Assessing Interactions Among Changing Climate, Management, and Disturbance in Forests: A Macrosystems Approach

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Forests are experiencing simultaneous changes in climate, disturbance regimes, and management, all of which affect ecosystem function. Climate change is shifting ranges and altering forest productivity. Disturbance regimes are changing with the potential for novel interactions among disturbance types. In some areas, forest management practices are intensifying, whereas in other areas, lower-impact ecological methods are being used. Interactions among these changing factors are likely to alter ecosystem structure and function at regional to continental scales. A macrosystems approach is essential to assessing the broadscale impacts of these changes and quantify cross-scale interactions, emergent patterns, and feedbacks. A promising line of analysis is the assimilation of data with ecosystem models to scale processes to the macrosystem and generate projections based on alternative scenarios. Analyses of these projections can characterize the range of future variability in forest function and provide information to guide policy, industry, and science in a changing world.

Keywords: macrosystems, forestry, disturbance regimes, forest management, climate change, modeling
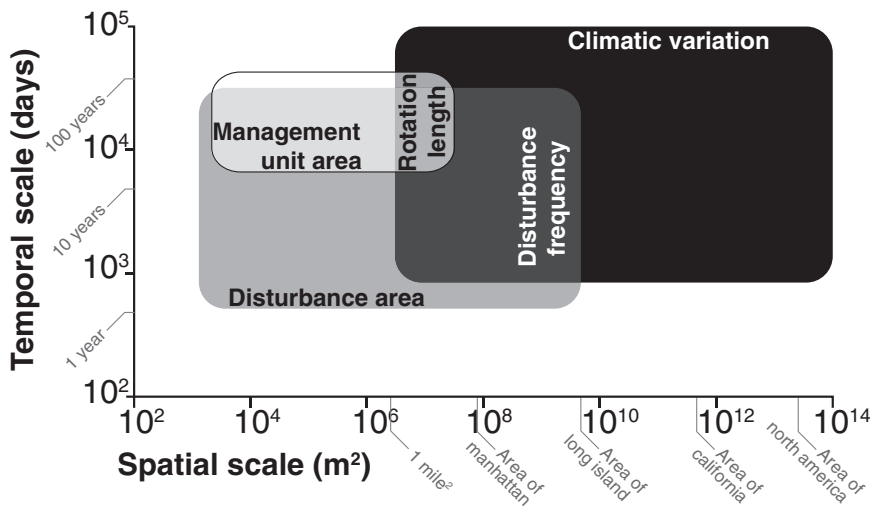
Forest management is a poorly understood factor in global change, especially at regional or larger scales. Forests account for 50% of terrestrial primary productivity, and all forests are managed to some extent. For example, close to 70% of North American forests have a management plan (FAO 2010). Management approaches are changing in these forests (Franklin et al. 2007, Wear and Greis 2013) alongside ongoing changes in climate and disturbance regimes. Consider the southeastern United States, where forest area has remained relatively unchanged over the past 60 years but where there has been a significant shift from naturally regenerated forests to pine plantations (figure 1). Management practices are becoming more intense in some areas (Allen et al. 2005) and changing to resemble natural disturbance processes in others (Franklin et al. 2007). These changes are occurring in response to changes in climate (D'Amato et al. 2011), disturbance regimes (Dale et al. 2001), policy (Law and Harmon 2011), economics (Davis et al. 2009), and scientific understanding. Climate change is leading to new levels of species turnover (Zhu et al. 2014), range shifts (Harsch et al. 2009), changes in forest productivity

(Boisvenue and Running 2006), and an increased interest in using forests for climate change mitigation (Maness TC 2009). Disturbances such as drought, fire, and pest infestations are changing in frequency and intensity because of alterations in climate and human activities (Dale et al. 2001). Complex interactions among these factors are driving new studies across a variety of research foci, but left unaddressed is the question of what the net effects are of interactions among changes in climate, disturbance regimes, and forest management on forest ecosystem function at regional to continental scales.

Assessing changes to forest ecosystems from these factors at broad spatial and temporal scales is crucial, because it is at these scales that climate, disturbance, and forest management processes intersect (figure 2). Broadscale climate changes have the potential to alter finer-scale ecological and biogeochemical processes in forests, which could, in turn, feed back to the climate system (Bonan 2008). Plot-level studies are likely to miss such cross-scale interactions, or their results may not apply to broader scales because of nonlinear scaling or emergent properties. Furthermore,
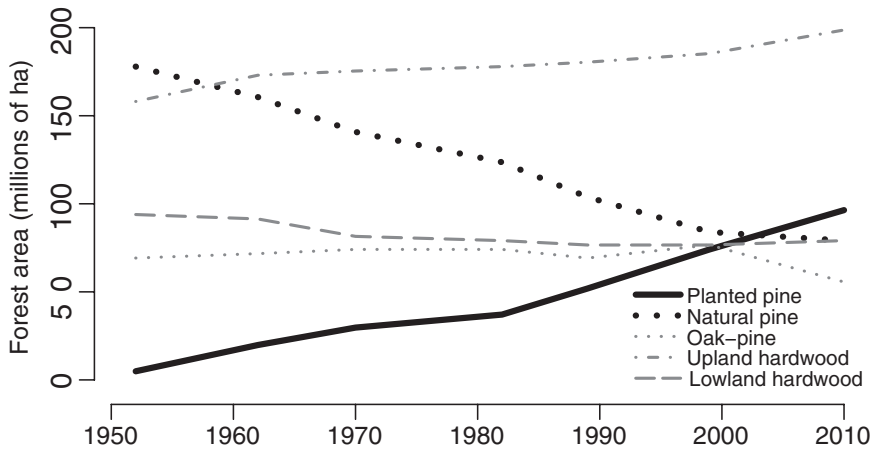
Figure 1. Change in area of forest management types in the southeast United States from 1950 to 2010. Although overall forested area was relatively stable, the area of planted pine increased to over 96 million hectares (ha). In that same period, naturally regenerating pine forest has lost close to 100 million ha. Adapted from Wear and Greis (2013).

Figure 2. Stommel diagram of overlapping spatial and temporal scales of climate variation, disturbance regimes, and forest management. The large area of overlap implies a high likelihood of cross-scale interactions among components of these factors. Abbreviation: m^2, square meters.

forest management methods maintain or increase forest productivity or carbon storage? Will these changes enhance or hurt the forest products industry and have cascading economic effects at state, regional, and national scales? Without a broadscale assessment of forest changes and the interactions among them, such questions cannot be answered.

Addressing questions about the effects of changes in climate, disturbance regimes, and forest management requires a macrosystems ecology approach to characterize interacting ecological, social, and climate phenomena at multiple spatial and temporal scales (Heffernan et al. 2014). Macrosystems ecology aims to understand patterns and processes at regional to continental scales by including biological, geophysical, and social components in analyses of cross-scale interactions, emergent patterns, feedbacks, and teleconnections (Soranno et al. 2014, Heffernan et al. 2014). For example, ecosystem models may be used to combine plot and landscape-scale measurements of forest processes from ecological observation networks with remote-sensing data to quantify and characterize interactions among factors and make predictions at broader scales. Here, we explore a macrosystems approach to evaluate interactions among factors involved in broadscale forest change. Our objectives are to review and synthesize the current and predicted changes in climate, disturbance regimes, and forest management; to discuss how research that crosses scales in time and space can improve our understanding of the role of management in forest ecology; and to explore a macrosystems ecology approach to assessing and projecting the interactive effects of these changes on ecosystem processes at regional to continental scales.

understanding these processes and interactions at regional to continental scales allows scientific studies to better inform strategic planning and policy decisions that are made by governance institutions at state, regional, and national levels. At these scales, important questions include the following: Will North American forests as they are currently managed be a net sink of carbon in the future? Will changing disturbance regimes in forests under current management practices lead to positive feedbacks and further climate change? How will social demands for ecosystem services affect future forest management? Can the adoption of ecological

Converging changes in climate, forest management, and disturbance regimes

Climate, forest management, and disturbances are made up of dynamic processes that change and interact with one another across multiple spatial and temporal scales. Forest management practices vary in intensity, spatial extent, and frequency, each of which mediates management impacts on forest ecosystem properties, processes, and a variety of

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Box 1. Forest management functional types.

Production forestry seeks efficient production of wood and wood products using agronomic models but constrained by current economic criteria (i.e., return on investment). This typically means short rotations of even-aged, single-species plantations that are clear-cut at harvest. Structural complexity and spatial heterogeneity are minimized in pursuit of this goal, greatly reducing the forest's ability to provide habitat for biodiversity and sustain other functions, such as watershed protection.

Ecological forestry uses principles from natural forest ecosystems in developing forest practices that contribute to sustaining all ecological functions, including the provision of habitat for biological diversity. For example, it uses harvest practices that are similar to those created by natural disturbances (Franklin et al. 2007). These natural-process-simulating management practices often vary regionally with the local disturbance regime (e.g., prescribed burns in regions with naturally high fire frequencies). Compared with production forestry, forests under ecological forestry management have higher species diversity and greater structural complexity (Franklin et al. 2007).

Preservation management maintains a forest ecosystem in some baseline state to preserve species, ecosystem services, recreation, and aesthetic value. These forests are not harvested, though they may have been in the past. Although the goal of preservation is to maintain an ecosystem in some historic state, other priorities often limit managers' abilities to do so, especially with respect to restoring historic disturbance regimes. For example, adjacency to human settlements may require fire suppression.

Passive management involves regular timber extraction of valuable species with little or no management between harvests (Carey 2006). This includes many nonindustrial private forests that have been completely or selectively harvested in the past and were allowed to spontaneously regenerate. These lands may have no current use or may be used for hunting and other recreation activities. Passively managed forests contain the legacies of both past timber harvests and their altered disturbance regimes, including greater structural complexity than production forests and higher densities of nonnative or ruderal species.

ecosystem services (box 1, figure 3; Dale et al. 2001, Kurz et al. 2008). Climate change is altering forest ecosystems with novel combinations of temperature and precipitation and with altered disturbance regimes, all of which can affect the composition, productivity, and resilience of these systems (Scheller and Mladenoff 2005, Boisvenue and Running 2006, Johnstone et al. 2010). Moreover, the direct effects of management interact with changes in both climate (Scheller and Mladenoff 2005) and disturbance regimes (Mitchell et al. 2014); therefore, these factors should be considered together to understand their cumulative effects (figure 4).

Climate and forests. Climate and forest ecosystems are interconnected and affect each other in multiple ways, with both positive and negative feedbacks (Bonan 2008). Rising greenhouse gas concentrations and the associated climate change are likely to continue for the coming decades, affecting the extent, composition, structure, and productivity of forests and the services they provide (IPCC 2013). Changes in temperature and precipitation are likely to affect forest composition (Harsch et al. 2009, Mann et al. 2012). Elevated levels of carbon dioxide may increase growth rates and overall productivity, although the long-term effects are uncertain (Norby et al. 2010). These ecological changes have direct and indirect feedbacks on the climate system, through changes in albedo, energy balance, water balance, and carbon exchange (Bonan 2008). For example, at broader spatial scales, the impacts of changes in forest cover on albedo and evapotranspiration may have a stronger effect on climate dynamics than changes in carbon cycling (Bala et al. 2007). These changes and feedbacks are complicated by simultaneously changing disturbance regimes and management practices, which can affect the extent and direction of changes in forest processes and structure (figure 4).

Forest management. Forest management is influenced by a variety of factors, including ecological conditions, economic trends, policies, and social priorities. In response to those factors, forest management practices are changing variably across landscapes and jurisdictions. In some areas, forestry practices and timber harvests are becoming more intense to maximize return on investment in wood products. In other areas, forest management methods are shifting to more closely resemble natural disturbances to meet a variety of goals, including ecological restoration and the production of forest products while sustaining ecosystem services.

The intensification of forest management practices is occurring on private lands across the country where the primary goal is the production of wood products. In the southeastern United States, for example, where 90% of forested lands are in private ownership, the area of naturally regenerated pine has declined, whereas planted pine forest, mostly managed through production forestry, has grown in the past 60 years and is expected to continue growing (figure 1; Wear and Murray 2004, Wear and Greis 2013). The intensification of production forestry methods places greater emphasis on practices that accelerate stand development such as fertilization (Coyle et al. 2008), herbicide use (Sartori et al. 2007), and the introduction of genetically improved tree varieties (Fox et al. 2007).

Further changes are likely in the future with the establishment of short-rotation plantation forests to feed biomass
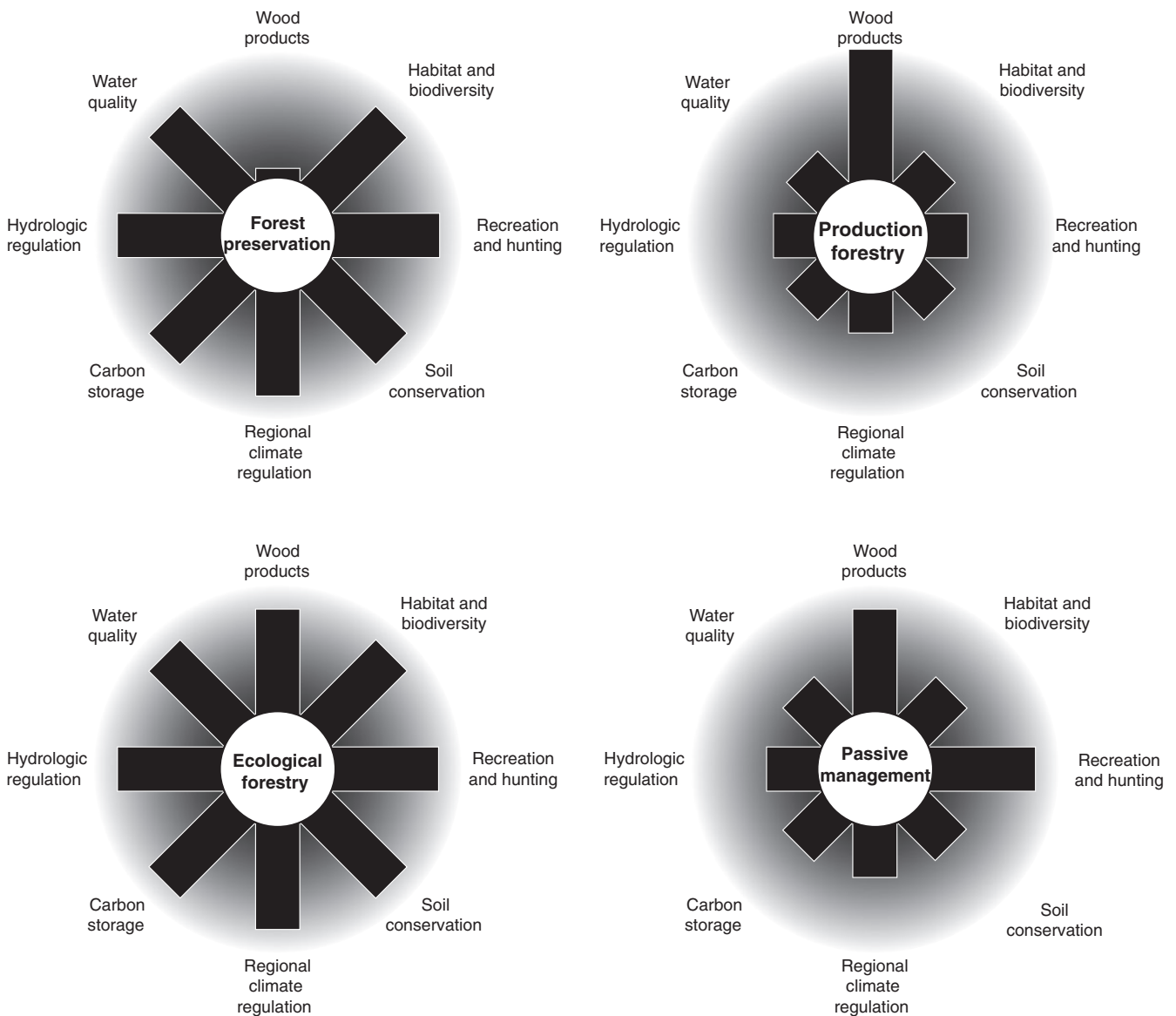
Figure 3. Hypothesized values for the balance of services provided by different forest management functional types. Production forestry maximizes wood product production while sacrificing other ecosystem services, preservation management produces no wood products, and ecological forestry aims to balance all forest ecosystem services.

energy production (Munsell and Fox 2010), changes in land ownership patterns, and market changes within the wood products industry (Wear and Greis 2013). For example, urbanization and land-use change from forest to low-density residential lands are expected to be larger factors in southeast forest change than timber market changes (Wear and Greis 2013). The nature of institutional ownership will also affect harvest rates and forest composition on private lands using production forestry. As a result of changes in tax policy and investment preferences, virtually all industrial timberlands in the United States have been converted to investor ownership over the past 15 years (Zhang et al. 2012). This includes real estate investment trusts (REITs) and timberland investment management organizations (TIMOs). Management

on lands owned by TIMOs and REITs in the southeastern United States involves more frequent harvests and a preference for planting softwood species than deos management on other privately owned forestlands (Zhang et al. 2012).

Changes in social priorities and public policy alter how forests are managed and affect the amount of timber slated for harvest on public lands. Many public forestland managers are increasingly turning to ecological forestry methods that allow continued timber production with practices that resemble natural disturbance regimes and maintain many of the ecosystem services marginalized or eliminated with more intense silvicultural practices (Franklin et al. 2007, Mitchell et al. 2009). These methods include the use of uneven-aged stands (Hanson et al. 2012), variable density
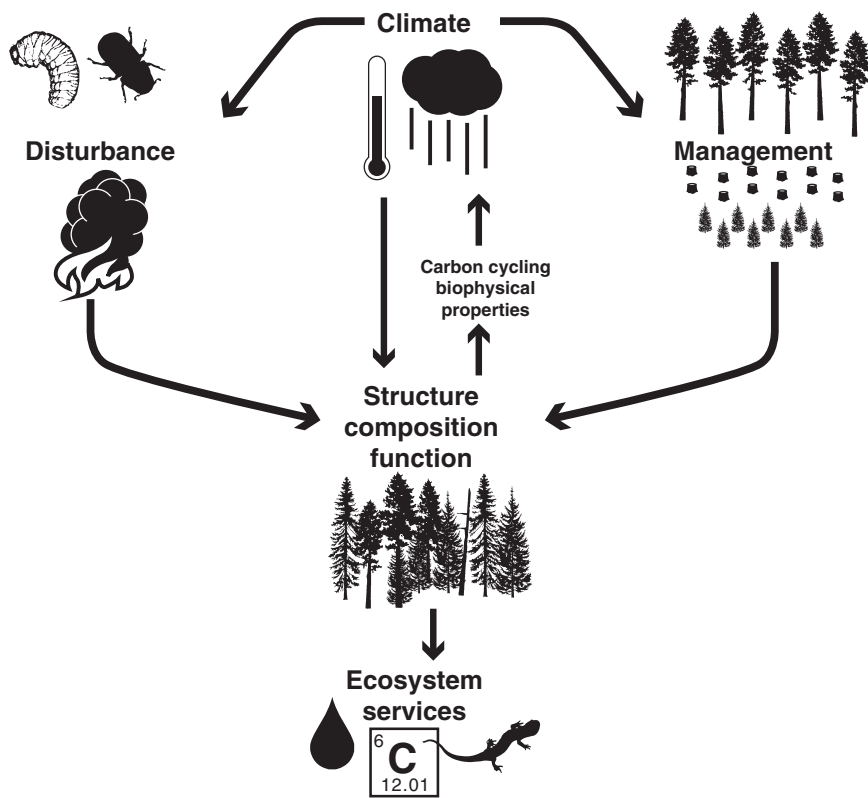
Figure 4. Interactions among climate change, forest management, and various disturbances. Climate has direct effects on disturbance regimes and forest structure, composition, and function while also affecting forest management practices and goals. Disturbance and management affect forest structure, composition, and function, which, in turn, control ecosystem services such as water resources, carbon uptake and storage, and wildlife habitat.

manage for and adjustments to forest management practices (Keskitalo 2011). Managers must also respond to the new economic and sociocultural status of forests as climate change mitigation tools (D'Amato et al. 2011). If forests were to be used as part of a national climate change mitigation strategy, forest managers would have to consider managing forests on the basis of their utility as carbon sinks and for the provision of wood products, both for energy production and as substitutes for more fossil fuel–intensive products (Malmsheimer et al. 2011). The rate and direction of economic growth and the degree to which wood biomass energy projects are established have the potential to alter forest carbon stocks at the national level (Nepal et al. 2012). Collectively, these changes in forest management could potentially alter forest function at broad scales, but the broadscale effects of these changes have yet to be quantified.

Changes in forest management are important because of their implications for many ecological processes, including carbon cycle dynamics, hydrology (e.g., water use via evapotranspiration), nutrient retention, and the maintenance of habitat for biodiversity and rare species. In the short term, forest plantations have faster rates of carbon dioxide uptake than do naturally regenerating forests (Powell et al. 2008); however, the carbon losses from frequent harvests mean that shorter rotation times (i.e., the periods between harvests) lead to reduced carbon storage (Harmon et al. 2009). Evidence from mesic interior Douglas fir (*Pseudotsuga menziesii*) forests shows that longer rotations and the retention of some trees at the time of harvest can significantly increase carbon storage, much more so than increasing growth rates in short-rotation plantations through genetic improvements or fertilization (Man et al. 2013).

Groundwater projections also often do not consider differences in forest management, even though important management characteristics such as rotation length, basal area, genetic improvements, and stand structure can all affect water yields (McLaughlin et al. 2013). Lower-density plantings likely have lower evapotranspiration rates and lead to greater water storage (McLaughlin et al. 2013). Therefore, continuing the introductions of fast-growing, genetically improved varieties (McKeand et al. 2003) will likely lead to further changes in regional hydrology and potentially to lower levels of water storage and yield. In addition, ecological forest management practices increase overall native biodiversity and habitat for rare species by maintaining the

thinning (Pukkala et al. 2011), variable retention harvesting (Franklin et al. 2007), and prescribed fire (Mitchell et al. 2009).

Forest management on federal lands is strongly impacted by social preferences and policy changes. For instance, the 2012 regulations under the National Forest Management Act prioritize ecological restoration and the maintenance of ecological integrity as two of the primary goals of national forest management (77 Federal Register 21162). On federal lands, timber harvest dropped by 85% between 1988 and 1995, in large part because of wildlife conservation policy changes and other economic influences, and timber harvest rates remain at these lowered levels today (Wear and Murray 2004, Thomas et al. 2006). Although some lands are still managed for timber production, the timber harvest in several US Forest Service regions today is aimed largely at affecting fire behavior for community protection or ecological restoration (Schultz et al. 2012).

Forest management is also changing in response to current and future climate change (D'Amato et al. 2011). Forest managers adapt to changes in temperature, water availability, and disturbance regimes through a variety of management changes, including changing the species and varieties they

stand structural complexity and diversity of forest age classes that are necessary to sustain a habitat for the full array of native species (Fischer et al. 2006).

Management practices also affect how forests respond to changes in disturbance regimes. Different harvest philosophies (individual tree selection to clear-cutting) can have contrasting effects on the remaining individuals and forested area at broader scales. Across the range of harvest practices, stand thinning has been shown to increase drought resilience (D'Amato et al. 2013), to affect the severity of wind damage (Scott and Mitchell 2005), and to change the landscape-level impacts of fires (Gustafson et al. 2004). Management and disturbance regimes vary within and among regions, and their interactions will likely vary as well. This fact underscores the need for cross-region assessments of these factors that capture both the within-region heterogeneity and the region-wide effects on carbon cycling and other climate relevant processes.

Disturbance. Disturbance regimes can be dramatically altered by climate change, which can lead to subsequent shifts in ecosystem function (Dale et al. 2001). Furthermore, feedbacks exist among disturbances such that one type of disturbance can alter forest structure and create conditions that facilitate the development of other disturbances, such as interactions among drought, bark beetles, and fire (Simard et al. 2012). This means that differences in management or climate that affect one type of disturbance can indirectly influence the frequency or severity of other disturbances (Jactel et al. 2012). Disturbances, such as fires or insect outbreaks, can force managers to compromise long-term management goals for a short-term disturbance response because of limited budgets and the primacy of short-term ecological, social, and political priorities. These feedbacks and indirect effects highlight the need for an approach that simultaneously assesses the effects of multiple disturbances along with climate and management.

Fire is a leading disturbance for many forests, especially in western North America. Numerous studies have predicted significant alterations in fire regimes with the current and future climate warming across forests of North America (Westerling et al. 2011, Mitchell et al. 2014). Fire seasons are predicted to lengthen, whereas fire rotations may shorten (Westerling et al. 2011). Exacerbating the issue is the prediction of increased drought frequency, which could, in turn, affect fire frequency and intensity, as well as the ability of resource managers to use prescribed burns to lessen the intensity of wildfire (Mitchell et al. 2014). Fire-adapted forests may lose their resilience because of these complex interactions, which could result in forests shifting to new states (Johnstone et al. 2010).

A number of weather factors influence disturbance characteristics. Drought stress and damage from insect or fungal pathogens may exacerbate each other causing growth loss and mortality (Jactel et al. 2012). Interactions with other weather related disturbances are less predictable.

Windstorms, ice storms, and landslides are likely to interact with other disturbances, and their impacts may be influenced by management practices. For example, ice storm damage can leave forests more susceptible to pests such as southern pine beetle by weakening trees and creating breeding sites (Bragg et al. 2003). These weather-related disturbances are likely to increase in frequency and intensity with climate change (IPCC 2013), but the ultimate effects of combined interacting disturbances are difficult to predict.

Climate warming is increasing the range and impact of insects and pathogens that damage forests, and their effects on the carbon cycle are on the same order of magnitude as fire (Hicke et al. 2012). Increases in insect outbreaks such as the mountain pine beetle (*Dendroctonus ponderosae*) can reduce forest net primary productivity (Kurz et al. 2008), affect fire patterns (Simard et al. 2012), and alter the biophysical impacts of the forest on climate (Maness H et al. 2012). Interactions between insect outbreaks and droughts have also been observed in several ecosystems (Jactel et al. 2012). However, the extent of these impacts may depend on the temporal and spatial scales at which they are analyzed. For example, in British Columbia, the mountain pine beetle outbreak is estimated to release 270 megatons of carbon (36 grams of carbon per square meter per year on average over 374,000 square kilometers of forest for 20 years; Kurz et al. 2008), but stand-scale observations suggest that the impacts will not be as severe (e.g., Brown et al. 2010).

Interactions among climate, disturbance, and management practices. The direct effects of climate on these disturbances, together with the indirect effects of interactions among climate, disturbances, and management practices suggest a complicated picture: three interacting factors, each with components and drivers occurring at different spatiotemporal scales, all of which are changing at different rates, with feedbacks within and among them. We can also expect changes in forest area and management in response to sociocultural factors, such as land-use change, market prices for land and timber, and policy changes. A reductive approach that views one of these factors changing in isolation from the others may provide important information about that factor but will likely (perhaps inevitably) miss interactions that a comprehensive approach would capture. This comprehensive approach must be able to consider the important biological, geophysical, and sociocultural processes occurring at multiple spatiotemporal scales, their interactions within and across scales, feedbacks, and the possibility of emergent patterns. To increase feasibility, this broad view could be used to isolate the crucial factors, feedbacks, and interactions at the scales most useful for analysis.

Scale

The multiscale nature of interactions among climate, forest management, and disturbance (figure 2) makes the issue of scale central to any question we might ask. The wide range of scales at which these processes occur and the heterogeneity within systems lead to scale mismatches among ecosystem
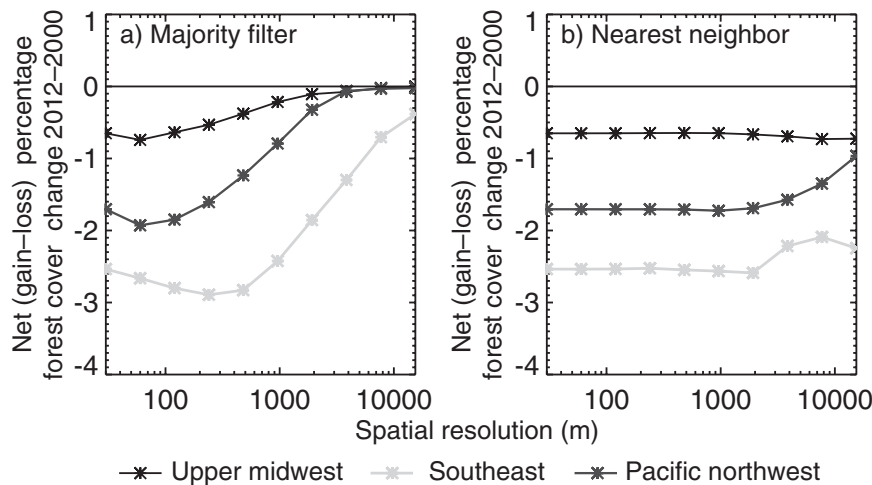
Figure 5. Relative net change (gain minus loss) of forest cover between 2000 and 2012 for three US regions as a function of averaging scale and choice of averaging filter. Scale dependency is a function of region, reflecting differing scales of management and disturbance, and also averaging filter (majority versus nearest neighbor), reflecting the influence of scaling methodology. In all three regions, a nearest neighbor approach better preserves the net change rates of the highest resolution. The original data were derived from the 30-meter-resolution Landsat forest change analysis of Hansen and colleagues (2013).

processes, properties, and their measurement. Forest disturbances can occur across a wide range of scales, from the region (e.g., hurricanes) to individual trees (e.g., forest gaps). Even in large disturbances, there can be substantial heterogeneity down to the individual tree scale (or smaller), and demographic responses fundamentally occur at the individual level (Clark et al. 2011). Similarly, although we are frequently interested in the regional response of ecosystems to climate change, such as range shifts, the observed regional response is actually the result of fine-scale individual responses to weather, not species responses to climate (Clark et al. 2011). Furthermore, the varying size of management areas creates a mosaic of different management practices overlaid on finer-scale patterns such as soil variation and broadscale patterns such as disturbance regimes and climate. These factors combine to create differences in forest structure and composition and ultimately affect responses to changes occurring at broader scales (figure 4).

The combined effects of processes operating at different scales and spatial heterogeneity create several issues requiring attention in the study of changing climate, forest management, and disturbance regimes. These issues include representing subcell heterogeneity in Earth system models and analyzing data collected at different scales. Earth system models must specify how subgrid variability influences the whole grid cell, and this is typically done by representing the probability distribution of such processes. These probability distributions are typically approximated analytically, statistically, or through discretization (Dietze and Latimer 2012). These approximations are *spatially implicit*, meaning that the explicit spatial location of these different areas is not

tracked and, therefore, the behavior of the aggregate grid cell is strictly the linear combination of the dynamics within the subgrid fractions. Nonetheless, the net response is frequently nonlinear, in the sense that the mean across such heterogeneity diverges from the response to the mean of the heterogeneity (i.e., Jensen's inequality). This is due to ecosystems responding nonlinearly to both the underlying environmental heterogeneity and having heterogeneous responses to larger-scale forcing (e.g., climate).

Where genuinely spatial dynamics are important (e.g., dispersal or contagious disturbances such as fire and insects), spatially implicit approximations will be inadequate. Although many such parameterizations have been shown to be scale dependent, it is not known whether the subgrid variability in forest management and its influence on carbon cycle, hydrology, and vegetation dynamics is scale dependent or whether these processes scale linearly or with a known distribution. This is not just a question about approximations in models but is a fundamental question about the relative importance of truly spatial interactions versus heterogeneity in contributing to the variability we see in ecological systems.

The need for combining data from different scales adds challenges, because the choice of scaling methods can produce different results (Hall et al. 2015). For example, with respect to increasing the grain size of forest change data, the choice of averaging filter can alter the regional sum of forest loss, and this difference varies among regions (figure 5). The development of quantitative scaling approaches is an area of active research; the crux of the issue lies in the variable information content at different resolutions driven by the subpixel heterogeneity of the process of interest (Stoy et al. 2009). One approach is to use functional relationships to map data from one source at a given resolution to another different resolution (Asner et al. 2010). This general approach of mapping data to a common resolution, in which one data source is assumed to be known with little or no uncertainty, is relatively common; however, this may be a tenuous assumption. Aggregating to coarser resolutions can mask subpixel heterogeneity; however, in some instances, this can be accommodated in the error structure of a data model in a hierarchical modeling context. Analyses that explicitly account for uncertainty in the data, driven by varying resolution, can yield greater certainty with respect to parameter estimation (Calder et al 2003). In the statistics literature, this is known as the *change of support* problem, and a number of new approaches exist that have seen limited application in the ecological literature (Gotway Crawford and Young 2004).

The macrosystems ecology approach

Ultimately, to better predict how changes in climate, disturbance regimes, and management practices influence the functioning of ecosystems, a cross-scale data synthesis is necessary. Through the combination of ecological monitoring networks, remote-sensing information, field studies, and ecosystem models, cross-scale interactions among changing drivers of future forests can be evaluated. Ecological monitoring networks serve as the basis for understanding interactions in a variety of ecosystems and provide data both to parameterize ecosystem models and to evaluate their output. Remote sensing can provide data to characterize patterns in forest disturbance and management across space and time and the means by which measurements of processes can be scaled to the regional or continental scale. Ecological models provide the ability to scale up measurements and assess the simultaneous effects of future scenarios of climate, disturbance regimes, and management practices on forest ecosystems. Moreover, models can be run at broad scales, allowing for the combination of these factors at the scales at which cross-scale interactions among multiple connected ecosystems can be detected.

We can combine these tools to evaluate combined scenarios of climate, management, and disturbance that span the range of future possibilities. These results could provide projections of forests in the future, important insights into interactions among these factors, and information about where gaps in our understanding lie, all of which could feed back to inform the management and design of monitoring networks and future ecological experiments.

Ecological monitoring networks. The development of continental (or global) ecological monitoring networks is a promising tool for understanding complex, broadscale problems. These networks provide data on a variety of ecosystems across the continent, ideally with consistent measurement protocols, instrumentation, data formats, and cyberinfrastructure. The Long Term Ecological Research (LTER) Network has more than 20 sites in North America and includes long-term ecological experiments and observations, many of which predate the existence of the network and possess decades of data; however, each site functions independently, with its own goals and methods of data collection. FLUXNET is a global network of over 600 sites using the eddy covariance technique to measure trace gas, water vapor, and sensible heat flux, although the equipment and data processing methodology varies to some extent. By contrast, the newly established National Ecological Observatory Network (NEON) promises to deliver fully standardized data across the United States, with a long list of ecological and biogeochemical variables collected with standardized methods and equipment (Keller et al. 2008). A growing group of networks are less formal but use distributed, standardized data collection; these include the Nutrient Network (*www.nutnet.umn.edu*) and the Smithsonian Center for Tropical Forest Science plots (*www.ctfs.si.edu*). Large, standardized data sets such as

the National Forest Inventory and Analysis program and a variety of coordinated distributed experiments can also contribute to macrosystems projects (Fraser et al. 2013).

Research networks such as these form the core of macrosystems assessments and projections, because they are the primary source of standardized data collected in a consistent manner across all major ecosystems of North America. A primary need for supporting a macrosystem approach is the synthesis of open data across these networks in machine-readable formats (Peters et al. 2014). The extent to which this already occurs among the observation networks varies, and a consensus on common protocols for ecological databases is lacking. Achieving this goal would greatly improve macrosystems analyses and empower researchers to answer new and more complicated questions faster (Peters et al. 2014).

Remote sensing. Satellite and airborne sensing technologies can be used to monitor forest processes at regional scales, map forest disturbances and management practices, and scale up plot-scale measurements of forest processes. The utility of these data sets is growing as new analysis methods are established and the data from long-term remote-sensing programs continue to accumulate. These include widely used systems such as Landsat and high frequency data such as MODIS, Suomi-NPP, NPOESS, and GOES-R. The Landsat program has more than 30 years of data in North America at a 15–30-meters spatial resolution and MODIS has more than 10 years of high temporal frequency data at a 250–1000-meter spatial resolution. All of these systems have been widely used to make broadscale measurements of biological processes (e.g., net primary production) and forest disturbances (e.g., wildfire, drought, and insect infestations). Now that these systems can supply a long time series (Masek et al. 2006), they are becoming more useful for monitoring disturbance frequencies in forests (Kennedy et al. 2010) and could potentially aid in delineating forest management practices or mapping the forest structure that these management practices create. Forest harvest intervals may be detected if the length of the time series is longer than the average harvest interval. Specific management practices such as harvests, plantings, thinning, and prescribed burns may be optically detectable if imaging occurs shortly after they occur or through active remote sensing of forest structure using LIDAR or radar. The utility of these data sets continues to grow as more observations are collected and more methods for using these data are developed.

Ecosystem modeling. Computational simulations of the Earth system have the ability to represent the dynamics of energy, water, and element cycles in terrestrial ecosystems over spatial and temporal scales that are difficult to achieve through observation and experimentation. Models are common tools for the projection of long-term ecosystem functions in response to climate change, changes in atmospheric carbon dioxide, nutrient addition, disturbance, and even changes in

management (Moorcroft 2006). Although ecosystem models can test hypotheses across multiple spatiotemporal scales and incorporate data from diverse sources, many models have yet to incorporate forest management and disturbances realistically.

Simulations could be used to evaluate different management practices and how they might interact with the effects of changing climate (Ravenscroft et al. 2010). Questions of scale can be explicitly tested in models (Turner et al. 1993), and through model–data fusion, models can also serve as the scaffold for data synthesis (Dietze et al. 2013). Similarly, data assimilation and experiments that simulate ecological observing systems can be conducted to test the fidelity of the existing observation networks and identify locations for targeted additional observations of forest, climate, disturbance, and management processes.

There is a wide variety of forest models, from simple stand models of yield to global models of forest productivity. Although most of these models have incorporated forest responses to climate variables (temperature, precipitation, solar radiation, and atmospheric carbon dioxide concentrations), few have incorporated a wide range of forest disturbance, and most do not account for forest management practices. Primarily, disturbance is treated as a stochastic or probabilistic, stand-clearing process, with fixed fractions of biomass added to litter or released to the atmosphere, the latter sometimes depending on the type of disturbance, such as a fire or windstorm (Gustafson et al. 2004, Scheller and Mladenoff 2005). This approach ignores many forms of disturbance including pests and less destructive but ecologically important disturbances such as low-intensity fires.

Although detailed forest management models exist at the stand scale, most larger-scale models at most specify anthropogenic land clearing and probability matrices for land-use change. Forest management has been added to some models, but few represent the range of basic practices commonly used (e.g., prescribed fire or thinning). These approaches ignore many potentially ecologically important forest management practices, including thinning, planting, retention harvesting, prescribed fires, and herbicide use.

Specifically, we argue that the development of management functional types as conceptualized in box 1 could be a path forward to evolving these models to realistically incorporate and run scenarios of management practices. This approach could compare different relative abundances of management functional types but would miss possible feedbacks between forests and social factors that affect the relative abundance of management functional types. These factors might include wood product markets, policy changes, public perceptions, demographics, and land prices. To capture interactions among these and ecological or management factors, a more complex coupled ecological–social modeling system could be used. Another approach could include developing dynamic scenarios of management and forest cover based on ongoing research and existing knowledge. These dynamic scenarios would be reassessed and altered at regular time steps to reflect feedbacks from changing ecological conditions to the social factors that affect forest area and management.

Several fundamental questions must be answered for the credible incorporation of management and disturbance processes into forest ecosystems models. Because models with the most detailed representations of management and disturbance operate at the finest spatial scales, there are fundamental informational and computational limitations to incorporating detail into a broadscale model. Two questions of crucial importance are what level of detail of human decision making, biomass removals, soil disturbance, corridor creation, and harvest canopy structure is required to incorporate management and disturbance into models at the macrosystems scale and what data are needed to support these projections. Without these, the more interesting hypotheses on how management practices interact with disturbance and potentially lead to cross-scale interactions in ecosystem services (carbon storage, hydrologic regime changes, species successional trajectories, habitat) remain untestable.

For example, low-intensity prescribed fire, which is used as a management tool in frequent-fire southeastern forests, has varying ecological effects depending on the composition and quantities of fuels (Mitchell et al. 2009). Which elements and relationships in these processes must be included in models in order to effectively model their cumulative effects at broad scales? Models can be used to answer such questions by serving as incubators for testing new model formulations, parameters, and responses. Sensitivity analyses can be applied to determine which processes are important at which scales and which processes can be effectively ignored. These issues need to be bridged for us to be able to examine the multiple disturbance types and management methods occurring in a mosaic of different forest types across a region while minimizing computational effort and excessive parameterization requirements.

Conclusions

Simultaneous changes in climate, disturbance regimes, and forest management lead to great uncertainty about the structure and function of forests in the future. To develop policy and management strategies for the future, we must be able to predict the possible future trajectories of forest composition and function at broad scales. This macrosystems understanding is crucial to informing policymakers about the status of forest ecosystems at regional and continental scales.

This macrosystems approach allows for the design of policies to achieve societal goals, which focus on maintaining and providing multiple ecosystem services across spatiotemporal scales. The results from these analyses would support forest stakeholders in understanding the contribution of forest ecosystems to ecosystem services of interest and advocating for forest management according to their priorities; public forest managers in determining whether management actions are having an impact on ecosystem structure and function at scales that are relevant to the factor

Box 2. Recommendations.

Standardization of data formatting and metadata in observational networks.

Observational network synthesis of disturbance and management processes and identification of these processes across time and space.

A redefinition of forest management into a set of functional types for ecosystem models.

Incorporation of forest management and disturbance into models at the macroscale.

of interest; complying with administrative requirements to conduct monitoring and assessment at multiple scales (e.g., specific multiscale monitoring requirements in the 2012 National Forest Management Act regulations [77 Federal Register 21162]); and contributing to international monitoring protocols, which require data on conditions and trends on both public and private lands (Floyd et al. 2001). Private landowners would benefit from such information when they are participating in forest certification processes or are subject to legal requirements. Understanding the possible range of future conditions could also direct social science researchers toward investigating the factors that could play the most significant roles in changing forest management practices and priorities.

We now have the tools to answer questions that are important to local and global climate change, the forest industry, and the ecological integrity of forests in general. However, several important steps need to be taken before these questions can be answered (box 2). Through remote sensing, we can detect how forests are being managed currently and evaluate future management scenarios. We can also detect current forest disturbance regimes and incorporate possible interactions among disturbances into simulations. We can model these systems at regional and continental scales at which the results will be relevant for climate studies and for policy and economic interests. The goal is to identify unexpected patterns and processes occurring from a nexus of climate variation, disturbance regime shifts, and management responses to provide credible projections to guide policy, industry, and science by highlighting interactions that might have significant consequences. Furthermore, examining these questions at the broad scale will highlight areas that need more study and experimentation at the fine scale.

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