities.	Forest primary productivity can be strongly reduced in the short term after tree pathogen outbreaks, slowing carbon sequestration. A forest stand can switch from carbon sink to source under these conditions, but this can reverse over the long term as productivity recovers. Multiple outbreaks can reduce carbon sequestration and storage at landscape scales, but long-term impacts are not well understood. Increased frequency of extreme heat and drought with climate change increases forest pathogen outbreak likelihood.	[2,92,111,131–134]

Table A2. Cont.

Stressors	Ecosystem Services		References
	Water Quality, Hydrology, and Soils	Forest Carbon Storage	
Wildland fire	Intense wildland fires can increase streamflow, soil erosion, and stream sediment loads and alter soil and water chemistry in the short term. Appalachian forests have not shown large impacts of this kind, with impacts typically followed by rapid recovery. Impacts are more likely for intense fires after fuel buildup than for low-intensity, frequent-interval fire. Thus, fire suppression can increase likelihood of fire with negative impacts.	Wildland fire releases carbon dioxide into the atmosphere, while forest regrowth after fire captures and stores carbon over longer time scales. Thus, fire is one driver of forest carbon cycling. The overall contribution of fire regimes to long-term forest carbon balances is not well understood in eastern upland forests where fire is relatively infrequent.	[2,111,130,135–137]
Stressors	Ecosystem services		References
	Timber and nontimber forest products	Outdoor recreation and rural landscape values	
Urbanization and fragmentation	Urbanization and associated population increase, more pronounced in the southern than the northern Appalachians in recent decades, reduce the land area available to support working forests, and alter the dynamics of nontimber forest product harvest, fishing, and hunting in nearby forests. Absence of fish from degraded streams can cause loss of fishing opportunities.	Urbanization and low-density development can negatively impact the sense of place of rural Appalachian communities in forest- and agriculture-dominated landscapes. As rural landscapes and water supplies are converted to more intensive uses, outdoor recreation opportunities are expected to decline, even while population growth and urbanization place increased demand on nearby recreation sites.	[2,39,69,94,101,108,112,138–143]
Energy development	Surface mining—the largest driver of land cover change in the central Appalachian coalfield region—reduces land area available to support working forests. Loss of timber-related economic activity can result, particularly since some common reclamation efforts can impede forest recovery. At regional scales, timber stocks and production have remained fairly stable in recent decades, but declines may be experienced over the long term.	Infrastructure and forest fragmentation associated with gas wells, wind turbines, and surface mining will continue to impact central Appalachian landscapes. Associated forest loss, stream degradation, and biotic and aesthetic losses impact natural landscape character. Stream degradation and toxic dissolved solids in watersheds with surface mines are associated with lost fishing opportunity and reduced game fish abundance, fish biomass, and species diversity.	[120,121,123–125,139,144]
Climate change	Suitable habitat for harvested species may undergo geographic shifts. At the local level, expected declines in economically important species may not be fully compensated by increases in other harvested species. Climate change may interact locally with harvest pressure to increase declines, a risk posing special concern for many nontimber forest products that are not well monitored or regulated.	Climate change can impact sense of place and quality of life when rural economic activities and natural landscape character are affected. Broad ecological changes including endangerment of some unique Appalachian ecosystems can affect tourism, recreation, and long-term patterns of rural migration, as visitors and new residents seek out particular conditions.	[2,89,94,103,104,112,130,140,141,145–151]
Invasive species and forest pathogens	Forest tree pathogen outbreaks are one of the most important risk factors for harvested species. Associated changes in forest structure and composition can also reduce habitat quality for nontimber species such as harvested understory herbs. Invasive, non-native plants can reduce regeneration and productivity of economically valuable species. Impacts on harvested species can be exacerbated by facilitators of pathogen outbreaks or invasions including climate change, forest fragmentation, and fire.	Impacts of invasives and forest pathogens can detriment scenic and recreation values. Examples include tree mortality from balsam wooly adelgid (<i>Adelges piceae</i>) in southern Appalachian spruce–fir forests, which are prime tourism areas, and gypsy moth (<i>Lymantria dispar</i>) in northern oak forests. Economic and cultural losses for local communities can occur through a variety of impacts including loss of timber revenue, habitat loss for culturally important nontimber species, and loss of tourism income.	[2,69,89,92,94,101,141,151–153]

Table A2. Cont.

Stressors	Ecosystem services		References
	Timber and nontimber forest products	Outdoor recreation and rural landscape values	
Wildland fire	Wildland fire in eastern forests does not typically have strong negative impacts on timber productivity or quality. Historically, fire has helped maintain commercially valuable Appalachian forest types, including upland hardwoods. Fire suppression has resulted in declines of important species such as oaks (<i>Quercus</i> spp.), replaced by faster-growing species. Prescribed fire can help maintain upland fire-associated ecosystems that sustain harvested species.	People living near lands affected by uncontrolled fire may experience risk to lives and property, and health and safety risks from smoke and ash. Recently burned landscapes may be viewed negatively by recreationists and others seeking to enjoy forest landscapes, although aesthetically and ecologically desirable conditions can be enhanced by fire over the long term. Trade-offs in competing values and activities will be needed to ‘live with fire’ in fire-prone landscapes.	[94,101,130,136,152,154–157]

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