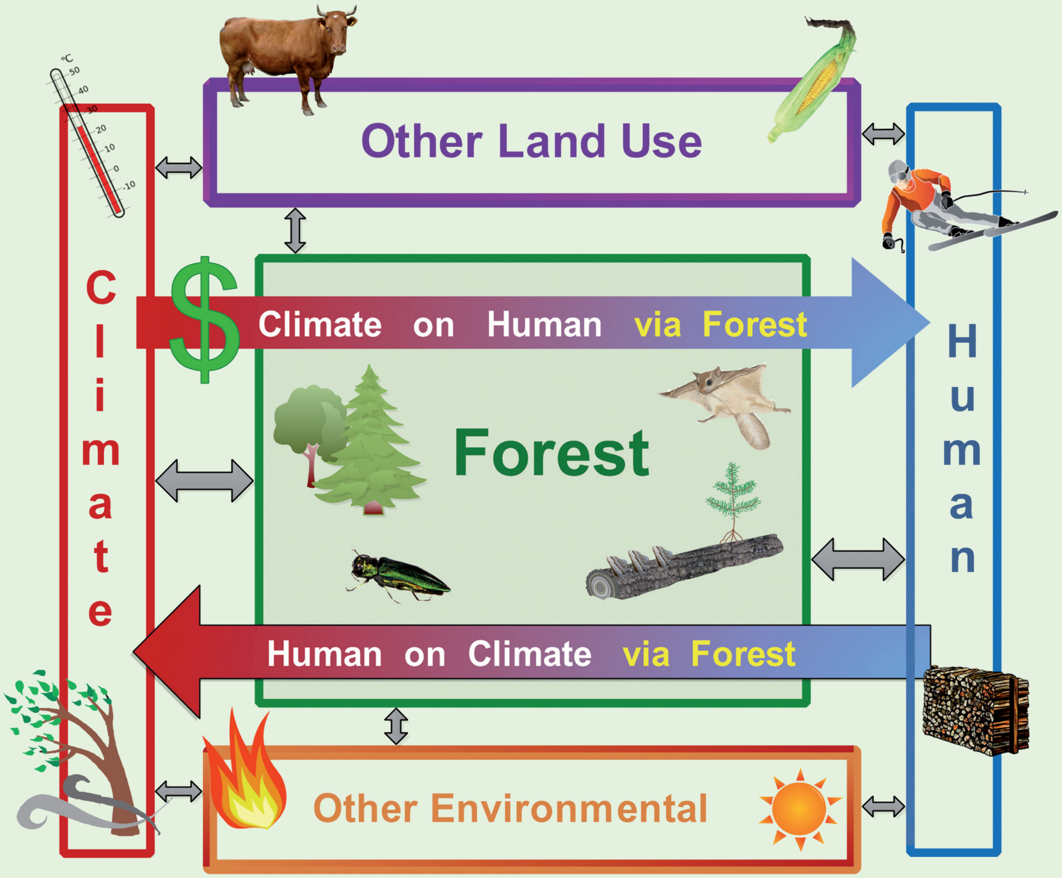
United States Department of Agriculture

# Indicators of Climate Impacts for Forests:

## Recommendations for the U.S. National Climate Assessment Indicators System



Forest Service

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# ABSTRACT

The Third National Climate Assessment (NCA) process for the United States focused in part on developing a system of indicators to communicate key aspects of the physical climate, climate impacts, vulnerabilities, and preparedness to inform decisionmakers and the public. Initially, 13 active teams were formed to recommend indicators in a range of categories, including forest, agriculture, grassland, phenology, mitigation, and physical climate. This publication describes the work of the Forest Indicators Technical Team. We briefly describe the NCA indicator system effort, propose and explain our conceptual model for the forest system, present our methods, and discuss our recommendations. Climate is only one driver of changes in U.S. forests; other drivers include socioeconomic drivers such as population and culture, and other environmental drivers such as nutrients, light, and disturbance. We offer additional details of our work for transparency and to inform an NCA indicator Web portal. We recommend metrics for 11 indicators of climate impacts on forest, spanning the range of important aspects of forest as an ecological type and as a sector. Some indicators can be reported in a Web portal now; others need additional work for reporting in the near future. Indicators such as budburst, which are important to forest but more relevant to other NCA indicator teams, are identified. Potential indicators that need more research are also presented.

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# Indicators of Climate Impacts for Forests:
## Recommendations for the U.S. National Climate Assessment Indicators System

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# PREFACE: CONTEXT AND SCOPE

The Third National Climate Assessment (NCA) process for the United States focused in part on developing a system of indicators to communicate key aspects of the physical climate, climate impacts, vulnerabilities, and preparedness to inform policy makers, managers, and the public in their decisionmaking. To maximize access to the indicators, an ultimate goal of the NCA indicators process is to produce a Web portal which will be maintained, updated, and accessible to the public. Because climate is interwoven with all facets of the environment and society, the climate issue was delineated into commonly used categories such as agriculture or energy to organize the work. A team of scientists was convened for each category to conduct research to develop a basis from which to recommend core indicators.

Initially, 13 teams were organized: adaptation and hazards, human health, mitigation and greenhouse gas emissions, oceans and coasts, physical climate, freshwater ecosystems, grassland, forest, agriculture, water cycle and management, phenology, energy, and infrastructure. The adaptation and hazards team started later due to the need for additional research. A 14th team on biodiversity was added during the overall effort. This publication documents the work of the Forest Indicator Technical Team.

Forest team members were invited for their expert understanding of forests either as a sector or as an ecological type, or both. As our work proceeded, we invited scientists to serve as contributing authors in specific areas where more expertise was needed. In addition, we recognized that some important ecological, societal, or climatic processes relevant to forests were also likely to be even more important and relevant to other teams. To ensure the important aspects were not overlooked, we also provided a list of indicators for other teams.

The two appendixes are included for full transparency of the process and to maximize use of the information our team produced. Appendix 1 features our detailed responses to the requested evaluation criteria. Appendix 2 contains the memo on potential indicators and research gaps which we produced and submitted to the NCA Indicator Working Group. This request memo highlights research needs and opportunities to guide future research. We have attempted to minimize duplication of text between the main text and the appendixes, but some material is repeated for ease of comprehension.

The long list of authors reflects the scope and significance of forestland of the United States. Major contributors to each indicator are listed with that particular indicator in the main text, and they also contributed to that indicator's section in Appendix 1. Authors listed as team members determined the final list of recommended indicators. Contributing authors focused mainly on the sections associated with their names. All authors were given the opportunity to comment on the entire work. Sarah Anderson, Guy Robertson, and Rich Pouyat in particular worked on the forest conceptual model; Anderson also provided the summary of forest and cross-cutting indicators in the main text, and compiled the input from team members into an initial report. Pouyat assisted with coordination issues for ecological indicators. Marla Emery gave steady advice and assistance throughout the effort from a social science perspective. As team lead, Linda Heath suggested and invited additional team members, designed the general outline and the conceptual model for the forest team's overall effort (see Figure 1 on page 8), and wrote the introduction and methods section. She coordinated handling the review comments, and went through final drafts and modified or augmented the text as needed for the document to "flow" with consistency.

We sadly report that team member Dr. Alan Lucier passed away in March 2014. Al was always a steady, dedicated, insightful force for forests and people. He provided important contributions and ideas to our effort, and he enriched the discussion on our recommended indicators.

In addition to the authors, we recognize the team leading the overall NCA indicator system efforts, including coordinating the technical teams and working with principals of agencies and working groups: Melissa A. Kenney (principal investigator of Indicators Research Team, University of Maryland), Anthony C. Janetos (National Climate Assessment and Development Advisory Committee Indicators Working Group chair, Boston University), Richard Pouyat (Indicators Research Team, U.S. Forest Service), and Ainsley Lloyd (Indicators Research Team, University of Maryland). The work of Kenney and the Indicators Research Team was supported by NOAA grant NA14NES4320003 (Cooperative Institute for Climate and Satellites-CICS) at the University of Maryland/ESSIC. We also recognize and thank H. Ken Cordell, scientist emeritus, U.S. Forest Service, Southern Research Station for his suggestions and contribution on possible recreation and amenity indicators, and Linda Geiser, air program manager of the U.S. Forest Service, lgeiser@fs.fed.us, for her contributions to the potential lichen diversity indicator. We thank Elizabeth Burrill, U.S. Forest Service, Durham, NH, for developing Figures 3 and 8. We appreciate the many reviewers who provided comments throughout the process, especially review comments from anonymous reviewers from the blind-peer review process of the U.S. Forest Service, Northern Research Station, for helping improve the quality of this effort.

We view our work as a first version of indicators that will be coordinated with other NCA indicator system teams, to be refined and updated in the future. We hope our effort will focus additional research on important forest-climate indicators, and encourage the collection of critical measurements and observations.

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# INTRODUCTION

The Third National Climate Assessment (NCA) process for the United States focused in part on developing an indicators system to communicate key aspects of the physical climate, climate impacts, vulnerabilities, and preparedness to provide both decisionmakers and the public scientific information which is useful for decisionmaking. An indicator system is an approach that provides specific information about the state or condition of an area of interest, used to focus attention on items of fundamental importance. Workshops were held on ecological, societal, and physical indicators (U.S. Global Change Research Program [USGCRP] 2011a, 2011b, 2012, and additionally summarized in Janetos et al. 2012). The overall effort is led by the National Climate Assessment and Development Advisory Committee (NCADAC), chartered under the Federal Advisory Committee Act, for the Subcommittee on Global Change Research, Office of Science and Technology Policy.

The goals for the NCA indicators are to:

- Provide meaningful, authoritative climate-relevant measures about the status and trends of key physical, ecological, and societal variables and values;
- Inform decisions on management, research, and education at local to regional to national scales;
- Identify climate-related conditions and impacts to help develop effective mitigation and adaptation measures; and
- Provide clear analytical methods by which user communities can derive their own indicators for particular purposes.

The NCA indicator system is not intended to be a vehicle for documenting rigorous cause-and-effect relationships, but rather to serve as an information base for: 1) those factors that may affect variability and change in the climate system; 2) the resources and sectors of concern that are affected by climate; and 3) how society chooses to respond. These indicators will be tracked as a part of ongoing assessment activities, with adjustments as necessary to adapt to changing conditions and understanding. A Web portal is planned to make the indicator system publicly available.

Climate has an effect on all facets of the environment and society. Initially, 13 teams were organized: adaptation and hazards, human health, mitigation and greenhouse gas emissions, oceans and coasts, physical climate, freshwater ecosystems, grassland, forest, agriculture, water cycle and management, phenology, energy, and infrastructure. The adaptation and hazards team started later due to the need for additional research, and other teams were asked not to focus on adaptation. A 14th team was added later on biodiversity. Each team was charged with recommending indicators for use in this system. To keep the full indicator set manageable, the guidance to each team was to recommend about 10 or fewer indicators.

This study was conducted by the Forest Indicator Technical Team (hereafter called the forest team). Like all teams, we were assigned a specific format to follow with a list of evaluation criteria, with the objective of recommending indicators for forestland. Specific details we developed and used for this effort are presented in Appendix 1. First, we present general facts about forests in the United States, and use this exploration to help formulate a systems model for forests as a sector and ecological type. We discuss our refined approach for identifying the indicators that we recommend for use by the NCA indicator system, and present our recommendations including example outputs which can be derived from existing or needed data. Indicators considered to be more relevant to the topic areas of other teams, are also discussed. Finally, we discuss research gaps on recommended indicators, and also areas that look promising for indicators but would need more research. The details of our work on potential indicators and research gaps are provided in Appendix 2.

## Why U.S. Forests Are a Category in the NCA Indicator System

U.S. forests are significant. Forestland is a foundation for improved livelihoods and a premium quality of life. Forests provide major opportunities for recreation, hunting and fishing, breathtaking vistas and unbroken serenity; are a major source of superior freshwater supply; protect soil from erosion and build organic matter stores; clean our air and provide other human health benefits; are essential for wood supply to build our homes and to manufacture a wide variety of products from renewable materials; sequester and store a significant amount of carbon with continued storage in long-lived wood products; contribute to local livelihoods and the national economy; and provide a major source of renewable energy. Forests are the home for much biodiversity—wildlife, plants, and other organisms—and have an intrinsic existence value. Forests offer low-cost options for climate mitigation, which delivers other additional multiple environmental and social benefits, and forests can play a significant role in ecosystem-based adaptation activities.

The following points illustrate the importance of U.S. forests:

- Forests account for about one-third of the total land base in the United States (Oswalt et al. 2014).
- In recent decades, U.S. forests have sequestered substantial amounts of carbon, annually offsetting 10 to 20 percent of U.S. fossil fuel emissions (Heath et al. 2011).

- In 2009, almost 19 billion activity days were spent viewing or photographing nature in forests, 2 billion activity days were devoted to backcountry activities, and 408 million activity days were spent hunting. In 2000, 56 million people went camping in forests (Cordell 2012).
- Total forest-related direct jobs are estimated to be almost 3 million, about 2 percent of all U.S. employment (U.S. Forest Service 2012), and receive about $102 billion in payroll. Jobs in forestry, forest products manufacturing, and wholesaling produce $262 billion in annual sales and contribute 6.7 percent of total manufacturing revenue (Wan and Fiery 2013).
- More than 200,000 plant and animal species have been documented on the lands and waters of the United States (Stein et al. 2000). Many of these species are associated with forests in at least part of their range or life cycle. Twenty percent of U.S. forestland is under some type of conservation program (Alvarez 2007).
- Energy from wood biomass accounts for at least 20 percent of renewable energy consumption in the United States (U.S. Energy Information Administration 2013).

As complex ecosystems, forests are vulnerable to impacts from climate change (Melillo et al. 2014). Climate change is expected to alter U.S. forestlands and the goods and services they produce.

## Forest Indicators Related to Climate

Given the significance of forests in the United States and their relationship to climate, forest is an important category for the NCA indicator system. In this effort, we focus on indicators related directly to forest ecosystems, as well as associated social and economic systems as they relate to climate change detection, mitigation, and adaptation. An existing set of indicators designed to measure the sustainability of forest ecosystems may include indicators relevant to the NCA effort. The existing set, the Montreal Process Criteria and Indicators for Forest Sustainability, has been used to produce two periodic reports on forest conditions and their sustainability in the United States (U.S. Forest Service 2004, 2011). The most recent report[1] (U.S. Forest Service 2011) identifies the interaction of forest, climate change, and bioenergy as an overarching issue that promises to be of crucial importance in future years. That report discusses how certain Montreal Process indicators relate to climate change, but these indicators were not developed to specifically measure climate change impacts.

Recently published forest-focused NCA and related documents should also prove useful in this effort; in particular, see Vose et al. (2012) and Melillo et al. (2014). Additionally, the Resource Planning Act (RPA) Assessment (U.S. Forest Service 2012) analyzes current and projected forest conditions based on the

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[1] A third edition of the report is due for publication in 2016.

Intergovernmental Panel on Climate Change (IPCC) climate scenarios (IPCC 2007). The RPA Assessment projections, however, are not based on an explicit conceptual model of indicators, but some of the outputs could prove useful to indicators of climate impacts for forests.

## METHODS

The charge to each team from the USGCRP through the NCADAC Indicators Working Group was to: 1) develop a conceptual model for this sector or land use; 2) identify and recommend core indicators which could be addressed within a year, including a few that would be already available for an early pilot Web site; and 3) identify gaps in research on the recommended indicators. A common template was provided for each team to complete for reporting.

As stated previously, one goal of the effort is for the USGCRP to host a Web portal that would feature the approximately 120 climate-related indicators recommended through this process. The target audience includes policy makers, analysts, and the public. The following decision criteria were to guide teams' approach to identifying indicators: Indicators should 1) be scientifically defensible, 2) link to the conceptual framework, 3) have a defined relationship to climate, and 4) be scalable; the team should 5) build on or augment existing agency efforts (in other words, consider existing datasets, data availability, and data use) and 6) consider both current and leading indicators.

### Template

The template provided to each team consisted of specific questions about the decision criteria and other information for each indicator. Because this template was a fundamental part of our methods and documentation, we provide the content of the template here:

1. Summary About the Indicator (Text)
   a) Additional descriptive text, b) Data sources, c) What is the link to climate variability and change or relevance? d) What are the drivers of this indicator, and what are their impacts? e) Has this indicator been used as an indicator by anyone else; if so, by whom, and how was it used and when was it initiated? f) Relevance to management decisions, g) Other indicators considered but not recommended at this time, h) Usefulness for education purposes.
2. Data Availability
   a) Length of records of dataset, b) Metadata, c) Stability/Longevity of dataset and indicator, d) Notes about the data (recent changes in analysis or collection methods), e) Spatial and temporal scalability, f) Models/ Scenarios (if leading indicator or based on model output).

3. Details About the Indicator
   a) Type of indicator (current, leading, both; if both, need to describe data/models and methods separately because of different approaches), b) Geographic scope and scale of analysis, c) Approach (e.g., single measure, composite), d) Purposes and conceptual framework, e) Composition and methodology; f) Scientific validity of indicator, g) What are the plans for further development of the indicator?
4. Considerations for Selection of Indicator
   a) Advantages, b) Disadvantages
5. Literature Cited
6. Other Resources
   Literature cited and other resources may include Web site links, peer-reviewed publications about the indicator, and contact information about the data or indicator.

Janetos et al. (2012: 5) provide the definitions for current and leading indicators: "Current indicators describe current status and trends relative to a historical baseline. Leading indicators are used to project changes in important parameters that could result from possible climate changes." In other words, leading climate-related indicators foretell that climate is changing. To describe some phenomena, a single indicator may be adequate, or multiple indicators may be necessary, or a composite of multiple indicators may prove ideal. A composite indicator is typically based on a theoretical framework in which single indicators are combined in a way to reflect what is being measured. The template concluded with a summary table (see Table 1) for the recommended indicator; we present this table as an illustration of one step of our methods. For full transparency of the information we developed and considered in our process, and to provide details for those developing a Web portal of the indicators, the completed templates and summary tables are provided in Appendix 1.

## Additional Decision Criteria

In addition to the guidance provided to the team on the process for identifying recommended indicators, the forest team adopted a strategy after some discussion early in the effort. We agreed that 1) the indicators should cover the range of the proposed conceptual model to the extent possible, 2) our indicator set should feature at least a few indicators that could currently be reported on, 3) we should consider indicators that were used for other purposes such as sustainability, but that also are related to climate change, 4) we should consider indicators needed for information to interpret climate change effects related to forest such as the extent of forest, and 5) we should consider important indicators that could require much more development and data collection, but that had notable potential. In some cases practical issues associated with data availability and tractability helped determine our choice of indicators. The resulting indicator set was designed to be updated as new information and research results become available, rather than a permanent set. In other words, we focused on providing a first version of indicators, some of which could be incorporated in a pilot Web

**Table 1.—Summary of information for decision criteria completed for one of the resulting recommended indicators (Human influence on Climate Domain via Forest)[a]**

| Decision criterion | Ranking | Justification |
|---|---|---|
| **Link to conceptual framework** | Best | Explicit link to conceptual model (arrows 4 and 11) |
| **Defined relationship to climate, feedbacks, or impacts** | Best | Direct link to human response to climate change and carbon stocks and fluxes resulting from human activity |
| **Spatial scalability** | Sufficient | National unit of analysis. Some components may be scalable to regional and state levels. |
| **Temporal scalability** | Best | Annual time series data are available. |
| **Of national (not necessarily nationwide) significance? Should link to the conceptual model** | Best | Strong link to influences in atmospheric carbon concentration and forest conditions. Responsive to national climate policy as it relates to energy production. |
| **Relevance to management decisions** | Best | Tracks U.S. industry’s response |
| **Usefulness for educational purposes** | Sufficient | Information is useful but could be more fully described in relation to other categories such as emissions. |
| **Is it a leading indicator?** | Needs improvement | Not proposed as a leading indicator |
| **Builds on existing data sources** | Best | Indicator already developed and published |
| **Builds on existing indicator products** | Best | Indicator already exists in Montreal Process and national reports |
| **If new indicator proposed, likelihood of development and testing within 1 year given existing funding sources (no funding available from USGCRP or indicator system team)** | Existing indicator, but could use some attention | Existing indicator reported on for sustainability. Usefulness in terms of climate and how it could contribute to full suite of NCA indicators could be more fully developed, but additional funding is unlikely. |
| **Stability/Longevity of dataset** | Sufficient | Domestic portion of indicator has already been successfully produced for two report iterations, but indicator is dependent on disparate data reporting streams. |
| **Stability/Longevity of indicator** | Sufficient | See preceding (stability of dataset). |
| **Scientific validity of indicator** | Sufficient | Previous iterations have been subject to peer review. |
| **Data publicly available and transparent** | Sufficient | Data are available, but analysis and transformation are required. |
| **Indicator methods fully transparent and documented** | Best | Full documentation of previous indicator development is available. |

[a] Acronyms: NCA = National Climate Assessment; USGCRP = U.S. Global Change Research Program

portal that decisionmakers and the public could visit and thereby concretely experience the usefulness of the indicators system. We also provide information that could lead scientists to work on indicators more relevant to future indicator efforts.

Based on our collective experience, we recognized that different technological methods may be in current use that could provide perhaps conflicting data for the same indicator. Methods typically have advantages and disadvantages. Often the difference is a combination of what various audiences need and the perceived maturity of the methods. Therefore, we decided to adopt a broader definition of indicators, one that encompasses metrics. In some approaches, indicators are defined as the measurable factors of interest, and the term "metric" is not used. In our approach, the term "indicator" refers to the factor of interest, and the term "metric" describes the specific item that is the measure. For example, the extent of forest is an important indicator because location is needed to ensure the area being analyzed is forest. However, it is also important to delineate the location of forestland, grasslands, and croplands (agriculture), simply to help define these individual categories in the indicators system, including the shifts of land between these categories as vegetation changes. The extent of forest can be determined by a remote sensing approach, or by a forest inventory approach, which uses ground plots (and traditionally uses a second phase involving aerial photographs or remote sensing). One approach produces extent of forest by land cover, whereas the other approach results in extent by land use. We describe and present each as a possible metric (measure) of the indicator forest extent.

## Domains of the National Climate Assessment Indicator System

The forest team is one of many indicator teams working on the suite of NCA indicators. To better understand this context, we developed a conceptual model to represent the overall system from our point of view. Our conceptual model (Fig. 1) shows all the categories of indicators included in the initially proposed indicator set in five domains: 1) climate, 2) forest, 3) other land use, 4) other environmental, and 5) human. In addition, categories can span more than one domain. We call the categories which include multiple domains phenomena. An example of a phenomenon is phenology. After the completion of most of our study, a biodiversity team was added to the effort. Biodiversity is also a phenomenon, and if we added it to Figure 1, it would be shown in a box parallel to phenology.

Forestland is dynamic because over time it can be converted to or from other land uses (Other Land Use Domain), and there can be changes in the structure and function of ecosystems within the Forest Domain as well. We focused on indicators that are strongly related to the Forest Domain. If we identified an indicator with strong links to other teams, we spoke with other teams to encourage them to recommend the indicator. If the other teams do not recommend the indicator, the forest team needs to reconsider including the indicator.

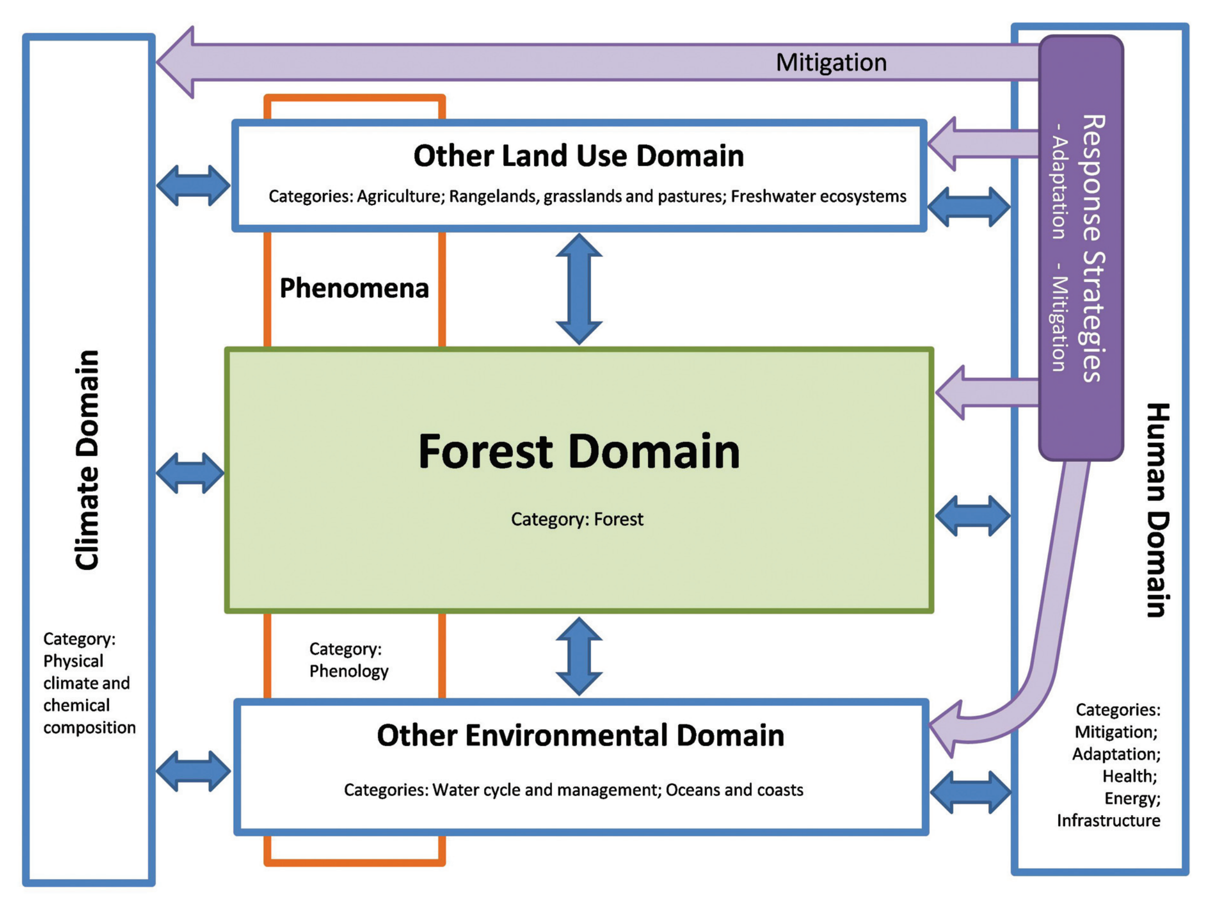

Figure 1.—The Forest Indicator Technical Team's conceptual model showing how the team viewed the role of forests in relation to other National Climate Assessment indicator categories (teams).

An advantage of having NCA teams focused on cross-cutting phenomena is that the resulting indicators in theory would be seamless and consistent across land uses and thus facilitate integrated consideration of adaptation and mitigation options across ecosystem boundaries. A disadvantage is that some methods may be more accurate (and therefore more applicable) for some land uses or sectors than for others. Coordinating with the relevant teams would ensure broad usefulness of the indicators.

## Definition of Forestland

Not all land with trees is considered forest. We adopt the definition of forestland used by the U.S. Forest Service's Forest Inventory and Analysis (FIA) program to compile forest inventory statistics for the nation (Oswalt et al. 2014):

> Land at least 120 feet wide and 1 acre in size with at least 10 percent cover (or equivalent stocking) by live trees, including land that formerly had such tree cover and that will be naturally or artificially regenerated. Trees are woody plants having a more or less erect perennial stem(s) capable of achieving at least 3 inches (7.6 cm) in diameter at breast height, or 5 inches (12.7 cm) diameter at root collar, and a height of 16.4 feet (5 meters) at maturity in situ. The definition here includes all areas recently having such conditions and currently regenerating or capable of attaining such condition in the near future. Forestland also includes transition zones, such as area between forest and nonforest land that has at least 10 percent cover (or equivalent stocking) with live trees and forest area adjacent to urban and built-up land. Unimproved roads and trails, streams, and clearings in forest areas are classified as forest if they are less than 120 feet (37 meters) wide or an acre (0.4 hectare) in size. Forestland does not include land that is predominantly under agricultural or urban land use.

Note that lands with tree cover such as urban land are not considered forestland, whereas areas of forest that have been harvested but that are not being converted to other land cover or uses continue to be designated as forest. Forest indicators currently do not include urban forests unless explicitly noted otherwise. We recognize, however, that urban forest represents a notable and growing gap in

An extensive windbreak system. This is an example of agroforestry practices that do not generally meet the definition of forest even though they use trees and provide a variety of forest-derived benefits in support of other land. Photo by Natural Resources Conservation Service.

our understanding of the U.S. landscape. Urban areas in the conterminous United States covered 60 million acres (3.1 percent of the land area) in 2000, and if growth patterns continue, urban land is projected to reach 8.1 percent of the land base by 2050, with a considerable amount of this increase occurring on existing forestland (Nowak et al. 2013). In 2005, tree cover within urban areas was estimated at 35.0 percent (Nowak et al. 2013).

On agricultural land in the United States, trees in agroforestry systems provide forest-derived services which can support more climate-resilient productive agricultural operations and landscapes (Schoeneberger et al. 2012) or other nonforest uses. For example, agroforestry practices across the rural/urban continuum may serve multiple purposes, such as creating wildlife corridors across highly fragmented agricultural landscapes or treating stormwater runoff. There is little information about the extent and type of agroforestry practices occurring in the United States because they generally occur on nonforest land and are not included in operational forest inventories. At the same time, the agricultural community tends to focus on crop production and may not collect adequate information about the tree portion of their operations. These systems of increasing human–forest and human–tree interaction and their associated climate change impacts warrant additional consideration in an indicator system in the future.

In summary, indicators in the forest category focus on the Forest Domain, and we also consider important forest indicators with strong links to other domains and categories. In the future, more formal consideration should be given to urban forest and settlements as well as to agroforestry systems.

## RESULTS

### Conceptual Model for Forest Indicators

Our forest indicator conceptual model (Fig. 2) provides one way of looking at the key components of forest ecosystems as they relate to important drivers of change within these ecosystems. The model depicts forests assuming a broad-scale analysis for identification of indicators. The boxes outlined in blue represent the four main domains affecting the Forest Domain, which is represented in the center (shaded) box. The domains are: Climate, Other Environmental, Other Land Use (other than forest), and Human.

The three primary drivers of forest response are shown in the orange boxes. These “drivers” can directly or indirectly affect forest extent and ecosystem structure and function, and ultimately ecosystem services and goods that are

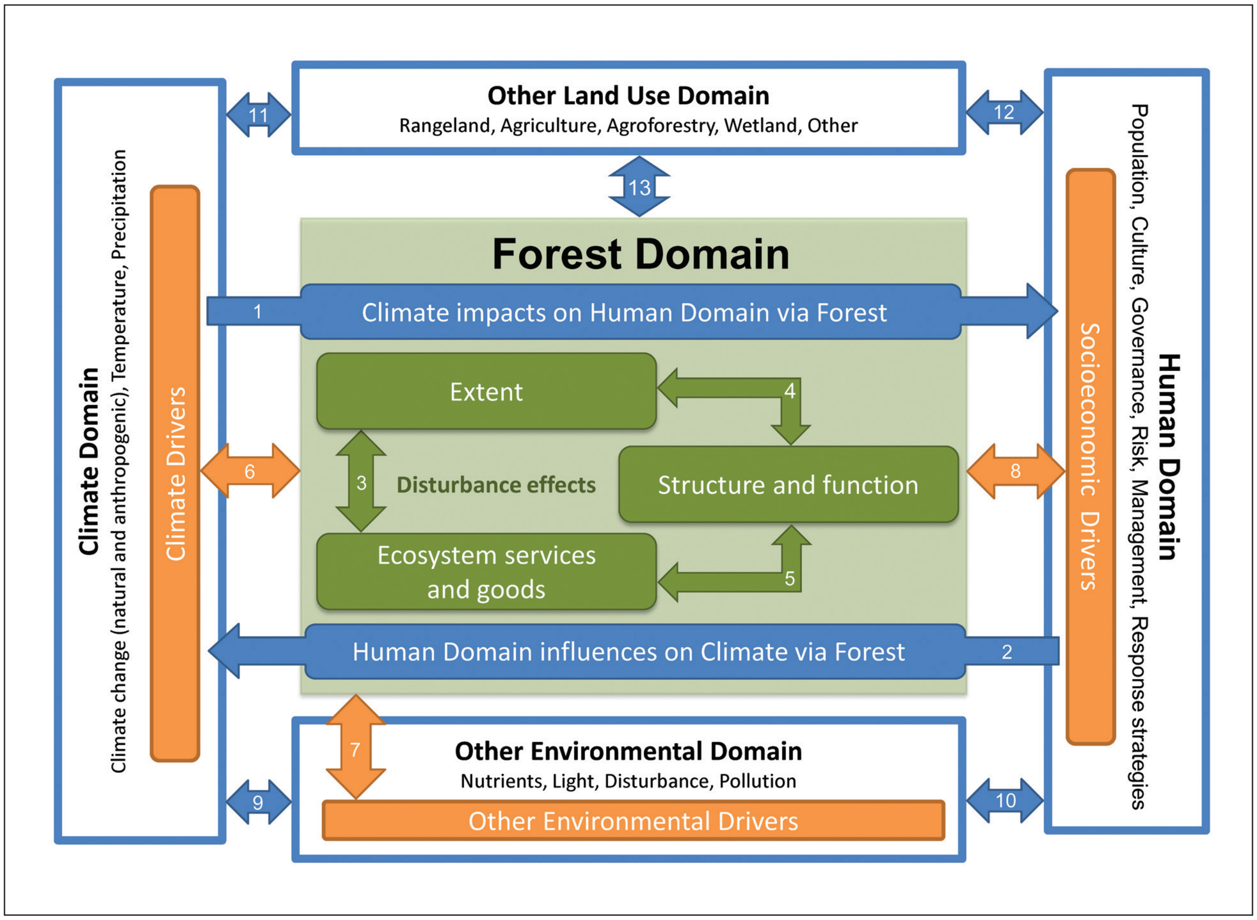

Figure 2.—The Forest Indicator Technical Team's conceptual model of the Forest Domain and important drivers and links. See text for explanation of numbered arrows.

provided by forestland. Drivers are climate (e.g., changes in variability and extremes of temperature and precipitation), other environmental factors (e.g., nutrients, light, disturbance, pollution), and socioeconomic factors (e.g., population, culture, governance, risk, management, response strategies of adaptation and mitigation). All three categories of drivers can affect the Forest Domain directly (represented by orange arrows) or indirectly through interactions with other drivers (represented by blue arrows). Thus, feedbacks mediated by each driver are implicitly included in the conceptual model. Within the Human Domain, people gather and assess information about all domains, along with risks to those domains associated with climate variability and change. Based on these risks, adaptation and mitigation response strategies are formed and response actions can then feed back to the Forest and other Domains. Also within the Human Domain, activities that depend on preferences, such as outdoor recreation, may be derived from the Forest Domain and in turn those activities may affect the Forest Domain.

Different climatic, anthropogenic, and natural drivers can cause areas to transition between land use types. Forestland can be converted to agriculture or agroforestry due to socioeconomic drivers. Conversely, abandoned rangeland or agriculture land can change back to forestland over time. These different land uses can be dynamic in a given area depending on climatic, other environmental, and socioeconomic drivers affecting forest ecosystems.

Major drivers of forest change are climate variability and change, other environmental change such as disturbances (e.g., wildfire, and natural forest growth and dynamics), and socioeconomic drivers that result in development or change which creates land use other than forest. As a result, forest extent, structure, and function, ecosystem services and goods, and disturbance effects are major attributes of forestland, interacting over time and across the landscape of the Forest Domain. These components encapsulate major aspects, relationships, and characteristics of forest systems that are and will be affected by environmental change including climate change. One example of a driver is a strong hurricane (disturbance) that blows down or breaks off the tops of many trees (structure), some of which are harvested (goods), thereby affecting forest growth (function) and carbon sequestration (service), and increasing biomass of dead wood (structure); some of the disturbed forest area may potentially be completely cleared and developed, reducing forest area (extent). Extent defines the area designated as forestland, which is dynamic and can change to and from other land use types (indicated by arrow 13 between Forest Domain and Other Land Use Domain). Structure and function are core characteristics of forestland. Ecosystem services and goods are measures of the global- to national- to local-level environmental and societal benefits provided by forestland. Disturbances permeate the Forest Domain and their effects show up in the attributes extent, structure and function, and ecosystem services and goods.

Arrows define different relationships and feedbacks between domains and components within the Forest Domain. Arrows are defined as follows:

### Arrow 1

This arrow illustrates ways in which climate affects the Human Domain through forest ecosystem responses. One example of a climate event with major effects is “heat waves.” A heat wave may directly affect the Human Domain by increasing heat-related fatalities, but may also indirectly affect the Human Domain through impacts on some aspect of the forest ecosystem structure, function, and services. In this example, an indirect effect is increased tree mortality, which then affects the Human Domain through reduced carbon sequestration, increased fuel for wildfires, and reduced value of timber. Other examples are the indirect effects that climate may have on pollen production in ragweed (*Ambrosia* spp.), which aggravates allergies and affects human health, and the direct effects that changes in snow cover have on forest-based recreation activities such as cross-country skiing.

### Arrow 2

This arrow represents Human Domain drivers that indirectly influence climate through forest management or policy decisions. These drivers include those that influence deforestation (feedback loop that increases $CO_2$ emissions), and those that influence the use of harvested wood to produce bioenergy and renewable materials (feedback loop that mitigates $CO_2$ emissions).

### Arrows 3, 4, and 5 and Overarching Disturbance Effects

Forest extent, structure and function, and ecosystem services and goods are important attributes of the Forest Domain, interacting over time and across the landscape. Disturbance processes combine with endogenous growth, mortality, and recruitment to help determine the nature of these three components in a dynamic fashion. Forest area (extent) is determined by definition, and the delineated forest is additionally characterized by structure and its ability to function as a forest (arrow 4). Due to changes in market prices or opportunities, for example, the production of goods may result in conversion of nonforest to forestland or of forestland to nonforest (arrow 3, with land transferring through arrow 13), and changes in forest extent will affect the amount of ecosystem services and goods. Production of goods or recognition of services such as through designating protected areas can affect numbers and sizes of trees (structure) by changes in harvest or by planting or the growth of forests (function), perhaps by fertilization (arrow 5). Large-scale disturbances affect structure and function, can affect extent, and affect ecosystem services and goods.

### Arrow 6

The Climate Domain affects the Forest Domain system through physical drivers such as temperature, precipitation, and atmospheric conditions, and there are interacting feedbacks from the Forest Domain to the Climate Domain through changes in evapotranspiration, trace gas fluxes, and albedo.

### Arrows 7, 9, and 10

Other environmental drivers also interact with the Forest Domain directly and indirectly; drivers in the Other Environmental Domain additionally interact with the Climate Domain and Human Domain. Heightened frequency or intensity of forest fires owing to increased fuel loading from fire suppression activities is an example of an interaction between Other Environmental and Forest Domains (arrow 7). Chemicals released to the atmosphere resulting from activities in the Human Domain affect the Other Environmental Domain (arrow 10). Sunlight in the Other Environmental Domain can act on certain chemicals producing, for example, ozone, which in turn affects human health in the Human Domain. Black carbon from forest fires (arrow 7) can cause atmospheric warming when it is in the atmosphere (arrow 9), and absorbs more solar radiation when deposited on snow, leading to accelerated melting of the snow. The Other Environmental Domain interactions with the Climate Domain and Human Domain serve as a pathway through which Climate Domain drivers, Human Domain drivers, and the Forest Domain system may interact indirectly or through feedback loops.

### Arrow 8

Interacting components of the Forest Domain are affected by various socioeconomic drivers from the Human Domain such as management activities. These activities include response strategies to climate change such as adaptation and mitigation measures and responses to other environmental drivers (arrow 10) and other land use (arrow 12). Complex socioeconomic drivers in the Human Domain such as outdoor recreation may link to many arrows, domains, and attributes. Management takes into account risks, or at least perceived risks, to forestland and the larger human population while acting within the confines imposed by cultural norms and governance.

### Arrows 11 and 12

Like the Forest Domain, the Other Land Use Domain is influenced by and interacts with both the Climate Domain and Human Domain. It is affected by climatic drivers such as temperature and precipitation and by Human Domain drivers such as management, response strategies, and use, with interacting feedbacks to these domains.

### Arrow 13

Conversions between land use types due to drivers including development (e.g., conversion of forest to housing lots), management (e.g., plantations), and ecological succession are captured by arrow 13. The Forest Domain and Other Land Use Domain are not static but change as they are affected by each other, and by the other three domains: Climate, Other Environmental, and Human.

The complexity of the NCA indicator system effort (as well as the strengths and limits of our conceptual model) is easily revealed when using our conceptual model for complex socioeconomic activities and drivers in the Human Domain that are linked to the Forest Domain, such as outdoor recreation. For example, an outdoor recreation activity such as developed skiing that is affected positively by climate will probably cause forest to be converted to other land use, will affect forest structure, is an ecosystem service and good, and may affect the Other Environmental Domain in terms of pollution. Discussing individual activities when using this conceptual model may involve arrows 3, 4, 5, 6, 8, 11, 12, and 13, all domains, and the attributes in the Forest Domain.

## Recommended Indicators

To ensure a manageable suite of indicators across all teams, each team was asked to identify about 10 or fewer indicators in this effort. We recommend 11 indicators (Table 2). Each indicator is described in the next section, with additional information about each in Appendix 1.

**Table 2.—Recommended indicators of climate impacts for forests**

| Domain | Indicator group | Indicator title | Brief description |
|---|---|---|---|
| **Forest** | Extent | Forestland area and extent | Forestland area as defined by land use or forest area as defined by forest cover |
| | Structure and function | Forest biomass density | Calculated from U.S. Forest Service, Forest Inventory and Analysis (FIA) program data |
| | Ecosystem services | Diversity/abundance of forest-associated floral and faunal species | Assessing change in forest plant diversity through information from FIA; assessing change in forest faunal species through information from U.S. Geological Survey Breeding Bird Survey data to track avian population trends |
| | Structure and function | Forest growth/productivity | Net annual growth calculated from field data from FIA and moderate resolution imaging spectroradiometer (MODIS) for forest net primary productivity |
| | Disturbance | Wildfire effects | Burned area with supplemental information on number of large fires and burn severity |
| | Disturbance | Forest insect and disease damage | Area affected by insects and diseases |
| | Biophysical | Water balance deficit—an indicator of "plant-relevant" drought | The difference between potential and actual evapotranspiration as estimated from surface climate observations and vegetation data |
| **Human and Forest** | Extent/ Socioeconomic | U.S. wildland-urban interface | Area and population of wildland area containing human residents and structures under risk of wildfire as defined by combining information from U.S. Census Bureau data and National Land Cover Dataset |
| | Climate impacts on the Human Domain via Forest | Cost to mitigate wildfire risk | Expenditures on fire suppression activity, expenditures on forest treatments to mitigate fire risk, total payments for insurance premiums for policies against damage from forest fire |
| | Human Domain influences on the Climate Domain via Forest | Energy produced from forest-based biomass | Energy produced, domestically or in export markets, from biomass harvested from U.S. forests in British thermal units per year or carbon dioxide equivalent |
| | Socioeconomic/ Ecosystem services | Outdoor recreation | Number of U.S. ski/snowboarder visits, revenue of ski areas, participation days in cross-country skiing |

We identified other indicators of importance to forestland but that seemed more relevant to the other teams. We encouraged other teams to consider and include those indicators (see Table 3). Due to direction from the coordinators of the overall effort, we limited our discussion of adaptation response indicators related to forest. Once the work of all the teams is completed, the next priority step would be to revisit the entire list of indicators that could be of most relevance to forest, and reconsider our core list of recommended indicators and metrics. Some metrics for a given forest indicator may work better than others. The criteria to identify and decide on the best indicators that are relevant to multiple teams need to be clearly determined before evaluating the indicators.

## Important Links Between the Forest Team and Other Teams

We also identified multiple important links between forest and categories represented by other teams. Wildfire indicators are relevant to the forest, grassland, and phenology teams. The phenology and forest teams have developed slightly different metrics for a wildfire indicator to meet different stakeholders' needs. The forest team also sees many areas for collaboration with the phenology team besides those already mentioned. Species migrations and seasonal distributions of animals (namely birds), spring indices such as first leaf and first bloom especially for forest species, and phenological measurements from satellites are all phenology indicators that the forest team supports and endorses.

**Table 3.—Indicators recommended by the Forest Indicator Technical Team to other technical teams**

| Team | Indicator | Description[a] |
|---|---|---|
| **Physical climate** | Temperature | A measure of temperature, either station measurements or a modeled and gridded interpolation such as PRISM (PRISM Climate Group 2015) |
| | Precipitation | A measure of precipitation, either station measurements or a modeled and gridded interpolation such as PRISM (PRISM Climate Group 2015) |
| | Wind | Either a monthly wind climatology or wind direction and speed from reanalysis |
| **Physical climate or Water cycle** | Drought (in addition to the water balance deficit) | Measurements of soil moisture or drought indices, such as the Palmer Drought Severity Index or Standardized Precipitation Index |
| **Health** | Health impacts related to forests | Asthma and related respiratory impacts and health issues, such as Lyme disease, strongly related to forest |
| **Phenology** | Senescence | Possibly measured either from satellites such as MODIS or VIIRS or through the National Phenology Network |
| | Budburst | Possibly measured either from satellites such as MODIS or VIIRS or through the National Phenology Network |

[a] Acronyms: PRISM = parameter-elevation regressions on independent slopes model; MODIS = moderate resolution imaging spectroradiometer; VIIRS = visible infrared radiometer suite

Freshwater forested landscape illustrating need for links between teams. Photo by Sarah M. Anderson, Washington State University, used with permission.

The grassland and forest teams (and perhaps other teams) have a shared interest in indicators of primary ecosystem productivity. The vegetation productivity indicator identified by the grassland team may be meaningful to forest, but current discussion indicates that optimal approaches differ for the two land uses. Productivity is a major aspect of forestland, and a shared indicator potentially can be developed by using satellite data from the moderate resolution imaging spectroradiometer (MODIS) or another approach.

Drought has been identified as an important topic by the forest, agriculture, physical climate, and water cycle teams and has relevance to the freshwater and grassland teams as well. Additional work is needed to determine the best drought indicator and measurements most critical to decisionmakers in these various sectors. Alternatively, several indicators of drought may be needed to be most informative for specific teams.

The freshwater ecosystems team has overlapping interests with all the terrestrial land use teams. Topics of interest to both the freshwater and forest teams include wetland and riparian systems in forested landscapes and ecological aspects of these systems, such as biodiversity or methane generation. Indicators related to these and other topics merit discussion between the freshwater and forest teams.

Several indicators representative of the physical climate system are highly important to forest ecosystems. Some of these indicators are temperature, precipitation, and wind measurements. In future efforts, the forest team sees advantages in working with the physical climate team to ensure that indicators selected by the physical climate team will help support the forest team and our specialized issues and specific decisionmakers.

Last, the forest team shares terrestrial emission indicators for $CO_2$ and non-$CO_2$ emissions with the mitigation and greenhouse gas sources and sinks team. The land use and land management indicator proposed by the mitigation team also has details highly pertinent to the forest ecosystems. Forests currently serve as a major $CO_2$ sink. Covering one-third of the United States, they sequester and store large amounts of carbon, and are therefore important to consider when estimating terrestrial emissions and sequestration of greenhouse gases. The forest team would prefer to endorse this indicator to be housed within the mitigation and greenhouse gas sources and sinks team.

## Description of Recommended Forest Indicators

In this section, we present summary descriptions of each indicator, and the metrics for each recommended indicator. Although we would prefer to recommend fully functional indicators for this effort, many of the recommended indicators need additional work before they can be considered operational because this is a first effort. We have generally arranged the indicators so that the ones nearer the front are more developed and could be used for a pilot indicator Web site.

For each indicator we provide a figure or table of example data to better convey our recommendations. Some of these examples may be ready to use as an indicator in a Web portal system; others need more work, including one based on hypothetical data. Additional details for each indicator are presented in Appendix 1, following the template that the NCA indicator system coordinating team asked each team to fill out.

## Forest Extent Indicator: Forestland Area and Extent

Major contributors: Linda S. Heath and Alan Lucier

Metrics: Forestland area by land use, Forest area based on forest cover only

Extent of forest is important as an indicator partly because it defines forest boundaries and area. Extent of forestland can vary due to differences in definition or estimation approach, and can be locally dynamic due to human activities. Climate affects forest extent directly (e.g., long-term changes in climate may alter the continental forest distribution) particularly in climate-limited regimes such as alpine treeline or grassland/forest ecotones, and indirectly (for example, climate may influence insect outbreaks that cause broad-scale tree mortality). Specific management strategies to mitigate or adapt to climate change effects (e.g., fuels management, introduction of new tree hybrids, protected area establishment) could be informed by improved tracking of forest area.

The main metric is based on land use because this is the approach for the official forest statistics for the United States, which come from FIA data (U.S. Forest Service 2013). This approach uses the same definition of forestland as in the U.S. national greenhouse gas inventories submitted to the United Nations Framework Convention on Climate Change. Forest area in the United States was about 751 million acres (304 million hectares) in 2010 (U.S. Forest Service 2011). This is a mature metric, although it continues to be be improved. In practice, the estimation procedures may include observations that form the basis of the second metric.

The National Land Cover Dataset (NLCD) (Homer et al. 2012) based on remote sensing provides a second, geospatial metric of forest area, which is defined by forest (tree) cover (see Fig. 3). Some types of forest as defined by land use may be labeled “shrubland” or “woody wetland” in the NLCD, and some areas designated forest based on forest cover may be defined as nonforest based on land use. A remote sensing approach has advantages, such as wall-to-wall consistency and identification of changes in gross forest cover. However, this approach is computationally intensive, and interpretation can still be misleading, especially regarding temporary loss of cover that is misidentified as conversion to nonforest (Hansen et al. 2010, Nowak and Greenfield 2010). In addition, the level of consistency in the results may not be as high as expected, especially across forest types. Estimation procedures for this metric continue to be improved.

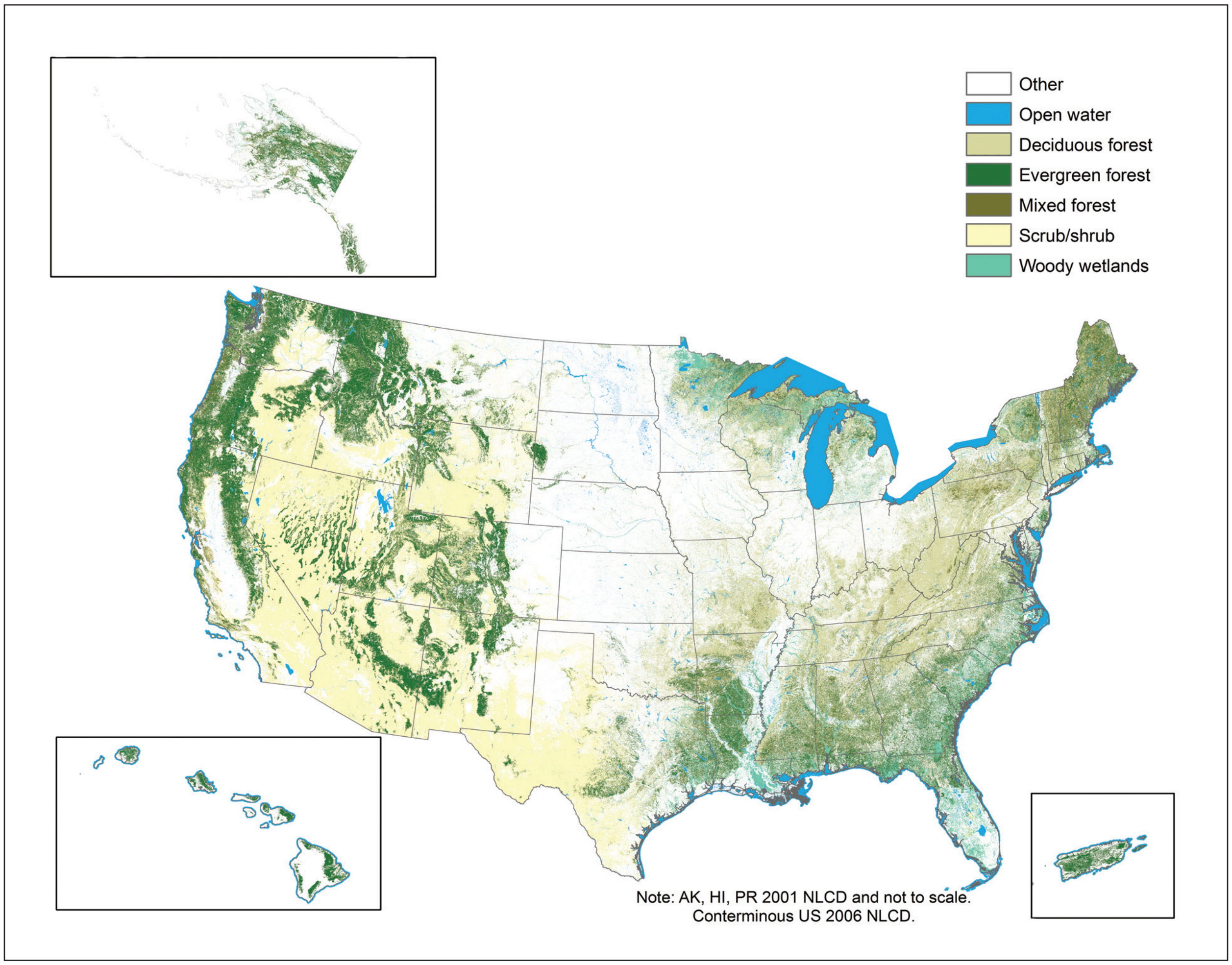

Figure 3.—Example map of forest and other land cover classes using the National Land Cover Dataset (Multi-Resolution Land Characteristics Consortium 2014), which could be used for this metric. Some areas defined as woody wetlands may be forestland and some areas may be shrubland. Conterminous U.S. map associated with the year 2006; Alaska, Hawaii, and Puerto Rico associated with the year 2001.

## Structure and Function Indicator: Forest Biomass Density

Major contributor: Linda S. Heath
Metrics: Aboveground live tree biomass per unit area, Dead wood mass per unit area

The indicator group Structure and function was identified in our conceptual model because these two features are often mentioned together. Because we can propose only a limited number of indicators, we chose aboveground live biomass of trees per unit area as the indicator even though it represents only structure, not function. Climate influences may result in a greater amount of dead biomass in relation to live biomass, so a second important metric is biomass in dead wood per unit area. Biomass in terms of dry weight of live and dead trees is about 50 percent carbon, so carbon can be estimated by multiplying dry weight biomass by 50 percent. As trees age, they accrue biomass through photosynthesis, and store mass and therefore carbon in their wood. Dead wood emits carbon as it decays.

The use of aboveground live biomass density (tons biomass per acre or metric tons biomass per hectare) as a metric of forest structure conveys information related not only to climate mitigation in terms of forest stocks, but also to potential availability of biomass for bioenergy, which can be used to produce energy as a substitute for fossil fuel. Biomass amounts are affected by climate, and climate variability can affect mortality, growth, regeneration, and decomposition; therefore, mass of both live trees and dead wood is important. Demand for biomass to lower overall emissions may result in decreased stocks of biomass.

Availability of data on biomass of trees in forests allows for biomass maps. As an example that could be used for this metric, forest aboveground live-tree biomass carbon stock per unit area by county shown in Figure 4 (U.S. Forest Service 2011), but estimates are relevant at all geographic sales, from national to local. Live biomass density or dead biomass density by county could be calculated annually or periodically. These estimates are calculated from FIA data (U.S. Forest Service 2013). Data for both metrics are available, and continue to be updated and improved.

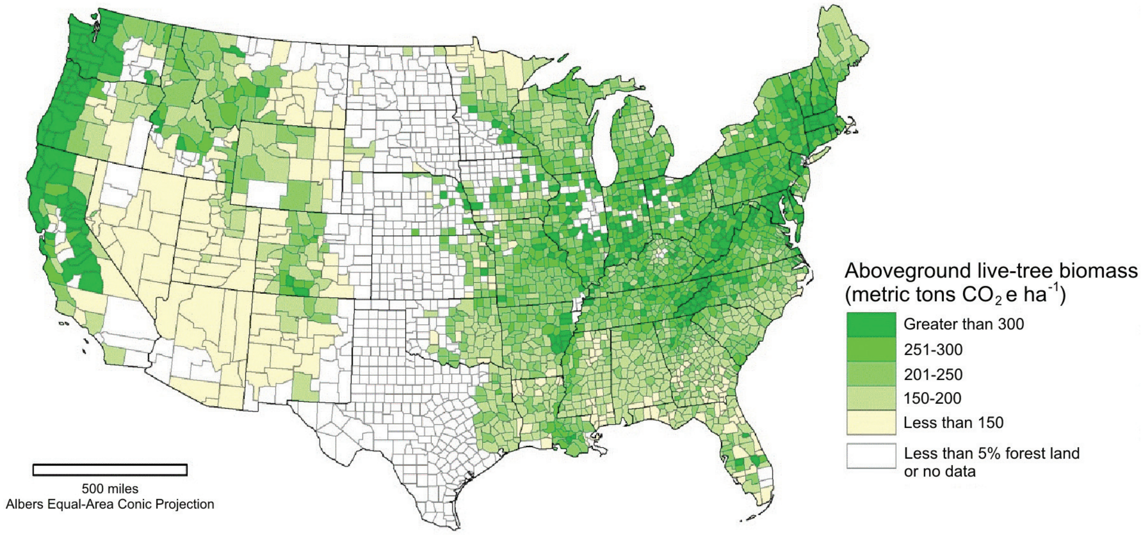

Figure 4.—Possible example metric of forest aboveground live-tree biomass: carbon stock density (metric tons of $CO_2$ equivalent per hectare) by county for the United States, 2006. Results are reported only for counties with more than 5 percent forestland, because small areas can be highly influenced by a few unusual observations. Source: U.S. Forest Service (2011).

## Ecosystem Services Indicator: Diversity/Abundance of Forest-associated Floral and Faunal Species

Major contributors: Kevin M. Potter (floral spp.) and Jinelle Sperry (faunal spp.)
Metrics: Forest tree biodiversity status and trends, Forest fauna biodiversity status and trends

Forest ecosystems serve as habitat for a wide range of floral and faunal species; consequently, climate-induced alterations in forest structure could have profound implications for forest-associated species. In turn, biodiversity conveys many functional benefits to forest ecosystems, including reduced susceptibility to invasive species after disturbance and enhanced ecosystem reliability (Balvanera et al. 2006). Research also has linked biodiversity to ecosystem primary productivity (Cardinale et al. 2007). Robust indicators of change in forest biodiversity will therefore be important for tracking forest community response to climate change. Dissimilarities in life history and population characteristics between plants and animals, in addition to differences in data availability, will require different approaches for tracking changes in biodiversity for each group. These metrics require additional work, especially for faunal species. We anticipate that these two metrics will be distinct enough that they each may have to be made a distinct indicator. When team efforts are reconciled, discussion with the biodiversity team would be useful for these indicators.

The foundation for assessing change in forest floral diversity is information available through the FIA program (Fig. 5). Spatially explicit analyses of changes in tree species diversity over time are therefore possible across much of the United States. Plant species are expected to respond in one of three ways to the numerous climate change effects that could push their current habitat out of their tolerance limits: 1) persistence in situ if within species' tolerance limits, 2) range shift, or 3) local extirpation (Davis et al. 2005). Indicators of change in seedling diversity are particularly useful (Potter and Woodall 2012).

It would be meaningful to consider several other possible indicators using the FIA data, including change in importance value of native tree species, mortality of mature native trees, and richness or cover of nonnative invasive plant species. Because we are limited in the number of indicators we can recommend, however, we propose the fundamental metric of tree biodiversity change.

In terms of metrics of biodiversity change for fauna, measures of forest-dwelling animals tend to focus on tracking trends in population and conservation status. Climate change can influence biodiversity through a variety of mechanisms including shifts in geographic range, phenological changes, and physiological stress (Thuiller 2007). Assessing trends in population would allow for a dynamic examination of possible climate change effects and could also help in studies of species range expansions and contractions (e.g., Hitch and Leberg 2007). The U.S. Geological Survey's (USGS's) national Breeding Bird Survey may currently offer the greatest potential (Fig. 6). Teasing out the responses of faunal populations to changes in climate versus changes in other factors will probably be challenging regardless of the data, so we expect more research will be needed to have confidence in the results.

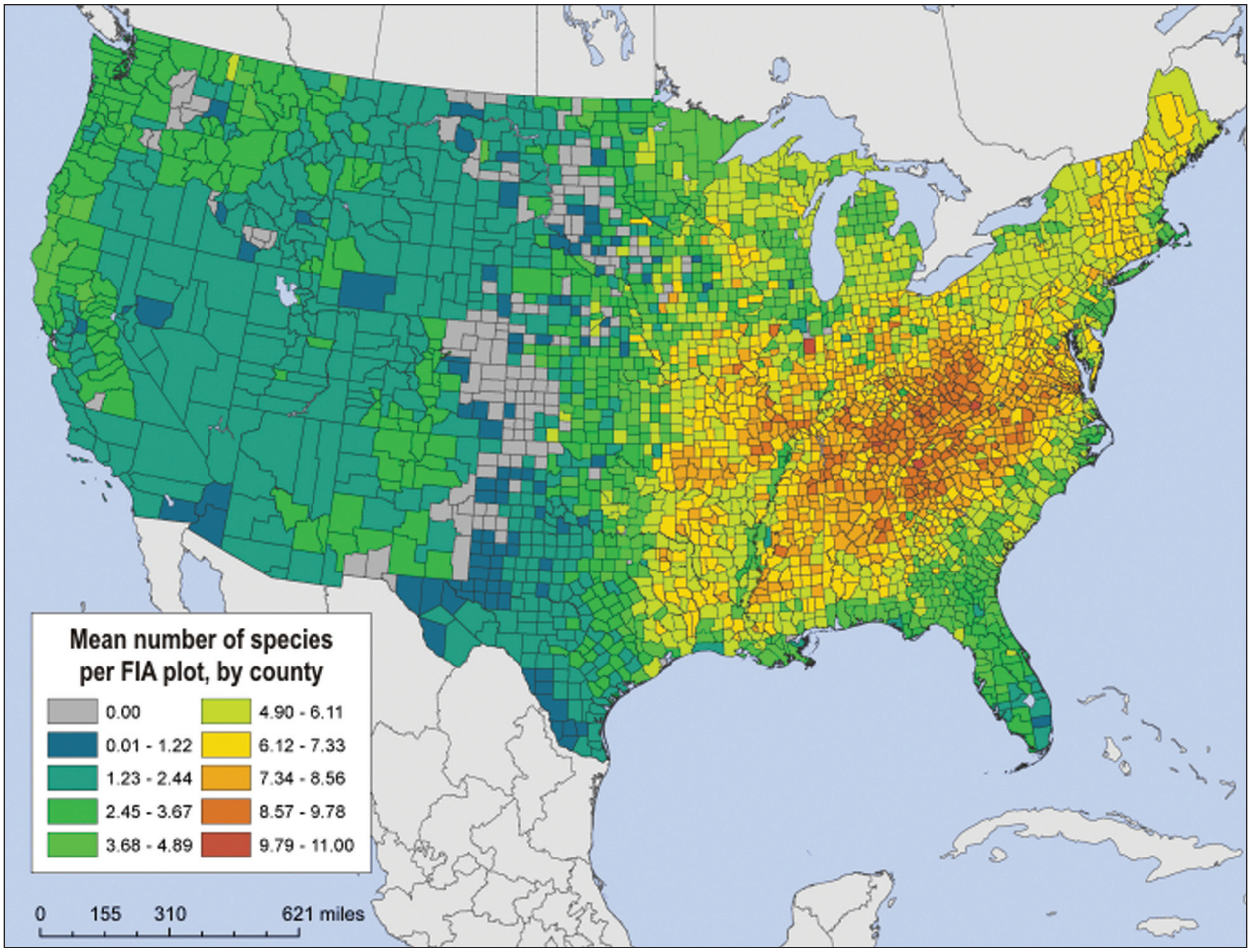

Figure 5.—Forest floral diversity (mean number of tree species per plot) by county, based on U.S. Forest Service, Forest Inventory and Analysis (FIA) data. This is an example of a potential illustration.

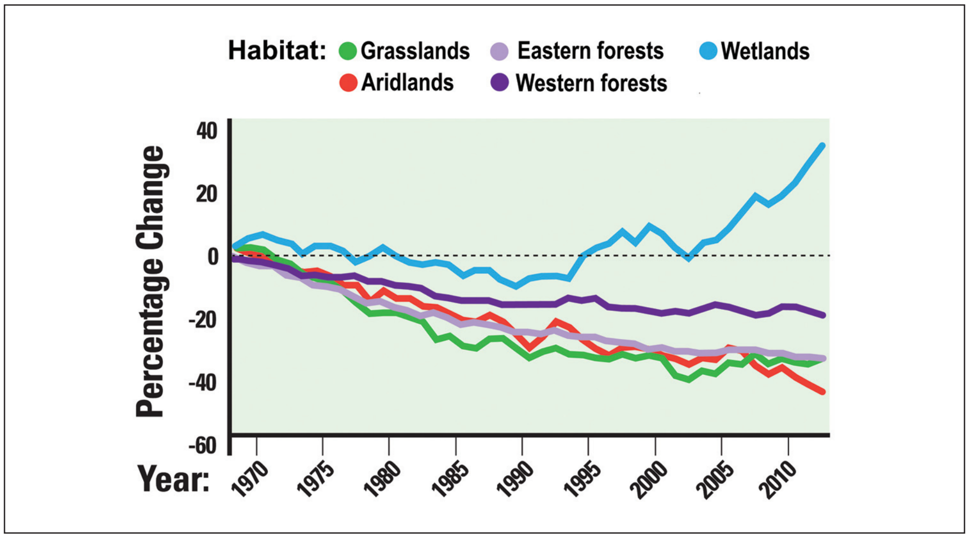

Figure 6.—Trends (percentage change) in number of birds counted in forest and other land use habitat based on, in part, the U.S. Geological Survey's Breeding Bird Survey data (figure from North American Bird Conservation Initiative, U.S. Committee 2014). This is only an example of how the final metric could be displayed.

## Structure and Function Indicator: Forest Growth/Productivity

Major contributors: Linda S. Heath and Jeffrey G. Masek
Metrics: Net annual forest growth, Forest net primary productivity

Net annual growth can be estimated from FIA data, and is defined as the average annual net increase in volume of trees during the period between inventories[2] (Oswalt et al. 2014). The volume of trees that died or that became nonmerchantable over the period is subtracted from the growth only of live trees, which means net growth may be a negative number. Net growth is important because it can be affected by changes in temperature, water availability, length of growing season, and increases in atmospheric $CO_2$. Silvicultural activities (e.g., fertilization, thinning, regeneration strategy) and ecological states can also affect growth, so results should be carefully interpreted. Net annual growth in U.S. forests totaled nearly 26.7 billion cubic feet in 2006, which is about three-and-one-half times the rate of mortality (Oswalt et al. 2014). Figure 7 is an example graphic of net annual growth.

We also propose that net primary productivity (NPP) estimated by using a remote sensing (i.e., MODIS) approach also be presented for forests, as a cross-cutting indicator that the phenology team could consider (see USGS, Land Processes Distributed Active Archive Center 2015 for observations). The MODIS product for gross primary productivity (GPP) and NPP, called MCD17, is based on a light-use efficiency model for photosynthesis, taking into account the satellite-based fraction of photosynthetically active radiation (fPAR) and leaf area. Productivity is modulated by water availability (e.g., vapor pressure deficit) derived from meteorological inputs (Running et al. 2004). There are a number of studies of ways to improve the standard MODIS NPP product for forests, and these should be considered (Turner et al. 2006). As an indicator, NPP can be more closely related to climate than can GPP because NPP records the biologic activity of forests, and depends directly on temperature, precipitation, and available solar radiation. Both metrics are available, and continue to be updated.

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[2] Specifically, components of net annual growth include “the increment in net volume of trees at the beginning of the specific year surviving to its end, plus the net volume of trees reaching the minimum size class during the year, minus the volume of trees that died during the year and minus the net volume of trees that became cull trees during the year” (Oswalt et al. 2014).

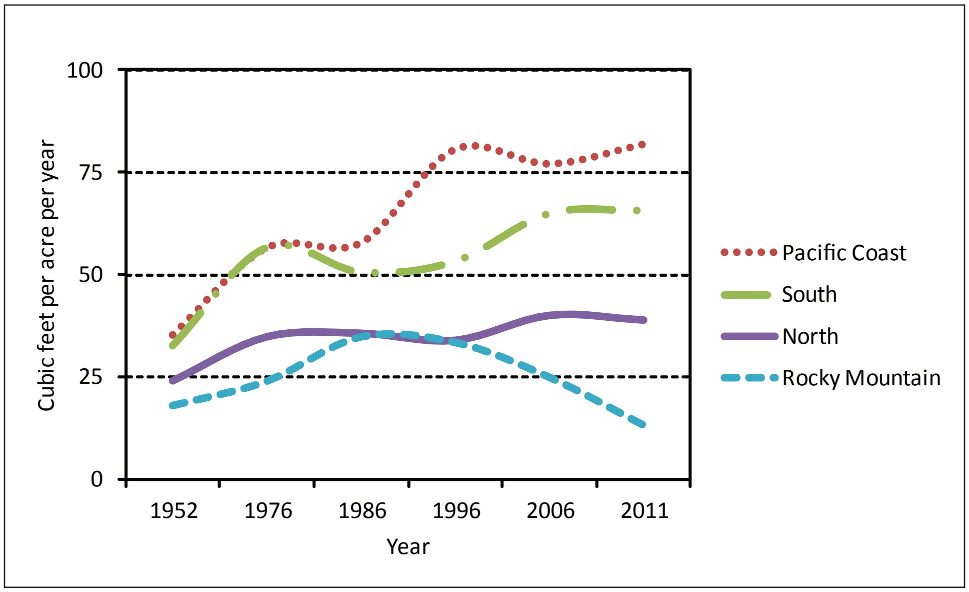


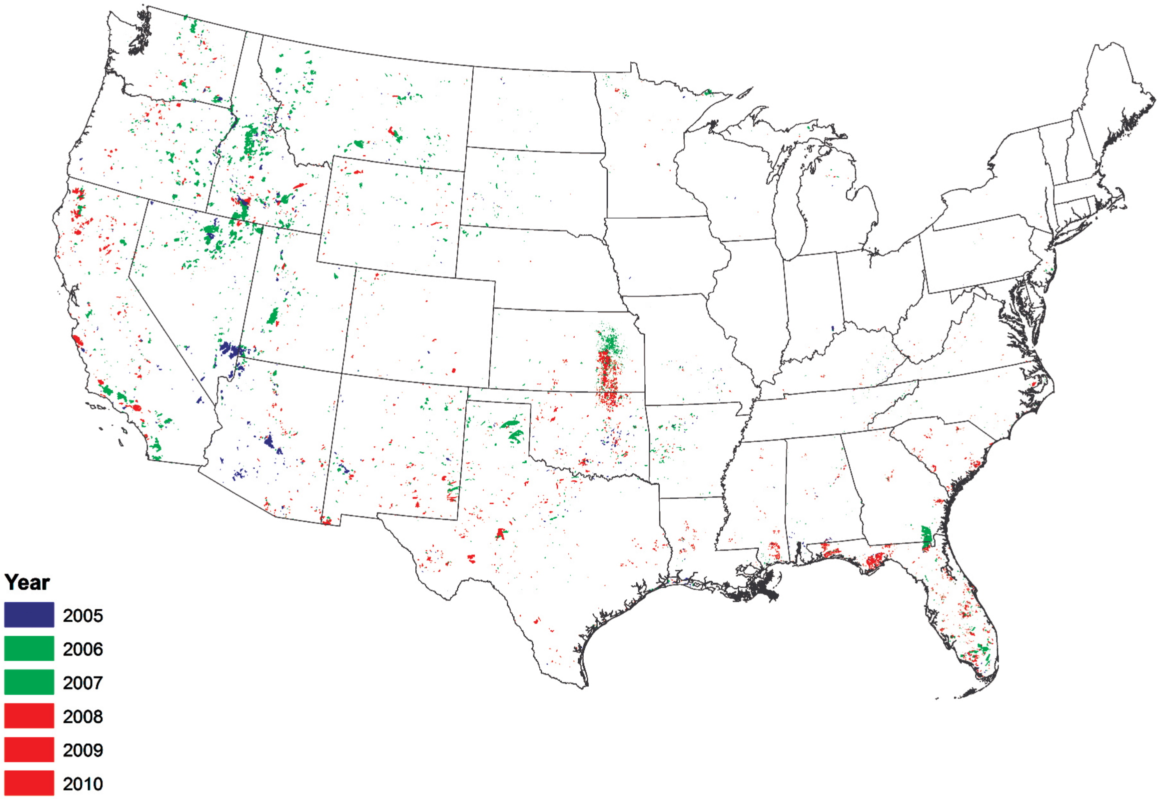
Figure 7.—Average net annual growing-stock growth per acre (cubic feet per acre per year) by U.S. region and inventory year (Oswalt et al. 2014). This is an example display for this metric.

## Disturbance Indicator: Wildfire Effects

Major contributors: David L. Peterson and Linda S. Heath
Metrics: Burned area, Number of large fires, Fire severity

Wildfire is one of the most significant disturbance agents in U.S. forest and rangeland ecosystems. It can drive changes in forest composition, structure, and function. Wildfire management is arguably the greatest current challenge for federal land management in the Western United States with respect both to vegetation management and restoration issues, and to financial expenditures for fire suppression and hazardous fuel reduction. Sufficient data exist to use wildfire as an indicator, but several metrics need to be considered to establish clear relationships between fire characteristics and climatic parameters. Observations are available from the National Interagency Fire Center (2015) and from the Monitoring Trends in Burn Severity (2013) project. The methods exist to produce these metrics, and they are currently available.

Burned area is a simple summation for a given area and time period, can be displayed on a map, and has been shown to be related to climate. Empirical analysis of annual area burned (1916 to 2003) for federal land in the West projected that for a temperature increase of 1.6 °C (2.8 °F), burned area will increase two to three times in most states. Number of large fires can be determined by summing occurrence at different threshold sizes. No particular threshold for "large" is assumed at this time. Fire severity typically is a quantification of canopy mortality caused by fire for a particular location; it can be expressed as area with a particular magnitude of severity. Fire intensity is expected to increase significantly as a result of warmer temperatures. However, fuel loading, and interannual and longer term variability in climate–fire relationships can affect trends, making it difficult to infer whether climate change is responsible. See Figure 8 for an example map of this indicator.



Source: MTBS 2005-2010 Fire Perimeters

Figure 8.—Example indicator map for areas burned by wildfire on both forest and nonforest land for a range of years in the conterminous United States (Monitoring Trends in Burn Severity 2013). Fire severity class of each area is also available.

## Disturbance Indicator: Forest Insect and Disease Damage

Major contributor: Jeffrey A. Hicke
Metric: Area affected by insects and diseases

Forest insects and diseases are major disturbance agents of forest ecosystems of the United States (Dale et al. 2001), and climate is an important driver influencing outbreaks of insects and diseases directly (Bentz et al. 2010, Sturrock et al. 2011) and indirectly by affecting host trees, which are then more susceptible to attack (e.g., Weed et al. 2013). The U.S. Forest Service conducts annual aerial surveys of insect- and disease-caused tree damage. Affected area is reported by insect or disease type and tree species, and is available at fine (polygon) and coarse (national) scales for summarizing as national totals for each disturbance agent as well as for producing maps (Fig. 9). These metrics are available, but more work is needed to use them as an indicator. In the future, ForWarn (U.S. Forest Service, Eastern Forest Environmental Threat Assessment Center 2015) may be developed enough to be used.

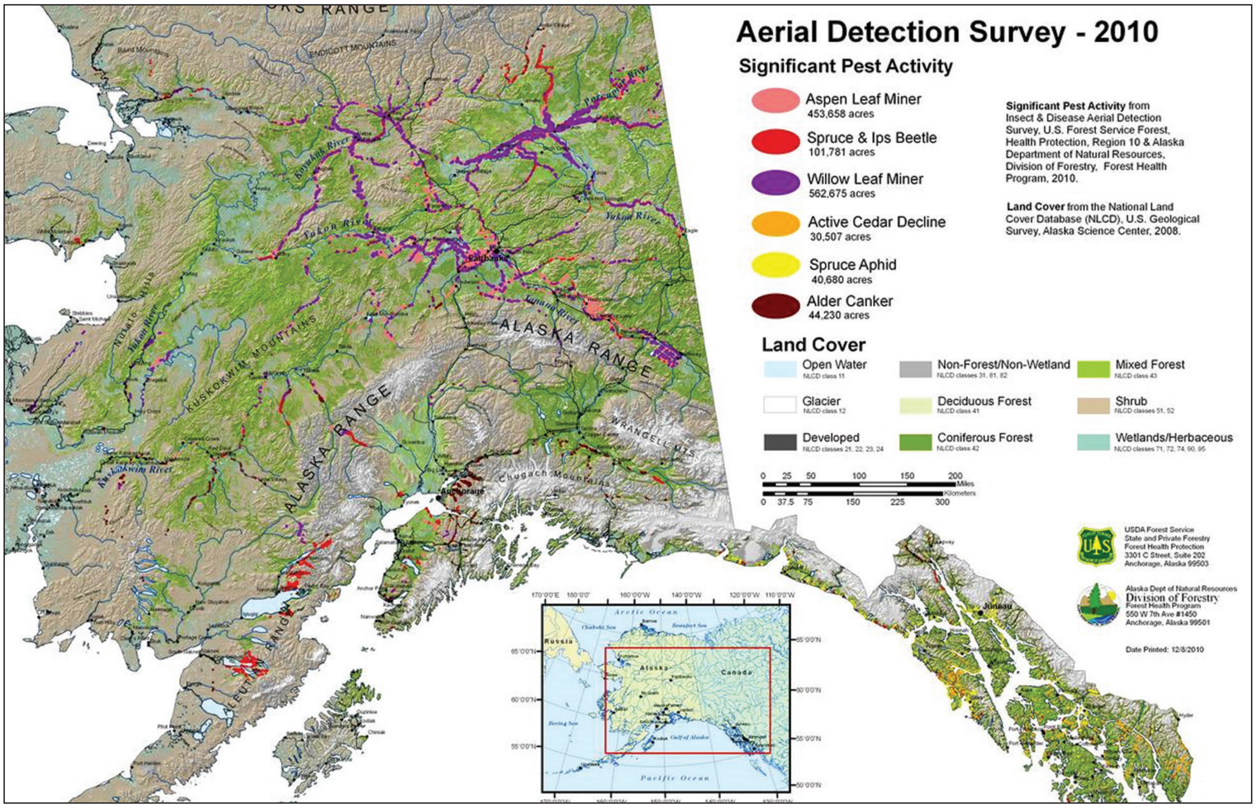


Figure 9.—Example map of insect activity in Alaska for 2010 that could be used for this metric (U.S. Forest Service, State and Private Forestry and U.S. Geological Survey, Alaska Geographic Science Office 2013). Note: Many of the most destructive diseases are not represented on the map because the agents are not detectable from aerial surveys. The Significant Pest Activity polygons are accented with a large border for visualization.

This indicator could focus on insects and diseases that damage trees over large areas: 1) bark beetles, including mountain pine beetle (*Dendroctonus ponderosae*), western pine beetle (*D. brevicomis*), spruce beetle (*D. rufipennis*), pinyon ips (*Ips confusus*), Douglas-fir beetle (*D. pseudotsugae*), and southern pine beetle (*D. frontalis*); 2) defoliating insects, such as spruce budworms (*Choristoneura* spp.); 3) pathogens, including *Dothistroma* needle blight, Swiss needle cast (*Phaeocryptopus gaeumannii*), and *Phytophthora* root disease; 4) declines, including sudden aspen decline and yellow-cedar decline; and 5) invasive insects and diseases that have a connection with climate, such as sudden oak death (*Phytophthora ramorum*), emerald ash borer (*Agrilus planipennis*), gypsy moth (*Lymantria dispar*), and woolly adelgids (*Adelges* spp.).

## Biophysical Indicator: Water Balance Deficit—An Indicator of “Plant-Relevant” Drought

Major contributor: Jeremy Littell
Metric: Water balance deficit (calculated as a difference)

Water balance deficit is the difference between potential evapotranspiration (PET) and actual evapotranspiration (AET) (Fig. 10). Some metrics use ratios of the two variables (AET/PET; e.g., Shinker and Bartlein 2010). The difference (or, if used, the ratio) is an indicator of the terrestrial water budget, which is the atmospheric demand for water via evaporation and transpiration from the land surface (PET) and the supply of water to satisfy that demand from the land surface and transpired by plants (AET). When PET exceeds AET, there is deficit; when AET is equal to PET, there is no deficit or surplus. There will be surplus water (runoff or infiltration) when water supply is greater than PET. In North America, water balance deficit is correlated with the distribution of biome vegetation (Stephenson 1990), tree growth in the Pacific Northwest (Littell et al. 2008), and area burned by fire in the Western United States (Littell and Gwozdz 2011; Littell et al. 2009, 2010).

The more-familiar Palmer Drought Severity Index (PDSI; Palmer 1965) is an index of crop-available soil moisture. Water balance deficit and climatic water deficit (see Appendix 1) have been shown to be at least as well correlated with both ecological (Littell et al. 2008) and hydrologic (Abatzoglou et al. 2014) responses as PDSI is. Mu et al. (2013) discuss some of the limitations of PDSI compared to more direct indicators of plant water status, but for ecological applications the two most important are that PDSI does not adequately address

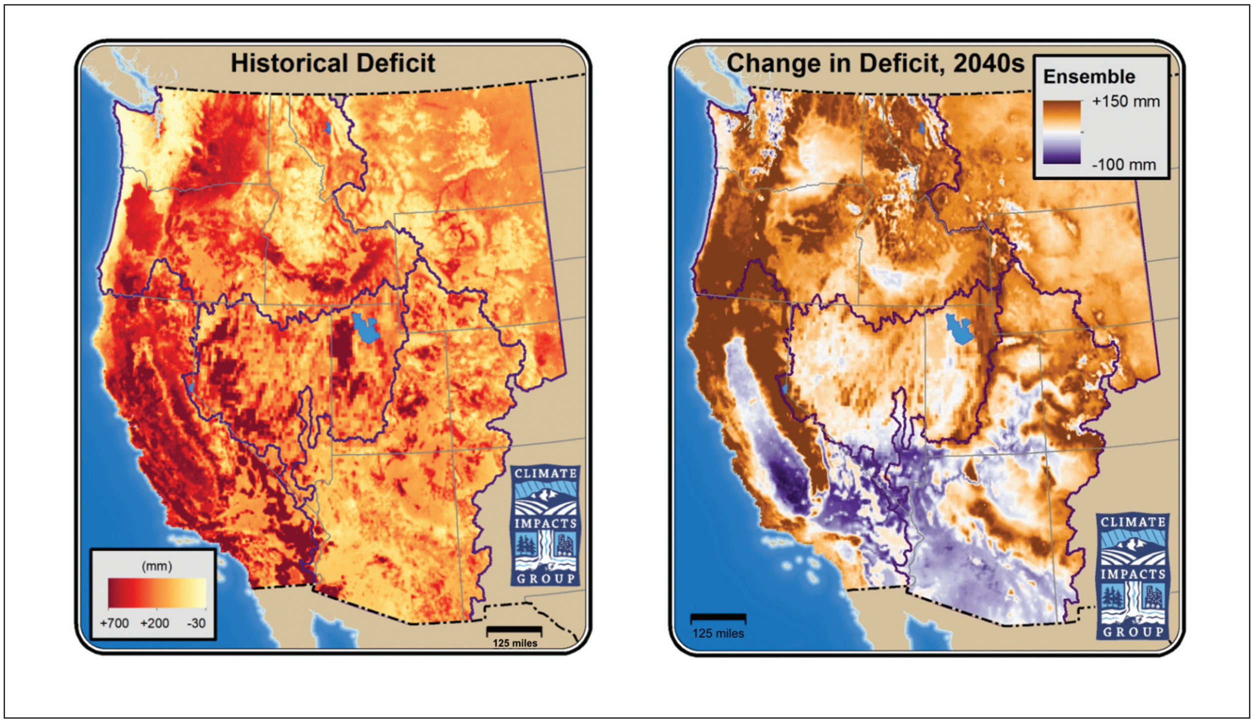


Figure 10.—Example maps for water balance deficit in the Western United States that could be used as the display for this metric. Left: mean summer precipitation deficit (millimeters), 1916-2006. Right: 2030-2059 ensemble change (from 1970-1999) in mean summer precipitation deficit (millimeters); ensemble is 10 global circulation models from the Intergovernmental Panel on Climate Change (2007) under SRES A1B.

snowpack storage and melt processes in its estimation of drought and that PDSI does not adequately account for evapotranspiration occurring at the potential rate. Dai (2011) advocated adopting metrics of water deficit other than PDSI. Additionally, both PET and AET can be estimated on continuous timescales and therefore can be related to extreme events at the timescales of weather or at longer term (monthly, seasonal to annual) timescales associated with climate. Dependence on longer (monthly) timescales is built in to PDSI, smoothing its response to shorter term moisture anomalies, and limiting application for some purposes. More information about issues with PDSI is provided in Appendix 1.

Direct measurements are less commonly made for PET and AET than for temperature, precipitation, and other climate variables. There are multiple methods to estimate both forms of evapotranspiration that range from simple to complex and also differ in the degree to which they approximate realistic observations for a given purpose. Most methods are based at least on surface climate observations (e.g., temperature and precipitation) and to varying degrees incorporate weather (e.g., wind and solar radiation), soil (e.g., field capacity and infiltration), and vegetation (e.g., aerodynamics and vegetation-specific resistance). Data sources exist and are either modeled or based on remote sensing, but more research is needed to make water balance deficit an operational indicator.

## Extent/Socioeconomic Indicator: U.S. Wildland-Urban Interface

Major contributors: Miranda H. Mockrin and Susan I. Stewart
Metrics: Area of wildland-urban interface, Population residing in wildland-urban interface

The wildland-urban interface (WUI) is the locus of direct interactions between human beings and wildland flora and fauna. Wildfire in the WUI may be of particular concern, especially in an era of global climate change (Fig. 11). The WUI is a context indicator that is arguably a result of adaptation to fire risk, which will also be important in adaptation to climate change. The WUI indicates where housing exists above the federally recognized density limit of 15.98 housing units per square mile (6.17 housing units per square kilometer) (U.S. Department of the Interior and U.S. Department of Agriculture 2001) and wildland vegetation is retained.

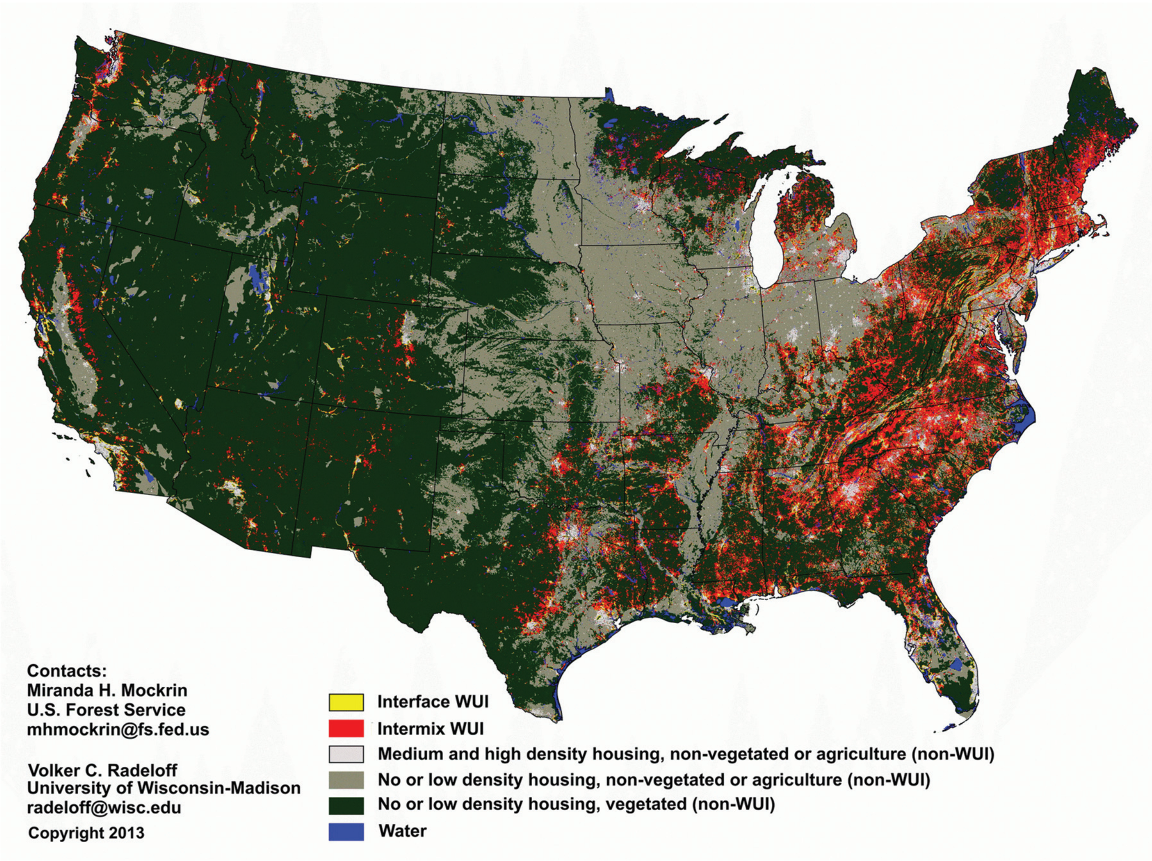


Figure 11.—Example map of the wildland-urban interface (WUI) in the United States, 2010, which could be used as a display for this metric (Stewart and Radeloff 2015).

Expansion of the WUI is not driven by global climate change (Theobald and Romme 2007). However, changes in the area and human population of the WUI are associated with processes that will affect wildland contributions and responses to climate change, such as degradation of wildland vegetation, migration of floral or faunal species, altered hydrology, increasing impervious surface, and introduction of exotic species of both flora and fauna (Fall et al. 2009; Radeloff et al. 2005, 2010). The growing size and spatial extent of human populations in wildland areas will bring people into immediate contact with climate change effects on wildland, magnifying social impacts with implications for human health, government budgets, recreation, and other social processes. The rate of WUI growth varies with people's environmental preferences, as well as economic and social constraints of their migration decisions. The past decades of WUI expansion have been driven by preferences for wild landscapes, rural lifestyles, flexible work patterns and new technologies (telecommuting), and lower home prices in rural areas. If these patterns change, the steady expansion of the WUI could slow.

Metrics for this indicator are currently available for operational use. Although we present this indicator as covering all wildland, we as the forest team can only recommend that this indicator be adopted as a cross-cutting indicator for land uses other than forest.

### Climate Impacts on Human Domain via Forest: Cost to Mitigate Wildfire Risk

Major contributor: Guy Robertson
Metrics: Expenditures on fire suppression activity, Expenditures on forest treatments to mitigate fire risk, Total payments for insurance premiums for policies against damage from forest fire. Units are inflation-adjusted dollars per year by category and (if available) by geographic region.

The extent of forest wildfires is currently measured in a biophysical sense, but the actual cost of fire to society extends well beyond the damages associated with specific fire events to include fire suppression and avoidance costs as well as premiums paid to insure against fire damage. Many of these costs are hidden (at least in comparison to the impact of major fire events), but they still impose a major cost on society and can act as a reliable proxy for the full financial impact of forest fires on society. We propose "Cost to mitigate wildfire risk" as an indicator to recognize the indicator group Climate impacts on the Human Domain via Forest.

More research is needed on this indicator, but the feasibility of providing metrics for this indicator is medium to high (e.g., see Lynch 2004). Federal fire suppression costs are readily available (Gorte 2011), but state and local expenditures make up an important piece of the picture, and their tabulation will likely entail state-by-state summation (see Figure 12, which uses only federal expenditures). The same is true for avoidance costs (i.e., for forest restoration and fuels treatments) with the added complication of defining what actually constitutes avoidance as opposed to forest management activities for other goals. Insurance premiums will depend on the availability of industry tabulations.

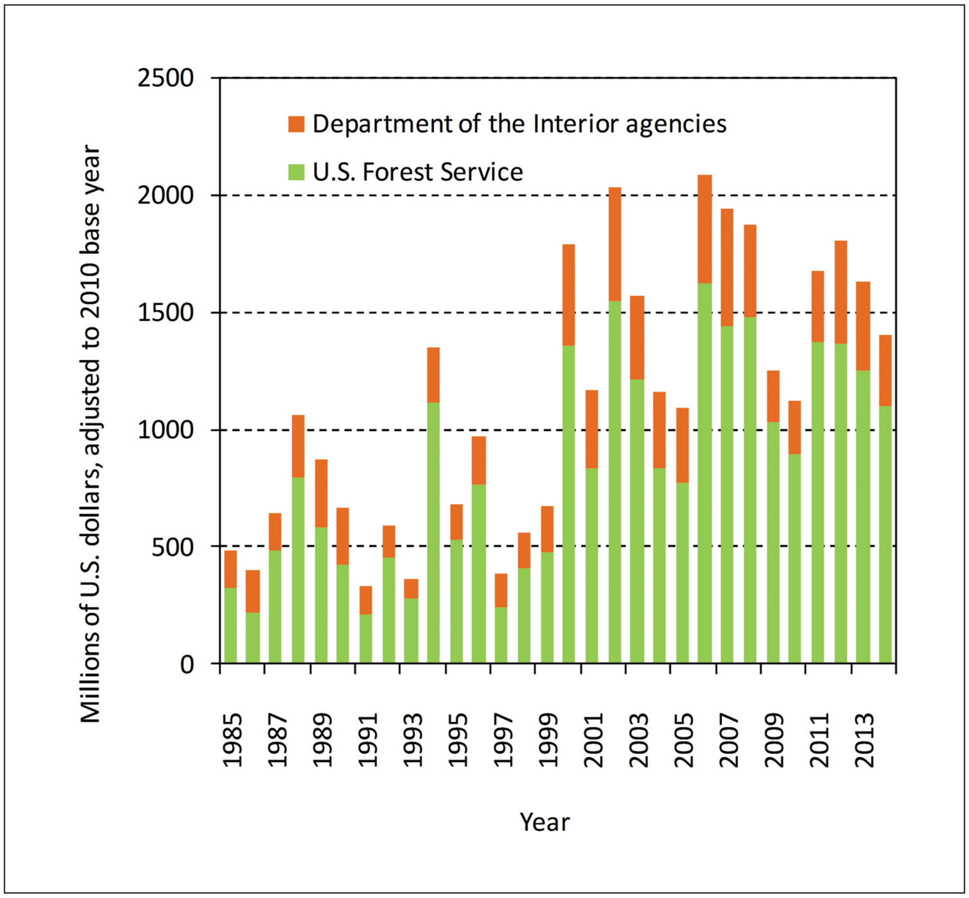


Figure 12.—Federal fire suppression costs, 1985-2014, in millions of dollars adjusted for inflation to base year 2010 shown for the U.S. Forest Service and for Department of the Interior agencies. This example lacks state and local forest wildfire suppression costs. Similar displays could be compiled for avoidance and insurance costs for all wildlands. Data: National Interagency Fire Center (2015).

## Human Domain Influences on Climate Domain via Forest: Energy Produced from Forest-based Biomass

Major contributor: Guy Robertson
Metric: Energy produced, domestically or in export markets, from biomass harvested from U.S. forests. Units are in British thermal units (Btu) per year and, if possible, $CO_2$ equivalent. (This is a measure of human influences on carbon sequestration.)

This indicator is proposed as a measure of human impact on atmospheric carbon concentrations via the forest sector and, more generally, as an indicator of social response to climate change (arrow 2 in the conceptual model). Aside from forest carbon sequestration, using forest-based biomass to produce energy is one of the most significant ways in which humans can influence atmospheric carbon through forest management activities. Forestland has long been used for energy production, either through the burning of wood in homes or, beginning in the last century, for cogeneration of heat and electricity in association with production of industrial wood products. In the last few years, pellet exports to Europe (in part as a response to the region's current carbon-neutral energy targets) have been expanding rapidly. Similarly, the use of wood to generate energy on an industrial scale independent of wood products manufacturing has been increasing, though the amount generated remains relatively small. And finally, the production of cellulosic ethanol and related fuels has been identified as a potentially nascent forest industry if the required technology becomes available. For all these reasons, forest-based bioenergy production is a key indicator relating climate change and forest to human activity.

Data readily exist to populate most of the indicator; a similar indicator has already been developed by the U.S. Forest Service (U.S. Forest Service 2011). We use an illustration from that source as a sample illustration for climate impacts (Fig. 13). Wood exports for foreign energy generation are not currently tracked, so work is needed to determine how to deal with measures or estimates of export volumes.

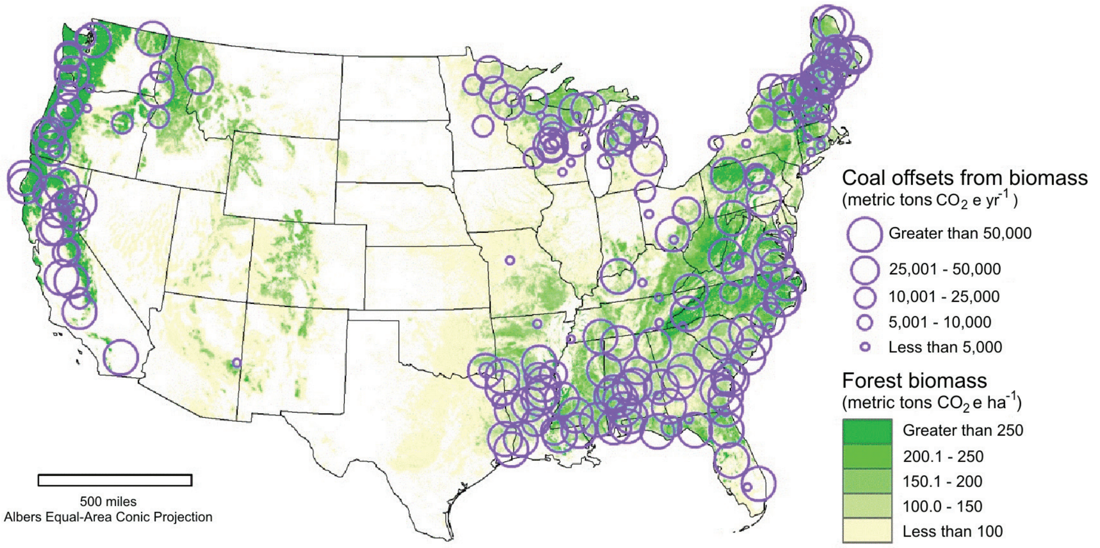


Figure 13.—Example display of a forest biomass energy indicator (metric tons of $CO_2$ equivalent per year). Source: U.S. Forest Service (2011).

### Socioeconomic/Ecosystem Services Indicator: Outdoor Recreation

Major contributor: Linda S. Heath, with major input from H. Kenneth Cordell
Metrics: Number of U.S. ski/snowboarder visits, Revenue of ski areas, Participation days in cross-country skiing

Outdoor recreation activities are a notable contribution to the U.S. national economy (see Cordell 2012), are of major importance to local and regional economies, and will be affected by climate variability (e.g., see Bowker et al. 2012, 2014). Snow sports such as downhill skiing, snowboarding, and cross-country skiing are associated with areas that have forests, although developed land use areas are not forestland. (However, when forest is identified by forest cover methods, developed land use areas that have trees may be considered forestland.) Snow-dependent activities are all expected to be influenced by climate variability, and by economic conditions and demographics. We chose developed skiing and cross-country skiing as the indicator area on which to focus. The links to climate are complex, so the impacts on the skiing industry are complex (Irland et al. 2001). For example, increased winter precipitation may be good for the skiing if it falls as snow and if skiers can travel to the slopes. But if the increase is in the form of rain, the effects are different.

Undeveloped cross-country skiing is thought to be affected most by ski conditions because resorts can manufacture snow for developed skiing, given adequate temperatures and access to adequate water. Using metrics for both developed and undeveloped areas may aid interpretation while more research is conducted.

Number of ski/snowboarder visits is a function of adequate snow, economic conditions, and demographics. It is defined as one person visiting a ski area for all or any part of a day or night one time. Participation days in cross-country skiing is the number of days during which an individual has participated in cross-country skiing regardless of location. This activity is more closely affected by climate variability than developed snow skiing overall. Revenue of ski areas is the amount of revenue that ski resorts receive. In 2011, total revenue was projected to be $2.6 billion, with net profit estimated at $182.6 million (Doré Group 2015). Table 4 provides an example of available data for number of visits.

Although these data are not new, and some have been used as indicators previously, more work is needed to ensure indicators are based on consistent datasets. Nearly all Americans enjoy some form of outdoor recreation, and data on participation in outdoor activities are collected at many levels. Some data sources from the recreation industry are available for purchase. Outdoor recreation is perceived to be strongly related to climate. To choose metrics relevant and useful to this indicator, we sought a major form of recreation clearly related to climate.

**Table 4.—Number of skier/snowboarder visits to developed ski areas, by region**

| | Skier visits[a] (millions) | | | | | |
|---|---|---|---|---|---|---|
| Season | Northeast | Southeast | Midwest | Rockies | Pacific | Total |
| 2012–2013 | 13.3 | 5.2 | 7.1 | 19.5 | 11.6 | 56.6 |
| 2011–2012 | 11.0 | 4.4 | 6.4 | 19.1 | 10.0 | 51.0 |
| 2010–2011 | 13.9 | 5.8 | 7.8 | 20.9 | 12.2 | 60.5 |
| 2009–2010 | 13.4 | 6.0 | 7.7 | 20.4 | 12.3 | 59.8 |
| 2008–2009 | 13.7 | 5.7 | 7.2 | 20.0 | 10.7 | 57.4 |

[a] The National Ski Areas Association defines a skier/snowboarder visit as one person visiting a ski area for all or any part of a day or night one time. This includes full-day, half-day, night, complimentary, adult, child, season, and any other ticket type that gives one the use of an area's facility. Data from National Ski Areas Association (2014); other data sources may show different estimates or trends (e.g., Cordell 2012).

## Research Gaps and Potential Indicators

Coordinators of the effort noted that many teams indicated more research is needed. After additional discussion, each team (including the forest team) was asked to submit a memo identifying high-priority indicators requiring more research, and discussing research gaps (see Appendix 2 for a revised copy of the memo). In this section, we first summarize research gaps for recommended indicators. Second, six areas are identified and described for additional indicator research. Although some of these indicators, such as permafrost, are not strictly focused on forestland, we list them here because our team members proposed them, and in addition it was unclear if the indicators fit well in another team. For more information on research gaps and potential indicators, see Appendix 2.

### Summary of Research Gaps

We identified four areas of research or development that would benefit all the recommended indicators. These areas are: research on the direct link and interpretation of indicators to climate impacts, discussions about links with indicators for other teams, guidance for determining when new approaches are better than existing approaches, and exploration about the concept of risk and its usefulness in terms of the indicators. For direct link and interpretation, studies are needed which explicitly investigate the connections between climate and the forest indicators, interpretation, and implications.

We have identified indicators that are useful to forests but most relevant to other teams, and discussing those links is crucial. Some users of these indicators may prefer a newer approach for the data, and uncertainty is inherent in all data. Guidance on how to decide between approaches for measures is needed to keep choices objective. Will the indicators be sensitive to response measures so that the effect of response activities will be detected? Furthermore, if the idea of risk is important to convey, how can risk be best conveyed through indicators? For additional details, see Appendix 2.

Specific research gaps or data needs were noted for four indicators (Table 5). Because of the differences in floral and faunal species in terms of trends in diversity/abundance, research gaps in these metrics are discussed separately. See Appendix 2 for the full text.

### Summary of Potential Indicators and Metrics

"Tribes and climate change" was proposed as an indicator, with three metrics: 1) Number of Native coastal communities relocated or needing to relocate in the next decade as a result of sea level rise or permafrost thaw, 2) Number of tribes developing climate change adaptation plans, and 3) Number of tribes and Native communities engaged with Climate Science Center/Landscape Conservation Cooperatives. As forest- and natural resource-dependent communities, Native peoples are among the first to be directly affected by accelerating climate

**Table 5.—Specific research gaps or data needs for selected recommended indicators**

| Indicator or metric | Research gaps or data needs |
|---|---|
| Diversity/Abundance of forest-associated faunal species | 1. Possible deficiencies in U.S. Geological Survey's Breeding Bird Survey data: a) Data collection focuses on single taxon, rather than a spectrum of forest-associated species; b) Known biases exist in data; some have been addressed, but others have not.<br>2. More work is needed to link trends to climate change effects.<br>3. Additional work is needed on the relation of faunal populations to influential factors other than climate. |
| Diversity/Abundance of forest-associated floral species | 1. Two issues for underlying data: a) Data from before 2000 are not consistent and methods to use them are needed; b) Options are needed for time-series use of Western U.S. data, which are expected to be measured only every 10 years; data series in the Eastern United States may not be long enough yet to assess biodiversity change associated with climate change.<br>2. Research is needed to determine the extent to which change in forest seedling diversity represents a leading indicator of climate change effects for overall forest biodiversity.<br>3. Research is needed to establish whether simple measures of biodiversity are sufficient, or whether biodiversity metrics that account for evolutionary relationships among species would be needed. |
| Climate impacts on Human Domain via Forest: Cost to mitigate wildfire risk | 1. Federal expenditures for fuels treatments and related mitigation activities can be accessed from federal budget reports, but the interpretation and use of measures need additional consideration.<br>2. Design of reporting activities for forest restoration activities will probably involve tallying expenditures to the state level, and may be labor-intensive.<br>3. Insurance premiums and related measures require additional exploration and conceptual development. |
| Human influence on Climate Domain via Forest: Energy produced from forest-based biomass | 1. A method or methods are needed to determine and include exports of forest biomass for energy production in current statistics.<br>2. Estimates of residential use and other diffuse energy production may require additional refinement, especially for emerging technologies or shifting markets. |
| Outdoor recreation (Developed skiing and cross-country skiing) | Additional available datasets could be used, especially in conjunction with local ski area monitoring, to better tie participation in developed skiing to location, and then to climate. |

change. With centuries to millennia in place, Native peoples also have a wealth of experience adapting to changes. In addition to humanitarian concerns, sea level rise and relocation of Native communities may challenge federal and state capacities to comply with treaty obligations, the American Indian Religious Freedom Act (1978), and other bodies of law. Because of the lack of information, these simple metrics based on numbers are suggested.

“Outdoor recreation and amenities” was proposed as an indicator area requiring more work, with three preliminary candidate metrics: 1) Mean high water, 2) Net internal rural migration rate, and 3) Number of participants and days of participation in hiking. This is an exploration of the current recommended indicator on outdoor recreation, augmented with amenities. An amenity is “an attribute that enhances a location as a place of residence” (McGranahan 1999). Although not strictly related to forest, mean high water would be of interest because in most coastal states, recreational access to beaches is granted to the public under the Public Trust Doctrine. As climate becomes warmer and sea levels rise, the public’s opportunities for using this outdoor recreation resource will change. Net internal migration rate, the difference between domestic in-migration to the area and out-migration from the same area during a time period, has been shown to be climate-sensitive (Cordell et al. 2011). Hiking is a popular activity that has been shown to be sensitive to climate (e.g., see Bowker et al. 2014).

A Permafrost indicator was discussed with a metric or metrics on extent and distribution of permafrost and peatland and associated changes in the depth of the active layer within boreal forest and tundra. Boreal forest and woodland are found in landscapes that include nonforest ecosystems. The ability to predict how climate change may affect these boreal systems hinges on our knowledge of the extent and distribution of permafrost and peatland, and the changes in active layer depth, typically rich in soil carbon. Permafrost is responding to changing temperature regimes, but it is unclear how this will affect near-surface processes in the long term (Abraham 2011). Advances in remote sensing techniques in recent years have provided new methods for mapping permafrost features (Abraham 2011) and peatland (Krankina et al. 2008, Torbick et al. 2012). The joint development of remote sensing methods with ground-based measurements to calibrate and verify remotely sensed results is critical, and appears to be within reach. Although permafrost does not occur throughout the United States, broad-scale changes in permafrost dynamics can have national implications.

A Lichen biodiversity indicator, in the indicator group Ecosystem services and goods, was proposed with metrics based on epiphytic lichen biodiversity or epiphytic lichen functional group. Lichens are highly climate-sensitive because they lack roots and are unable to retain water. Consequently, basic metabolic processes and fitness are closely tied to ambient temperature and moisture. We propose that a climate indicator be developed by using the FIA-based Lichen communities indicator. There already exists a large dataset of more than 8,000 epiphytic lichen surveys (1998-2013) collected by FIA and the U.S. Forest Service Region 6 Air Management Program, including many repeat measurements. Given the sensitivity of some lichens, these show promise as a potential leading indicator of climate change.

A Ground layer indicator, in the indicator group Structure and function, was proposed with metrics for effects of moss and lichen mats on biomass, elemental content (i.e., carbon and nitrogen), and functional importance. The indicator is based on the premise that simple measurements of the depth and area covered by mosses and lichens can be scaled into landscape-level estimates of biomass and elemental content based on prior calibrations. Functional importance is assigned to a dozen easily recognizable morphological groups, examples of which are soil stabilizers, nitrogen fixers, water regulators, and wildlife forage groups. Changing climates have the potential to shift species ranges, resulting in the gain or loss of major functional groups in ground layers. For example, a warming and drying climate can promote shrub expansion that excludes forage lichens (Heggberget et al. 2002). In wetland, lowered water tables coupled with more severe wildfires can eliminate critical peat deposits and the *Sphagnum* mosses which form them (Turetsky et al. 2011). Similar to the biodiversity of lichens, mosses may be a very climate-sensitive indicator.

*Usnea longissima* (Methuselah's beard), a good indicator of climate change. It is used by wildlife and requires a mild, moist habitat. Its main mode of reproduction is by fragmentation, which makes this species dispersal-limited. Photo by Sarah Jovan, U.S. Forest Service.

Ozone is an important greenhouse gas that also indirectly affects climate by limiting sequestration of $CO_2$ by vegetation (Sitch et al. 2007). An Ozone indicator with a metric of ozone concentrations in natural ecosystems may be strongly linked to climate. Additional research on the interaction of increased $CO_2$, temperatures, and ozone effects on individual forest tree species is needed. Little is known about the interaction of longer growing season, increased summertime ozone, and increased climate-induced vegetation stress such as drought on ecosystem response. Some data are available because an ozone indicator has been used previously in the U.S. Forest Service, Forest Health Monitoring program, although not in the context of climate change.

As stated earlier, this effort was designed in such a way that we did not consider adaptation indicators. There may be a number of crucial potential indicators of adaptation which are related to forests that will emerge only with dedicated attention to this area. For example, ecosystem-based adaptation is a commonly discussed management approach that merits greater attention. In addition, we may be recommending indicators and metrics which could be improved with a view that includes adaptation. We recommend additional investigation of indicators of forest-related adaptation.

## SUMMARY AND OBSERVATIONS

Many aspects of U.S. forestland are of national significance. Climate change impacts will also be of national significance. Response strategies in terms of mitigation are nationally important as well. We have identified 11 informative core indicators that have metrics available or close to being available for use in the NCA indicator system. The indicators are based on a comprehensive conceptual model we developed in which we treated forest as a land use and a sector.

We also identified seven indicators that are important in terms of climate impacts on forest, but that we thought were more relevant to other teams. Examples are temperature and precipitation, which we think the physical climate team will include, and budburst, which we encourage the phenology team to include. Wildfire indicators are relevant not only to forestland, but also to the grassland team and the phenology team. The phenology and forest teams to date, however, have developed different wildfire metrics, and the grassland team currently does not have a wildfire indicator. Additional discussions between the teams could help provide a leaner set of indicators with broader applicability.

As we worked through the assigned process, we realized there were many candidate indicators. We developed and adopted additional selection criteria, including the following: that overall our recommendations cover the range of our conceptual model, that selections feature a few indicators which could be reported on currently, and that we also consider important indicators not currently accessible for reporting. This approach provides immediate inputs for an indicator web portal, and identifies indicators requiring additional research to focus work on these areas. We did not identify any leading indicators within our core indicators. With more research, some of the potential indicators may serve as a leading indicator of climate impacts on forests.

We recognize that some indicators could be based on several different sources of data, each of which has various advantages and disadvantages to different stakeholders. We therefore adopted the definition of indicators as a description of the item, with the actual measure for the indicator called a metric. Additional research linking the metrics with climate change may prove one metric to be more broadly applicable than the others.

Because there are many interacting drivers of forest change, indicators may have a limited ability to represent only the impacts of climate change on forest. For example, land use decisions influenced primarily by economic considerations are expected to be major drivers affecting rates of afforestation and deforestation in the United States during the 21st century (Man 2012). Understanding the full context of the important drivers is necessary to properly interpret results.

In the future, more formal consideration of urban forest and settlements as well as agroforestry systems would be worthwhile. Although our charge did not include adaptation, activities involving urban forest and agroforestry are commonly mentioned in the scientific literature as possible adaptation approaches, and there is a need for forest-related adaptation indicators. In addition, one of our recommended indicators, the U.S. wildland-urban interface, may be an important indicator for adaptation responses. The indicator highlights urbanizing forest areas where social impacts of climate variability effects on wildland vegetation are expected to be magnified. This indicator is arguably a result of adaptation to wildfire risk, but it is also useful for adaptation responses to climate change. We also recognize the concept of risk in the context of indicators and climate change is important for decisionmaking, but more fundamental work is needed in that area before recommending an approach for use in an indicator system.

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# APPENDIX 1: Additional Indicator Details

We are including the material in this appendix for full transparency of our deliberations, and to provide details of the metrics and specifics of the recommended indicators for those who will be developing the Web portal. Some information presented here may be duplicated in the main text, but we have worked to reduce duplication while striving to make the entire publication understandable and readable.

## FOREST EXTENT INDICATOR: FORESTLAND AREA AND EXTENT

Metrics: Forestland area by land use, Forest area based on forest cover only

### Summary

Forestland area by land use is determined from U.S. Forest Service, Forest Inventory and Analysis (FIA) program information (U.S. Forest Service 2013) and may include observations from the National Land Cover Dataset (NLCD) (Multi-Resolution Land Characteristics Consortium [MRLC] 2014) or U.S. Census for area calculations. Units are acres (hectares).

Forest area based on forest cover only is determined by using a remote sensing approach, with observations compiled into the NLCD (MLRC 2014). Units are acres (hectares).

Both metrics are currently available, and are periodically updated and improved.

### Additional Descriptive Text

This indicator (Table 6) defines the forest category in terms of location on the land, distinguishing it from other land uses such as grassland. Climate affects forest extent directly (e.g., through increased mortality or enhanced recruitment), and indirectly (e.g., through increased prevalence of wildfires).

In terms of land use, forestland area in the United States was about 751 million acres (304 million hectares) in 2010 (U.S. Forest Service 2011). Scenario projections indicate decreases in forestland are likely in the future (U.S. Forest Service 2012). Since 2003, forestland area has shown a net increase by about

**Table 6.—Decision criteria for Forest extent indicator: Forestland area and extent**

| Decision criterion | Ranking | Justification |
|---|---|---|
| **Link to conceptual framework** | Collectively, the metrics are best. | The extent attribute largely indicates the geographic location of the Forest Domain, with changes and interactions illustrated by arrows 3, 4, 6, 7, 8, and 13. Each metric has its advantages and disadvantages. Showing the map and listing the statistics in a table is a good compromise. |
| **Defined relationship to climate, feedbacks, or impacts** | Individually, each is sufficient; collectively, the metrics are best. | Broad pervasive link to climate, but many confounding factors present |
| **Spatial scalability** | Best | One approach is best graphically; the other, statistically. |
| **Temporal scalability** | Sufficient to best | One approach may be available annually; the other is periodic. |
| **Of national (not necessarily nationwide) significance. Should link to the conceptual model** | Best for context in particular | We need to know where the Forest Domain is to discuss it. |
| **Relevance to management decisions** | Best for context in particular | We need to know where the Forest Domain is to discuss it. |
| **Usefulness for educational purposes** | Individually, each is sufficient; collectively the metrics are best | Yes, it is important to understand the location of forest. |
| **Is it a leading indicator?** | No | Not applicable |
| **Builds on existing data sources** | Yes | Yes, information is readily available but not necessarily for a specific year. |
| **Builds on existing indicator products** | Yes | Both build on existing sources. |
| **If new indicator proposed, likelihood of development and testing within 1 year given existing funding sources** | Not applicable | Not applicable |
| **Stability/Longevity of dataset** | Best | One may go back to the 1970s and the other to the 1950s, but these data are improved over time. Looking forward, the future of both datasets is sound. |
| **Stability/Longevity of indicator** | Collectively best | Improvements in research and development may eventually result in one map and one set of statistics but not yet. |
| **Scientific validity of indicator** | Each approach is valid in its own way. | Improvements in research and development may eventually result in one map and set of statistics but not yet. |
| **Data publicly available and transparent** | Best | Data are available on Web sites and are generally transparent. |
| **Indicator methods fully transparent and documented** | Sufficient to best | Access continues to improve. Both are documented, and documentation continues to improve. |

7.9 million acres (3.2 million hectares). In coastal areas, forestland is decreasing due to urban development, whereas in the interior United States, an increase in forest area is attributed to woody plant encroachment in grassland from fire suppression, changes in grazing patterns, or abandonment of agricultural land. The national estimates are updated about every 5 years. As noted in the Introduction, the FIA definition of forestland does not include narrow corridors or small patches of trees, and thus may not include riparian corridors, agroforestry, or urban forests.

The National Land Cover Dataset may also be used in conjunction with the U.S. Forest Service ground data estimates to increase mapping accuracy. Methods continue to be refined, thus improving the results and interpretation. Therefore, the approaches used for this indicator probably will have to be periodically updated, and the metrics recalculated for consistency over time.

### What Is the Link to Climate Variability and Change or Relevance?

Forest area responds to climate directly (through increased mortality or enhanced recruitment, or both) and indirectly (e.g., through increased prevalence of fire and insect outbreaks). Particularly in climate-limited regimes such as alpine treeline or grassland/forest ecotones, the area of forest can provide a direct indicator of biologic response to climate change.

### What Are the Drivers of This Indicator, and What Are Their Impacts?

Both human activities and climate affect forestland extent and area, as described above.

### Relevance to Management Decisions

The timber industry is important for the U.S. economy, and accounts for about 2 percent of U.S. employment. Understanding climate-induced changes in the distribution of U.S. forest cover will allow improved forecasting of U.S. timber production. Specific management strategies to mitigate climate change effects (fire suppression, introduction of new tree hybrids, establishment of protected areas) could be informed by improved tracking of forestland area.

### Other Indicators Considered But Not Recommended at This Time

Other remote sensing products include the National Aeronautics and Space Administration’s (NASA’s) moderate resolution imaging spectroradiometer (MODIS) land cover product (global since 2000). The resolution of the MODIS product is relatively coarse, however, and prospects for continuation past the current MODIS satellite lifetime are unclear. The U.S. National Resources Inventory (NRI) provides an alternate source for land cover information, but only on nonfederal land.

### Usefulness for Educational Purposes

Visualizing the distribution and changes to U.S. forestland can provide a graphic understanding of how climate and climate change affect the nation’s timber resources.

## Data Availability

### Length of Records of Dataset

FIA: Forest survey established by McSweeney-McNary Forest Research Act in 1928; continuous improvements since then. Transition to national, annualized reporting in 2000.

NLCD: First generated in 1992; subsequent versions in 2001, 2006. The 2011 version of NLCD is currently in production.

### Stability/Longevity of Dataset and Indicator

Both NLCD and FIA are long-term, operational products; FIA is Congressionally mandated.

### Notes About the Data (Change in Analysis or Collection Methods)

Both FIA and NLCD have improved their methods over time, and attention must be paid to whether observed decadal changes represent methodological effects, or real changes to forest cover.

### Spatial and Temporal Scalability

The FIA dataset is based on a geographic sample of forest cover, with known sampling error as a function of the land area being assessed. The NLCD is spatially explicit (30-m [100-ft] resolution), with per-pixel and regional accuracy evaluated by comparison with the FIA-based ground data.

## Details About the Indicator

### Type of Indicator (Current, Leading, Both)

Current

### Geographic Scope and Scale of Analysis

National

### Approach of Indicator (e.g., Single Measure, Composite)

The main metric on extent of forest is based on land use because this is the traditional approach used for the official forest statistics for the United States, based on FIA data (U.S. Forest Service 2013). Ground plots are visited and measurements taken. Based on the plots and census data estimates of land area, forestland area is calculated. Maps of forest biomass (e.g., Wilson et al. 2013) based on the plot data can be used for forestland.

A second metric on extent of forest can be based on the NLCD (Homer et al. 2012, MLRC 2014). This is a remote sensing approach, which differentiates forest based on forest cover using remote sensing with limited consideration of some land uses. The NLCD approach is also currently used to determine urban forest extent (e.g., see Nowak and Greenfield 2008), but there are methodological issues for use in determining forest as described in Nowak and Greenfield (2010).

### Purposes and Conceptual Framework

The extent attribute largely indicates the geographic location of the Forest Domain, with changes and interactions illustrated by arrows 3, 4, 6, 7, 8, and 13. Extent of forest is important as an indicator because it defines forest boundaries and the area involved. The amount of forestland can be locally dynamic due to human activities and can vary due to differences in definition or estimation approach. Climate affects vegetation and amount of forestland directly (e.g., extended drought may cause tree mortality or impede regeneration) and indirectly (e.g., climate may influence insect outbreaks that cause broad-scale tree mortality). Knowledge of forestland area and change of forestland over time by broad forest-group class is especially important for climate mitigation because decreases in forestland translate directly into increased greenhouse gas emissions from the forest sector. Scenarios indicate decreases in forestland are likely in the future (U.S. Forest Service 2012).

## Considerations for Selection of Indicator

### Advantages

Together, FIA and NLCD provide both a sample-based and geospatial representation of U.S. forestland, which is consistent with U.S. reporting to the United Nations Framework Convention on Climate Change.

### Disadvantages

Methodological changes in both FIA and NLCD can make long-term trend analysis difficult. The error characterization of remote sensing products such as NLCD needs to be carefully considered as a function of cover type, geography, and data quality.

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## STRUCTURE AND FUNCTION INDICATOR: FOREST BIOMASS DENSITY

Metrics: Aboveground live tree biomass density, Dead wood mass density

### Summary

Aboveground live tree biomass density (biomass per unit area) is calculated by using FIA data (U.S. Forest Service 2013). Data are measured from a statistically designed series of ground plots across the United States, using documented methods. Units are tons per acre (metric tons per hectare).

Dead wood mass density is calculated by using FIA data (U.S. Forest Service 2013). Data are measured from a statistically designed series of ground plots across the United States, using documented methods. In some cases, dead wood may be estimated. Units are tons per acre (metric tons per hectare).

Both metrics are currently available, and are periodically updated and improved.

### Additional Descriptive Text

The use of aboveground live biomass density as a metric of forest structure (Table 7) conveys information related not only to climate mitigation in terms of forest stocks, but also to potential availability of biomass for bioenergy, which can be used as a substitute for fossil fuel to produce energy. Climate change may directly affect live biomass by influencing mortality, growth, and regeneration; or the demand for biomass to lower overall emissions may result in decreased stocks of biomass. Forest health issues may result in a greater amount of dead mass in relation to live biomass, so a second important metric is dead wood mass density.

Table 7.—Decision criteria for Structure and function indicator: Forest biomass density

| Decision criterion | Ranking | Justification |
|---|---|---|
| **Link to conceptual framework** | Best | Fundamental attribute of structure (within structure and function attribute within Forest Domain), with changes and interactions represented by arrows 4 and 5, as well as connections with arrows 6, 7, 8, and 13. |
| **Defined relationship to climate, feedbacks, or impacts** | Best | Climate is one of the fundamental drivers of potential vegetation, and major structural changes across landscapes will affect weather. If changes are large enough, this becomes climate change. |
| **Spatial scalability** | Best | Data nationally available, but limited at small scales. Methods can be used locally for data to derive estimates. |
| **Temporal scalability** | Sufficient | Annual estimates can be derived. |
| **Of national (not necessarily nationwide) significance? Should link to the conceptual model** | Best | Yes, sequestration in U.S. forests offsets 10–20 percent of fossil fuel emissions. Indicator is of key significance to the Forest Domain. |
| **Relevance to management decisions** | Best | Direct impacts on forests usually affect forest area or forest structure (e.g., in terms of biomass) or both, making biomass density a very relevant indicator. Biomass (carbon) is a fundamental consideration in terms of climate mitigation. |
| **Usefulness for educational purposes** | Best | Yes, Americans are passionate about their forests. Increased mortality (in relation to live biomass) will be of interest, and will provide a basis for education on forest ecosystems and how they function. |
| **Is it a leading indicator?** | No | But projections are available, and it does speak to climate mitigation by forests. |
| **Builds on existing data sources** | Yes, best | Based on FIA data, is standard for the United States |
| **Builds on existing indicator products** | Best | It can build on existing indicator products or official reporting statistics. These will be similar but not the same. |
| **If new indicator proposed, likelihood of development and testing within 1 year given existing funding sources** | Not applicable | Not applicable |
| **Stability/Longevity of dataset** | Best | FIA dataset has existed for decades, and is expected to continue. |
| **Stability/Longevity of indicator** | Best | This is a fundamental indicator and is expected to be available for the long term. |
| **Scientific validity of indicator** | Best to sufficient | There are questions about the biomass equations, and research is currently being conducted. But the estimates are considered valid as is. |
| **Data publicly available and transparent** | Yes | Available for download |
| **Indicator methods fully transparent and documented** | Best | More research would be useful in terms of the connection with climate. Documentation in terms of the climate impacts on forests would be useful. |

Biomass per unit area can be more closely linked to climate than can total forest biomass, which is biomass per unit area multiplied by forest area. The interpretation of total forest biomass is confounded by the change in forest area, a change that may or may not be related to climate. We have included forest area as an indicator so that the effects of changing forest area can be more directly interpreted.

Total forest biomass stock is important in terms of policy-relevant climate impacts. For example, values for total live and dead wood forest carbon (which is a direct function of biomass) for the United States are required for the annual national greenhouse gas inventory reporting to the United Nations Framework Convention on Climate Change; the latest report is U.S. Environmental Protection Agency [EPA] (2013) (Table 8). Terrestrial contribution to greenhouse gas inventories is being considered as an indicator for the mitigation team. The carbon estimates are calculated by multiplying the carbon estimates by two to express carbon as dry weight biomass. Dividing by forest area produces the metric biomass density (per unit area), and conversely multiplying biomass density by forest area produces total biomass.

### What Is the Link to Climate Variability and Change or Relevance?

An overarching issue identified in the National Report on Sustainable Forests—2010 (U.S. Forest Service 2011) is the interaction of forests, climate change, and bioenergy. Climate change was recognized as presenting a profound challenge for forests and forestry in the United States, with possible altered forest patterns in the future (U.S. Forest Service 2012). Forests in the United States currently serve as a large carbon sink (Heath et al. 2010) and as a main source of renewable energy. Because aboveground tree biomass and dead wood mass are major components of carbon in forests reported in the national greenhouse gas inventories, this indicator is an important link to climate mitigation. Biomass estimates are important to inform possible availability for bioenergy. Biomass amounts are affected by climate, and climate variability can affect mortality, growth, regeneration, and decomposition, so mass of both live trees and dead wood is important.

**Table 8.—Million metric tons of total aboveground live and dead wood mass in U.S. forestland (U.S. EPA 2013)**

| | Year | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Component | 1990 | 1992 | 1994 | 1996 | 1998 | 2000 | 2002 | 2004 | 2006 | 2008 | 2010 | 2011 |
| Aboveground tree biomass | 24,568 | 24,962 | 25,368 | 25,808 | 26,258 | 26,682 | 27,110 | 27,580 | 28,062 | 28,512 | 28,952 | 29,172 |
| Dead wood | 4,322 | 4,358 | 4,396 | 4,434 | 4,492 | 4,546 | 4,600 | 4,656 | 4,708 | 4,766 | 4,822 | 4,852 |

### What Are the Drivers of This Indicator, and What Are Their Impacts?

Both climate and human activities affect this variable, as described above.

### Has This Indicator Been Used as an Indicator by Anyone Else; If So, By Whom, and How Was It Used and When Was It Initiated?

Biomass or carbon density of aboveground live trees and dead wood have been formally used as indicators at the national level (e.g., see U.S. Forest Service 2011) and are used at the project level.

### Relevance to Management Decisions

Biomass density of live trees and dead wood is the cumulative effect of changes to the forest. Accurate and precise biomass estimates are needed for climate mitigation reporting, determination of forest mitigation activities, and supply for bioenergy. Biomass estimates will help inform planning for ecosystem-based adaptation activities, such as those along riparian areas or shade for livestock. Biomass estimates are relevant at all geographic scales, from national to local.

### Other Indicators Considered But Not Recommended at This Time

Other forest carbon ecosystem components were considered for structure, but aboveground biomass density is the most dynamic and most precise. We considered reporting these as carbon stock density rather than in terms of biomass, but a simple conversion (biomass = 2 × carbon) is reasonably accurate. Biomass density is useful for bioenergy supply, although green weight biomass may be preferred for bioenergy. Biomass change was also considered, but greenhouse gas changes are more applicable for the mitigation category.

### Usefulness for Educational Purposes

Visualizing the distribution and changes to live and dead mass density can provide a graphic understanding of the cumulative effects of how land use, management, and climate change affect the nation’s forest resources. Changes in tree biomass density in locations not under direct human management such as at high elevations, and significant changes in the amount of dead wood mass in comparison to live mass may be due to climate. Biomass density is also directly essential for telling the story of the demand and supply for human needs for energy and resulting emissions, and identifying those areas where wood biomass may be available for bioenergy.

## Data Availability

### Length of Records of Dataset

FIA: Forest survey established by McSweeney-McNary Forest Research Act in 1928; continuous improvements since then. Transition to national, annualized reporting in 2000. Practically speaking, individual state-level tree datasets are available beginning in the late 1980s. Projections of this indicator, consistent with the current data, are available (e.g., see U.S. Forest Service 2012).

### Stability/Longevity of Dataset and Indicator

The FIA program is Congressionally mandated, and the data are expected to continue to be collected. Older datasets are occasionally revised and the sample design or protocols may change. Models to estimate biomass from tree measurements may occasionally change. However, these changes can be controlled for over time.

### Notes About the Data (Recent Changes in Analysis or Collection Methods)

The FIA program has updated its methods over time, and attention must be paid to whether observed changes represent methodological effects, or real changes.

### Spatial and Temporal Scalability

The FIA dataset is based on a geographic sample, with known sampling error as a function of volume or basis.

## Details About the Indicator

### Type of Indicator (Current, Leading, Both)

Current

### Geographic Scope and Scale of Analysis

National to state to county, although precision of the estimates decreases for smaller areas.

### Approach of Indicator (e.g., Single Measure, Composite)

The use of aboveground live biomass density as a metric of forest structure conveys information related not only to climate mitigation in terms of forest stocks, but also to potential availability of biomass for bioenergy, which can be used as a substitute for fossil fuel to produce energy. Climate change may directly affect live biomass by changing mortality, growth, and regeneration; or the demand for biomass to lower overall emissions may result in decreased stocks of biomass. The FIA program provides the official forest statistics for the United States, based on its data (U.S. Forest Service 2013); FIA's approach is the one traditionally used for this indicator.

Forest health issues may result in a greater amount of dead wood mass in relation to live biomass, so a second important metric is dead wood mass density. This metric is also relevant for the same reasons as live tree biomass, and the dynamics are related to live biomass in the sense that dead wood comes from live biomass. But the resulting fate of dead wood may be quite different. Past data on dead wood are limited.

### Purposes and Conceptual Framework

This indicator applies directly to the Structure and function attribute in the conceptual model. Aboveground biomass of trees is a fundamental, multipurpose indicator for context and climate mitigation. It can also be a useful measure to inform ecosystem-based adaptation planning, projects, and implementation. Biomass is a key determinant as to whether a land area is forest or some other land use.

### Scientific Validity of Indicator

The validity of the estimates is well established for climate mitigation purposes. More research is needed for understanding the direct effects that climate variability or change may have on biomass across the landscape.

### What Are the Plans for Further Development of the Indicator?

Research is currently being conducted to improve biomass equations. Much research is also being conducted by using new measurement techniques such as light detection and ranging (LIDAR). However, these have not been coordinated activities to improve the indicator per se.

## Considerations for Selection of Indicator

### Advantages

Data from FIA provide a sample-based representation of forest biomass that is consistent with U.S. reporting to the United Nations Framework Convention on Climate Change. These estimates are well used and well accepted by a wide range of stakeholders in the United States.

### Disadvantages

Methodological changes in FIA data can complicate long-term trend analysis. Estimates for dead wood mass are particularly limited before recent time periods.

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## ECOSYSTEM SERVICES INDICATOR: TRENDS IN DIVERSITY/ABUNDANCE OF FOREST-ASSOCIATED FLORAL AND FAUNAL SPECIES

Metrics: Forest tree biodiversity status and trends, Forest bird biodiversity status and trends

### Summary

Forest-associated floral biodiversity status and trends would be represented by data on forest tree diversity, using FIA data (U.S. Forest Service 2013). Spatially explicit analyses of tree species over time are possible for much of the United States. Units would be number of tree species; percentage change over time or change in species occurrence could be used.

Forest-associated faunal biodiversity status and trends would be represented by data on forest-associated bird species. A metric with the greatest near-term potential would use, in part, the national-level U.S. Geological Survey (USGS) Breeding Bird Survey (BBS) (USGS 2015b) data. Units would be number of birds; percentage change over time or difference from an average for categories of types of birds (i.e., eastern, western, boreal) could be shown.

Both metrics need further research and technical work, especially on fauna.

### Additional Descriptive Text

We propose the development of metrics for a forest biodiversity indicator that track biodiversity status and trends in forest tree (Table 9) and bird (Table 10) populations. Dissimilarities in life history and population characteristics between plants and animals, in addition to differences in data availability, will require different approaches for tracking biodiversity change between the two metrics.

### Forest Faunal Biodiversity Status and Trends

Although national-level data are limited for fauna other than birds, efforts such as the USGS Amphibian Research and Monitoring Initiative Database (see USGS 2015a) are currently expanding and may serve as useful indicators for other taxa.

Forest-associated species population status could also be monitored through changes in species conservation status. The International Union for the Conservation of Nature (IUCN) Red List of Threatened Species identifies conservation status of more than 45,000 species globally. Species are assigned to a Red List category, identifying their risk of extinction, based on a suite of objective criteria (IUCN 2001). Changes in the Red List category for a species can indicate changing population size, and a broad-scale analysis of suites of species (in this case, forest-associated) can provide a measure of changes in biodiversity (e.g., Butchart et al. 2004).

**Table 9.—Decision criteria for Ecosystem services indicator: Trends in diversity/abundance of forest tree species**

| Decision criterion | Ranking | Justification |
|---|---|---|
| **Link to conceptual framework** | Best | Links directly to Ecosystem services and goods attribute, coupled with Structure and function, arrows 4 and 5 |
| **Defined relationship to climate, feedbacks, or impacts** | Best | Studies show long-term impacts of climate on biodiversity; modeling studies indicate relationship. |
| **Spatial scalability** | Best | FIA data are collected (across about 130,000 plots) in a nationally consistent sampling protocol, with one plot representing 6,000 ac (2,428 ha) of land. |
| **Temporal scalability** | Best | FIA plots are inventoried every 5 to 7 years in the East and every 10 years in the West. |
| **Of national (not necessarily nationwide) significance? Should link to the conceptual model** | Best | Yes for national reporting. Several possible important management priorities are tied to biodiversity, so it is very relevant. |
| **Relevance to management decisions** | Best | Biodiversity is one of several possible management priorities. |
| **Usefulness for educational purposes** | Sufficient | Unless effects are dramatic, the metrics may not be easily understood by public. |
| **Is it a leading indicator?** | Not applicable | Not proposed as leading indicator |
| **Builds on existing data sources** | Best | Readily available |
| **Builds on existing indicator products** | Best | Readily available |
| **If new indicator proposed, likelihood of development and testing within 1 year given existing funding sources** | This is not necessarily new, but would be new in this context. | To our knowledge, no targeted funding specifically for this |
| **Stability/Longevity of dataset** | Best | FIA program is well-established. |
| **Stability/Longevity of indicator** | Sufficient | Additional calculations are needed for indicators. |
| **Scientific validity of indicator** | Best | Many scientific studies confirm its validity, although more research on the information that the indicator provides in a climate context could be useful. |
| **Data publicly available and transparent** | Sufficient | Data publicly available but somewhat complicated to use |
| **Indicator methods fully transparent and documented** | Best | See existing literature. |

**Table 10.—Decision criteria for Ecosystem services indicator: Trends in diversity/abundance of forest-associated bird species**

| Decision criterion | Ranking | Justification |
|---|---|---|
| **Link to conceptual framework** | Sufficient | Links directly (arrows 3 and 5, and Ecosystem services and goods attribute) |
| **Defined relationship to climate, feedbacks, or impacts** | Sufficient | Although data suggest that climate change is affecting avian populations, numerous other drivers probably influence this indicator as well. |
| **Spatial scalability** | Best | Breeding Bird Survey data allow analyses at the regional through national-level scales. |
| **Temporal scalability** | Best | Data are available from 1966 through the present. |
| **Of national (not necessarily nationwide) significance? Should link to the conceptual model** | Best | Data have national-level coverage and are available for more than 400 avian species. |
| **Relevance to management decisions** | Sufficient | Numerous management strategies have been suggested or implemented for maintaining avian biodiversity under climate change. The Breeding Bird Survey provides one measure of biodiversity (as included in the framework) but has data on only one taxon. |
| **Usefulness for educational purposes** | Best | This indicator already incorporates public education/outreach and, given widespread interest in bird species, has additional possibilities. |
| **Is it a leading indicator?** | Not applicable | Not applicable |
| **Builds on existing data sources** | Best | Data are readily available. |
| **Builds on existing indicator products** | Best | Data are readily available. |
| **If new indicator proposed, likelihood of development and testing within 1 year given existing funding sources** | Relatively new in this context | To our knowledge, no targeted funding specifically for this |
| **Stability/Longevity of dataset** | Best | Continuous data collection since 1966 |
| **Stability/Longevity of indicator** | Sufficient | Additional research may be needed, but sufficient information is available. |
| **Scientific validity of indicator** | Best | More than 450 scientific journal articles have used Breeding Bird Survey data in analyses. |
| **Data publicly available and transparent** | Best | Data (raw and trend estimates) are available on Web site. |
| **Indicator methods fully transparent and documented** | Best | Methods are well documented on Web site and in numerous published articles. More research to understand the information that the indicator provides in a climate context would be useful. There are many different species. Some may be more indicative of climate impacts than others. Additional research could prove fruitful. |

This indicator of climate change impacts on forest biodiversity status and trends will be particularly relevant given the importance of considering biodiversity in policy and management decisions, especially those involving large temporal and spatial scales (Hooper et al. 2005). The BBS will be the focus of the forest fauna biodiversity indicator because this team believes it to have the greatest potential. Other indicators that we considered are referenced in the text above and in the section on other considered indicators.

### What Is the Link to Climate Variability and Change or Relevance?

Forest ecosystems serve as habitat for a wide range of floral and faunal species. Consequently, climate-induced alterations in forest structure could have profound implications for forest-associated species. In turn, biodiversity conveys numerous functional benefits to forest ecosystems, including reduced susceptibility to invasion after disturbance and enhanced ecosystem reliability (Balvanera et al. 2006). Research also has linked biodiversity to ecosystem primary productivity (Cardinale et al. 2007). Robust indicators of change in forest biodiversity will therefore be important for tracking forest community response to climate change.

### What Are the Drivers of This Indicator, and What Are Their Impacts?

**Forest floral biodiversity status and trends**—Plant species are expected to respond in one of three ways to the numerous climate change effects that could push their current habitat out of their tolerance limits: 1) persistence in situ if within species' tolerance limits, 2) range shift, or 3) local extirpation (Davis et al. 2005). As plant species are eliminated from existing areas and are successfully dispersed to new areas, the last two responses could affect forest biodiversity and its associated ecological benefits. Weak correlations between change in tree seedling diversity and latitude have been detected in the Eastern United States, along with regional increases in the seedling diversity of species with longer-distance dispersal capacity (Potter and Woodall 2012).

**Forest faunal biodiversity status and trends**—Climate change can affect faunal biodiversity through a variety of mechanisms including shifts in geographic range, phenological changes, and physiological stress (Thuiller 2007). The ability of a species to respond or adapt to these changes is probably specific to the species and region.

### Has This Indicator Been Used as an Indicator by Anyone Else; If So, By Whom and How Was It Used and When Was It Initiated?

**Forest tree biodiversity status and trends**—The fundamental importance of biodiversity to forest management and forest health monitoring at a national scale is recognized by its incorporation into indicators of forest sustainability, including the Montreal Process Criteria and Indicators for the Conservation of Sustainable Management of Temperate and Boreal Forests (see U.S. Forest Service 2011).

**Forest bird biodiversity status and trends**—The use of wild bird surveys as an indicator of biodiversity and ecosystem health is widespread around the world. Wild bird indicators are in use by numerous European national governments (Gregory and van Strien 2010) and the Biodiversity Indicators Partnership. A recent study using BBS data found a general pattern of northward shifts in avian breeding range, consistent with expectations of climate change (Hitch and Leberg 2007).

### Relevance to Management Decisions

**Forest tree biodiversity status and trends**—Forest tree biodiversity is an important management concern at multiple scales. The following is from the FIA program Web site: "As the Nation's continuous forest census, our program projects how forests are likely to appear 10 to 50 years from now. This enables us to evaluate whether current forest management practices are sustainable in the long run and to assess whether current policies will allow the next generation to enjoy America's forests as we do today" (U.S. Forest Service 2013).

**Forest bird biodiversity status and trends**—Maintaining or increasing floral and faunal diversity is a goal of numerous land management agencies. A variety of management strategies, such as maintaining movement corridors, have been suggested for maintaining biodiversity under climate change. An indicator that allows examination of avian population trends could be used to help inform these management decisions.

### Other Indicators Considered But Not Recommended at This Time

**Forest floral biodiversity status and trends**—We considered two other metrics. One was assessments of tree species range shifts. These analyses may be possible. Most of the analyses would probably involve use of FIA data, but would require the identification of indicator species, which could prove challenging. Additionally, research is ongoing regarding how best to quantify tree range shifts. Finally, extra cycles of measurements on FIA plots over time may be required to be able to detect meaningful shifts. The other floral metric we considered was understory flora biodiversity status and trends. However, inventories of understory plants have been conducted on a subset of FIA plots in only a few regions, with remeasurements occurring on only a small number of plots. Indicators of forest plant diversity exclusive of trees would have to rely on static, county-level occurrence data available through the USDA Plants Database (Natural Resources Conservation Service 2015); assessing change over time would not be possible. Because of these limitations, we did not recommend either of these.

**Forest fauna biodiversity status and trends**—We considered a variety of indicators including indicators based on number of species (e.g., Global Biodiversity Information Facility [GBIF]) and indicators based on changes in species conservation status (e.g., IUCN Red List of Threatened Species). The advantage of these two approaches over the population trend indicator that we have suggested is that they include data for a large suite of taxa. The disadvantage of these types of biodiversity indicators is that many of them rely on museum records and so provide only a static representation of diversity. In contrast, the trend data allow a more temporally dynamic picture (which would be important for climate change). The disadvantage of the IUCN Red List of Threatened Species is that this index is not as quantitative and would not allow fine-scale spatial and temporal analyses of population trends. Data from BBS are available both in raw form and as estimates of trends.

### Usefulness for Educational Purposes

**Forest tree biodiversity status and trends**—Change in forest tree biodiversity is a relatively simple concept; people can easily grasp the concept of forests containing fewer or more species. The spatial scalability of the indicator can allow people to understand how climate change (along with other drivers) could be affecting the diversity of tree species that occur in their areas.

**Forest bird biodiversity status and trends**—The BBS can be useful for educational purposes for several reasons. First, education is already inherent in the indicator because the survey is conducted primarily by citizen scientists and thus relies on public education and outreach to achieve high-quality data. Second, bird watching is a popular recreational activity for a large number of people. An indicator that incorporates a taxon with such widespread popularity enables additional educational opportunities.

## Data Availability

### Length of Records of Dataset

**Forest tree biodiversity status and trends**—Initial federal forest inventory efforts were undertaken starting in 1930. The inventory program evolved over time, with additional information collected by using a variety of methods across the United States. The FIA sampling protocol was standardized across the country beginning about 2000, and the program's annual data collection approach is ongoing.

**Forest bird biodiversity status and trends**—The BBS has data available from 1966 through the present. Survey routes have been added over time, so earlier datasets cover less geographic area than more recent years' efforts.

### Metadata

**Forest tree biodiversity status and trends**—The FIA data and documentation are available at U.S. Forest Service (2013).

**Forest bird biodiversity status and trends**—Metadata are available at USGS (2015b).

### Stability/Longevity of Dataset and Indicator

**Forest tree biodiversity status and trends**—Standardized data collection began about 2000, varying by state. Eastern states (on a 5- or 7-year cycle) have finished their first inventory of plots and, in some places, the second inventory. Some western states have completed their first inventory of plots (on a 10-year cycle), but some lag. Ongoing data collection is expected to remain stable, depending on federal funding.

**Forest bird biodiversity status and trends**—The BBS appears to be very stable and has been gaining interest since its introduction in 1966.

### Notes About the Data (Recent Changes in Analysis or Collection Methods)

**Forest tree biodiversity status and trends**—Inventory data are available from before the transition from periodic to annual inventory (ca. 2000), but it is difficult to compare data collected under the two inventory approaches.

**Forest bird biodiversity status and trends**—Although the general data collection protocols have remained fairly consistent over time, the BBS is increasingly taking advantage of current statistical analyses and geospatial technology to augment the survey data.

### Spatial and Temporal Scalability

**Forest tree biodiversity status and trends**—Data from FIA are highly scalable spatially and, to a lesser degree, temporally. Data are collected (across about 130,000 forest plots) in a nationally consistent sampling protocol, with one plot representing 6,000 acres (2,428 hectares) of land. Plots are inventoried every 5 or 7 years in the East and every 10 years in the West.

**Forest bird biodiversity status and trends**—Data from the BBS allow regional through continent-wide analyses of avian species populations trends.

## Details About the Indicator

### Type of Indicator (Current, Leading, Both)

Current

### Geographic Scope and Scale of Analysis

**Forest tree biodiversity status and trends**—The geographic scope of the analysis would be national, using data from about 130,000 FIA plots. Plot-level results would be aggregated, most likely to ecoregions.

**Forest bird biodiversity status and trends**—Data are available for more than 4,100 survey routes and 400 avian species across the United States and Canada.

### Approach (e.g., Single Measure, Composite)

**Forest tree biodiversity status and trends**—The difference in data collection between the eastern and western states will require different approaches for the two regions. Given that the first 10-year cycle of data collection is not yet complete in much of the West (although plots have been revisited in some areas of some states), it will be necessary to determine baseline forest tree biodiversity for this region. Data would be collected for both trees and seedlings. In the East, most states are well into their second 5- or 7-year inventory cycle (with some starting their third), so it will be possible to establish baseline biodiversity and to assess change over time in biodiversity. Again, this effort would be for both trees and seedlings, as change in seedling diversity is expected to be a leading indicator of change in overall forest biodiversity. Biodiversity would be quantified primarily as number of tree species, although biodiversity metrics that account for the evolutionary relationships among species also have utility.

**Forest bird biodiversity status and trends**—Data from the BBS are available both in raw form and as trend data. Analyses could be conducted at the regional level up through a continent-wide approach. Data could be used in a variety of ways including general monitoring of forest avian population trends (e.g., increases/decreases in single or multiple species populations), changes in forest avian community structure, or changes in population ranges.

## Purposes and Conceptual Framework

In terms of the conceptual framework, biodiversity of flora links directly to the Ecosystem services and goods attribute, coupled with Structure and function, arrows 4 and 5. Biodiversity of fauna links directly to arrows 3 and 5, and the Ecosystem services and goods attribute. The fundamental importance of biodiversity to forest management and forest health monitoring at a national scale is recognized by its incorporation into indicators of forest sustainability, including the Montreal Process Criteria and Indicators for the Conservation of Sustainable Management of Temperate and Boreal Forests. Years of research have documented many functional benefits of biodiversity to natural ecosystems, including reduced susceptibility to invasion, enhanced ecosystem reliability, and increased productivity. Changes in forest biodiversity as a result of altered climatic conditions may affect the ability of forests to provide these functional benefits.

### Composition and Methodology

**Forest tree biodiversity status and trends**—Data can be used to evaluate change in the biodiversity over time of forest trees and seedlings on as many as 130,000 FIA plots across the conterminous United States and southeast Alaska, with plot-level results aggregated to the ecoregion scale.

**Forest bird biodiversity status and trends**—Methods of collecting data for the BBS may be described as follows:

> Each year during the height of the avian breeding season, June for most of the United States and Canada, participants skilled in avian identification collect bird population data along roadside survey routes. Each survey route is 24.5 miles long with stops at 0.5-mile intervals. At each stop, a 3-minute point count is conducted. During the count, every bird seen within a 0.25-mile radius or heard is recorded. Surveys start one-half hour before local sunrise and take about 5 hours to complete (USGS 2015b).

### Scientific Validity of Indicator

**Forest tree biodiversity status and trends**—Sampling protocols and data sampling methods for FIA are thoroughly documented and are based on years of rigorous statistical design; checks are conducted on data quality. Use of the FIA data to assess changes in forest tree and seedling biodiversity over time has been peer reviewed (Potter and Woodall 2012).

**Forest bird biodiversity status and trends**—Breeding Bird Survey data are widely applied across the scientific and ornithological communities. These data have been used in more than 450 scientific journal articles and in prominent national reports such as the U.S. Department of the Interior's "State of the Birds."

### What Are the Future Plans for Further Development of the Indicator?

**Forest tree biodiversity status and trends**—The indicator has been applied in eight eastern states, using two plot measurements 5 years apart on about 7,000 FIA plots. The statistical power and geographic extent of these analyses will increase as FIA remeasurement data continually become available from the approximately 130,000 plots across the conterminous United States and southeast Alaska, and as plot measurements are also repeated at regular intervals over a longer period of time. Repeated analyses will therefore occur at regular intervals.

**Forest bird biodiversity status and trends**—According to USGS documents (Ziolkowski et al. 2010), future developments for the BBS include continued geographic expansion (particularly into Mexico), improvements in population estimation analyses, and increased incorporation of geospatial information in trend analyses.

## Considerations for Selection of Indicator

### Advantages

**Forest tree biodiversity status and trends**—

1) Forest tree biodiversity is easily understood.
2) Changes in climate are expected to affect forest tree biodiversity.
3) Data are collected in a systematic fashion from FIA plots across the conterminous United States and southeast Alaska, at a relatively high spatial intensity.
4) The spatial intensity of the FIA data allows for analyses at multiple scales.
5) Plots are revisited on a regular basis, and will continue to be (assuming continued federal funding for the program), thus allowing for time-series analyses.
6) The FIA data are publicly available.

**Forest bird biodiversity status and trends**—

1) Data are available for more than 400 avian species across the United States and Canada.
2) Data are collected in a systematic fashion and, in many areas, has been continuously collected for decades.
3) The spatial intensity allows for analyses at multiple scales.
4) Data are publicly available (both raw data and trend estimates) at the BBS Web site.

## Disadvantages

**Forest tree biodiversity status and trends**—

1) The FIA data have been collected in a systematic fashion nationally only since about 2000. Data are available before that, but problematic to use.
2) The 10-year panel system in the West means that the options for time-series analyses in this region are limited, as each plot is visited only once every 10 years.
3) The 5- to 7-year window in the East may be too short a time to evaluate biodiversity change resulting from climate change, but additional measurements will extend the window of time.

**Forest bird biodiversity status and trends**—

1) Although an indicator that includes a wide range of forest taxa would be preferable, the BBS has data only for birds. Similar national-level wildlife survey efforts have been initiated for several other taxa (e.g., USGS Amphibian Research and Monitoring Initiative, National Ecological Observatory Network [NEON] efforts) but do not currently have the quantity and geographic range of the BBS.
2) Avian point count surveys, particularly those like the BBS that are conducted along roadways, have a variety of documented shortcomings, including species-specific detection probabilities. This method of surveying may not be suitable for all avian species.

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## Other Resources

Major contact: Forest Inventory and Analysis (FIA) program of the U.S. Forest Service (http://www.fia.fs.fed.us/)

## STRUCTURE AND FUNCTION INDICATOR: FOREST GROWTH/PRODUCTIVITY

Metrics: Net annual forest growth per unit area, Forest net primary productivity

### Summary

Net annual forest growth per unit area (acre or hectare) is defined as the average annual net increase in volume or mass of trees during the period between inventories. The volume of trees that died or that became nonmerchantable over the period is subtracted from the summed growth on live trees, which means net growth may be a negative number. Net annual forest growth is available from FIA data. Units are tons of carbon per acre (metric tons of carbon per hectare) per year or equivalent.

Forest net primary productivity (NPP) can be estimated by using a remote sensing approach based on MODIS. The estimates are modeled from observations, with estimates available annually. Units are kilograms of carbon per square meter per year or equivalent.

Both metrics are available, and continue to be updated. For the phenology team, NPP may be a more appropriate metric.

### Additional Descriptive Text

Net annual growth in U.S. forests totaled nearly 26.7 billion cubic feet in 2006, which is about three-and-one-half times the rate of mortality (Oswalt et al. 2014). Net growth is an important indicator because it can be affected by changes in temperature, water availability, length of growing season, and increases in atmospheric carbon dioxide ($CO_2$). The result may be an increase or a decrease in net growth (U.S. Forest Service 2011). Management activities can also affect growth, including species composition, so results should be carefully interpreted. Net annual growth is defined as the average annual net increase in volume of trees during the period between inventories. The volume of trees that died or that became nonmerchantable over the period is subtracted from the growth, which means net growth can be a negative number.

Net annual growth can be calculated for a range of geographic levels (e.g., national, subnational, ecological unit, and state). The smaller the area, the larger the confidence level around the estimate, so a smaller geographic resolution should be carefully considered. Because field data are remeasured every 5 or more years, growth changes are reported as averages over the period and changes cannot be easily attributed to any one year, which is often of interest when looking at climate events. Initial measurements begin in 1952, with a number of 5- to 10-year growth periods occurring through to current measurements. A new annualized inventory design was initiated state-by-state starting in different years in the 2000s, with net growth now being calculated from remeasured plots rather than changes in results aggregated over landscapes.

The MODIS product (USGS, Land Processes Distributed Active Archive Center 2015) is created every 8 days. Thus annual estimates of net growth can be derived, which is not feasible from the FIA data (Table 11).

### What Is the Link to Climate Variability and Change or Relevance?

Forest productivity is a biologic rate controlled directly by climate. On short timescales, productivity can be affected by interannual variability (e.g., drought). On 10- to 100-year timescales productivity is affected by shifts in temperature, growing season length, and moisture availability. In addition, increased $CO_2$ in the atmosphere has been postulated to enhance growth of individual plants, an effect that should be manifest in this indicator. Productivity can also be indirectly affected by climate (e.g., by increasing drought- or insect-related mortality).

### What Are the Drivers of This Indicator, and What Are Their Impacts?

Both human and climate drivers can affect forest productivity. Forest management can affect stand-level productivity through silvicultural practice (including fertilization, regeneration strategy, and thinning) and fire suppression.

### Relevance to Management Decisions

Growth rates directly affect the volume of merchantable timber within the United States and the rate at which that timber can be extracted. Slowing growth rates would influence both forest management decisions and the timber industry.

### Other Indicators Considered But Not Recommended at This Time

Productivity is a crucial aspect of forests that is known to be affected by climate. Growing degree days may be a similar indicator, but we thought that productivity was a more direct measure of change in forests, and that other teams may include growing degree days.

## Data Availability

### Length of Records of Dataset

FIA: net growth data available since 1952; available in annual panels based on remeasured plots since 2000.

MODIS: MODIS NPP product available at 8-day resolution, beginning in 2000.

### Stability/Longevity of Dataset and Indicator

The FIA program is operational and Congressionally mandated. Research supporting MODIS NPP is a long-term activity, although prospects for continuation past the MODIS lifetime are unclear.

### Spatial and Temporal Scalability

Data from FIA give regional information on growth rates with known sampling error as a function of number of plots incorporated into the analysis. MODIS NPP is a geospatial product with spatial resolution of 500 m (0.3 miles). The FIA program remeasures plots every 5 to 10 years, whereas MODIS NPP products are generated every 8 days, subject to cloud cover limitations.

**Table 11.—Decision criteria for Structure and function indicator: Forest growth/productivity**

| Decision criterion | Ranking | Justification[a] |
|---|---|---|
| **Link to conceptual framework** | Best | Links directly to Structure and function attribute. NPP through MODIS directly links to climate; net growth links to climate over a longer term. |
| **Defined relationship to climate, feedbacks, or impacts** | Best | MODIS NPP links directly to climate, so it may be an excellent visual to show climate change; net growth is the result of an actual measure and is directly affected by climate over the period. |
| **Spatial scalability** | MODIS best graphically; growth statistically | MODIS scalable to pixels; growth scalable down to counties or plots. |
| **Temporal scalability** | Best | MODIS available to an 8-day window; growth to 5-year period. |
| **Of national (not necessarily nationwide) significance? Should link to the conceptual model** | Individually sufficient; together best | Fundamental knowledge needed about forests, including in terms of climate mitigation. |
| **Relevance to management decisions** | Best | Knowledge of growth is a fundamental need to management, including management for climate response. |
| **Usefulness for educational purposes** | Best | MODIS NPP is actually related to climate and is visual, so it is easy to convey information about it. |
| **Is it a leading indicator?** | No | Not applicable |
| **Builds on existing data sources** | Best | Data sources exist and are available. |
| **Builds on existing indicator products** | Yes | Both build on existing sources. |
| **If new indicator proposed, likelihood of development and testing within 1 year given existing funding sources** | Not applicable | Not applicable |
| **Stability/Longevity of dataset** | Best for net growth; probably sufficient for MODIS NPP, which is a research product | Datasets are available; sometimes updates are made. The datasets are generally very stable. |
| **Stability/Longevity of indicator** | Best for net growth; probably sufficient for MODIS NPP, which is a research product | Indicator is expected to be of interest and stable for long term. |
| **Scientific validity of indicator** | Each approach is valid in its own way. | Peer-reviewed literature is available for both. |
| **Data publicly available and transparent** | Best to sufficient | Data are publicly available. |
| **Indicator methods fully transparent and documented** | Best to sufficient | Some research approaches for MODIS NPP will be less transparent than others. |

[a] Acronyms: NPP = net primary productivity; MODIS = moderate resolution imaging spectroradiometer

## Details About the Indicator

### Type of Indicator (Current, Leading, Both)

Current

### Geographic Scope and Scale of Analysis

National to state to county, although precision of the estimates decreases for smaller areas. Net primary productivity available as pixels.

### Approach (e.g., Single Measure, Composite)

The use of net growth as a metric of productivity provides measured data that are consistent with the approach used for greenhouse gas inventories, climate mitigation, and bioenergy supply. The FIA program provides the official forest statistics for the United States, based on data from its plots (U.S. Forest Service 2013), and thus this is the approach traditionally used. However, field data are remeasured no more often than every 5 years, so growth changes are reported as averages over the period. Thus changes cannot be easily attributed to any one year, which is often of interest when looking at climate events.

A second metric for the productivity indicator NPP is estimated by using a remote sensing (MODIS) approach. This may be a cross-cutting indicator across land uses, which another team might take the lead on. The MODIS GPP (gross primary productivity)/NPP product (MCD17) is based on a light-use efficiency model for photosynthesis, taking in the satellite-based fraction of photosynthetically active radiation (fPAR) and leaf area. There are many studies of ways to improve the standard MODIS NPP product for forests, and these should be considered (Turner et al. 2006). As an indicator, NPP can be more closely related to climate because it records the biologic activity of forests, and depends directly on temperature, precipitation, and available solar radiation. In addition the MODIS product is created every 8 days. However, MODIS NPP is an output of research products as opposed to being an operational product, and its longevity is not clear.

### Purposes and Conceptual Framework

In the conceptual framework, productivity links directly to the Structure and function attribute; NPP through MODIS directly links to climate and net growth links to climate over a longer term. Productivity (growth) is a fundamental important feature of forests driven by climate and affected by management.

### Scientific Validity of Indicator

The validity of the net growth approach is well established for climate mitigation purposes. Although the net growth approach is operational and has been scientifically valid for centuries, and the MODIS NPP approaches continue to be debated in scientific studies, the MODIS NPP approach may be thought of as being more relevant because its model is directly dependent on climate-related variables.

### What Are the Plans for Further Development of the Indicator?

MODIS NPP continues to be debated and methods improved in the scientific literature. In some ways it is a composite indicator of climate effects.

## Considerations for Selection of Indicator

### Advantages

Forest growth rates are strongly influenced by local climate, and long-term changes in growth rates provide unique information on how climate change affects forest ecology. Metrics of NPP from FIA and satellite-based sources provide complementary, mutually reinforcing information.

### Disadvantages

Changes in growth rates due to climate change can be expected to evolve slowly through time (over several decades), requiring careful, consistent measurement. The MODIS NPP record is a research product, and additional work is needed to understand its compatibility with long-term FIA measures of net growth.

## Literature Cited

Oswalt, S.N.; Smith, W.B.; Miles, P.D.; Pugh, S.A. 2014. **Forest resources of the United States, 2012: a technical document supporting the Forest Service 2015 update of the RPA Assessment.** Gen. Tech. Rep. WO-91. Washington, DC: U.S. Department of Agriculture, Forest Service. 218 p.

U.S. Forest Service. 2011. **National report on sustainable forests—2010.** FS-979. Washington, DC: U.S. Department of Agriculture. 212 p.

U.S. Geological Survey [USGS], Land Processes Distributed Active Archive Center. 2015. **MODIS data products table.** Sioux Falls, SD: U.S. Department of the Interior. Available at https://lpdaac.usgs.gov/products/modis_products_table. (Accessed 1 April 2015).

## Other Resources

U.S. Geological Survey, Land Processes Distributed Active Archive Center. 2015. **MODIS data products table.** Sioux Falls, SD: Department of the Interior. Available at https://lpdaac.usgs.gov/products/modis_products_table. (Accessed 1 April 2015).

National Aeronautics and Space Administration [NASA]. 2015. **Earth observatory, global maps of net primary productivity.** Available at http://earthobservatory.nasa.gov/GlobalMaps/view.php?d1=MOD17A2_M_PSN. (Accessed 15 March 2015). [Contains example images of the net primary productivity indicator.]

Running, S.W.; Nemani, R.R.; Heinsch, F.A.; Zhao, M.S.; Reeves, M.; Hashimoto, H. 2004. **A continuous satellite-derived measure of global terrestrial primary production.** Bioscience. 54: 547–560.

U.S. Forest Service. 2013. **Forest Inventory and Analysis national program: data and tools.** Available at http://apps.fs.fed.us/fiadb-downloads/datamart.html. (Accessed 17 June 2013).

## DISTURBANCE INDICATOR: WILDFIRE EFFECTS

Metrics: Burned area, Number of large fires, Fire severity

### Summary

The following metrics for wildfire effects (Table 12) are available from the Monitoring Trends in Burn Severity (MTBS; 2013) dataset, derived from remote sensing observations:

Burned area is an identification and simple summation for a given area and time period. The minimum burned area identified in the Western United States in the MTBS dataset is 1,000 acres, and 500 acres in the Eastern United States.

Number of large fires is determined by quantifying the statistical distribution of fire size over time. No particular threshold for “large” is assumed at this time. However, the minimum burned area identified in the MTBS dataset is 1,000 acres in the Western United States, and 500 acres in the Eastern United States.

Fire severity (typically damage to vegetation) is a function of the intensity (energy release during active burning) of fire.

Although wildfire is stochastic in space and time, sufficient data exist to establish clear relationships between fire characteristics and climate parameters. The methodology exists to produce these metrics, and they are currently available with some technical work and perhaps research.

### Additional Descriptive Text

Most of the variability in historical Burned area is attributed to combinations of seasonal temperature and precipitation. In most forest ecosystems, fire area is primarily associated with drought conditions, specifically, increased temperature and decreased precipitation in the year of fire and seasons before the fire season. In arid forests and woodland in the Southwest, fire area is influenced primarily by the production of fuels in the year before fire and secondarily by drought in the year of the fire.

**Table 12.—Decision criteria for Disturbance indicator: Wildfire effects**

**Burned area**

| Decision criterion | Ranking | Justification[a] |
|---|---|---|
| **Link to conceptual framework** | Best | Links directly (arrow 7 and Disturbance effects attribute), as well as to Forest extent. |
| **Defined relationship to climate, feedbacks, or impacts** | Best | It is a simple indicator that has already been shown to be well correlated with climate variability on an annual and seasonal basis. |
| **Spatial scalability** | Best | For NIFC data, should be possible. For MTBS data, polygons available to be summarized at different scales; minimum resolution differs in the Western and Eastern United States. |
| **Of national (not necessarily nationwide) significance? Should link to the conceptual model** | Best | Of national significance because area burned potentially leads to needs of land management and help to communities; policies need to consider these needs as well as operations. |
| **Temporal scalability** | Best | Annual, and can be aggregated |
| **Relevance to management decisions** | Best | Relevant in many ways: equipment and personnel needs, understanding for healthy forests and silvicultural needs, national policies and budgets. |
| **Usefulness for educational purposes** | Best | The drama of extensive damage will make this indicator of great interest to the public and policy makers; strong for education opportunities in climatic, biological, atmospheric, and ecological sciences, including the fact that wildfire has a natural place in forests and the world. |
| **Is it a leading indicator?** | Not being proposed as one | Research may show this could be used as a leading indicator. |
| **Builds on existing data sources** | Best | Yes, NIFC data available since 1916. MTBS data available since 1984. |
| **Builds on existing indicator products** | Best | Readily available |
| **If new indicator proposed, likelihood of development and testing within 1 year given existing funding sources** | New only in this context | It is unknown if resources are targeted for studying this indicator for this purpose. There are many studies regarding wildfire. |
| **Stability/Longevity of dataset** | Best to Needs improvement | The NIFC dataset is standard; additional information from MTBS dataset may not be funded going forward. |
| **Stability/Longevity of indicator** | Best | Expected to be of great interest as an indicator so should be stable. |
| **Scientific validity of indicator** | Best | Datasets accepted as standard, and many publications available. |
| **Data publicly available and transparent** | Sufficient | The data can be obtained from NIFC, but requires a formal request; the data are not online. MTBS data are available online. |
| **Indicator methods fully transparent and documented** | Sufficient, could use improvement | Additional research to understand the information that the indicator provides in a climate context would be useful. |

[a] Acronyms: NIFC = National Interagency Fire Center; MTBS = Monitoring Trends in Burn Severity

**Table 12 (continued).—Decision criteria for Disturbance indicator: Wildfire effects**

**Number of large fires (showing only those rows which differ from decision criteria for Burned area)**

| Decision criterion | Ranking | Justification |
|---|---|---|
| **Defined relationship to climate, feedbacks, or impacts** | Sufficient | Correlated with climate variability on an annual and seasonal basis, but not as closely as Burned area |
| **Of national (not necessarily nationwide) significance? Should link to the conceptual model** | Best | This is of national significance because 2 percent of the fires (the largest fires) are enormously expensive. This point currently is routinely being made in federal budget requests. |
| **Relevance to management decisions** | Best | Relevant in many ways: equipment and personnel needs, understanding for healthy forests and silvicultural needs, national policies and budgets. Fighting large fires has specialized needs as compared to average sized fires. |

**Fire severity (showing only those rows which differ from decision criteria for Burned area)**

| Decision criterion | Ranking | Justification[a] |
|---|---|---|
| **Defined relationship to climate, feedbacks, or impacts** | Sufficient | It is at least partially caused by weather conditions, although fuel loading and conditions are also important. |
| **Spatial scalability** | Sufficient | For MTBS data, polygons available to be summarized at different scales; minimum resolution differs in Western and Eastern United States. |
| **Temporal scalability** | Needs improvement | Data are available only for 1984–2010, but are available annually. |
| **Of national (not necessarily nationwide) significance? Should link to the conceptual model** | Best to sufficient | This is of national significance because increased fire severity could slow or stop regeneration, lead to increased erosion, and create major threats to health of forests and land; policies need to consider these implications as well as operations. |
| **Relevance to management decisions** | Best | Fire is especially viewed as linked to climate. Relevant in many ways: equipment and personnel needs, understanding for healthy forests and silvicultural needs, national policies and budgets. |
| **Usefulness for educational purposes** | Sufficient | Caution is needed to explain interaction of weather and fuels. |
| **Builds on existing data sources** | Best | Readily available online |
| **Builds on existing indicator products** | Sufficient | More research to understand the information that the indicator provides in a climate context is needed. |
| **If new indicator proposed, likelihood of development and testing within 1 year given existing funding sources** | Only new in this context | Unlikely funding would happen. |
| **Stability/Longevity of dataset** | Needs improvement | Additional information from MTBS dataset may not be funded going forward. |

**Table 12 (continued).—Decision criteria for Disturbance indicator: Wildfire effects**

**Fire severity (showing only those rows which differ from decision criteria for Burned area)**

| Decision criterion | Ranking | Justification[a] |
|---|---|---|
| **Stability/Longevity of indicator** | Needs improvement | In a theoretical sense, the need for the indicator is recognized. |
| **Scientific validity of indicator** | Sufficient | More research to understand the information that the indicator provides in a climate context is needed. |
| **Data publicly available and transparent** | Sufficient | The data can be obtained online; users need to spend time understanding how the data were derived. User satisfaction with these data differs for different applications. |
| **Indicator methods fully transparent and documented** | Sufficient | Methods documentation could be improved. |

[a] Acronym: MTBS = Monitoring Trends in Burn Severity

Number of large fires can be determined by iteratively using a different threshold to determine the number of fires exceeding it. The distribution of large fires over time probably will differ by region in the United States.

Fire intensity is expected to increase significantly as a result of warmer temperature. However, fuel loading, and interannual and longer term variability in climate–fire relationships can affect trends, making it difficult to infer whether climate change is responsible. In addition, forests with high fuel loading due to fire exclusion will continue to be susceptible to crown fire in the absence of active management. Longer time series of fire occurrence, when available, will allow better quantification of the influence of multi-decadal climate variability (e.g., Pacific Decadal Oscillation and Atlantic Multi-decadal Oscillation).

### What Is the Link to Climate Variability and Change or Relevance?

The effects of climate variability on burned area have been clearly documented, and one would expect this relationship to persist as the climate continues to warm. The relationship to number of large fires is not quite as strong, but is still apparent, especially in years when burned area is very high. Relationships to fire severity are mediated by local weather, which will on average be more extreme as the climate warms, and by fuel loading at any particular location.

### What Are the Drivers of This Indicator, and What Are Their Impacts?

Dry, combustible fuels (including both live and dead vegetation) are conditioned to burn under states of high temperature and low precipitation. Therefore, “dry” years almost always have more burned area and more large fires; in some cases, more severe fires occur. Increased burned area will be a potentially major driver of ecosystem change, because it causes such a rapid change in forest structure and processes, “clearing the slate” for regeneration and competition of a new cohort of forest vegetation. Increased fire severity may have the additional effect of altering species composition in some locations, especially if it occurs over large areas, thus modifying seed sources.

### Has This Indicator Been Used as an Indicator by Anyone Else; If So, by Whom, and How Was It Used and When Was It Initiated?

It has been suggested anecdotally that burned area in the Western United States during the past 30 years has been caused at least partially by climate change. This inference is confounded by normal multi-decadal climate variability and cannot be supported by the current time series of fire data.

### Relevance to Management Decisions

Wildfire management is arguably the greatest current challenge for federal land management in the Western United States in terms of vegetation management and restoration issues, as well as financial expenditures for fire suppression and hazardous fuel reduction.

### Other Indicators Considered But Not Recommended at This Time

**Fire season length**—Available from the National Interagency Fire Center. Our evaluation is that length of fire season is a poor quantitative indicator of climate change impacts, and we recommend that it not be used. This indicator may sound straightforward and definable, but it is not. First, there are many ways that could be used to define it, rather than one universally accepted way. Second, the time series of fire occurrence varies each year. If one early big fire is followed by 2 months without fire in a season, is this still defined as an "early" fire season? Third, the energy release component, which is derived from fuel moisture, is highly variable based on seasonal variations in weather. It is also confounded by the magnitude and spatial distribution of fuel loading in any particular location. Fourth, defining seasonality of flammability for any location would vary greatly by elevation, aspect, topography, and vegetation type. Finally, length of fire season is likely to be affected by multi-decadal modes of variability (e.g., Pacific Decadal Oscillation), thus obscuring any climate change "signal" for fire season, even across several decades.

**Fire evacuation costs (Canadian indicator)**—This appears to be more of an effect than an indicator. We are unsure of a source of this information in the United States.

**Fire suppression costs**—This appears to be more of an effect than an indicator. We are unsure of a source of this information in the United States.

### Usefulness for Educational Purposes

In the words of Flannigan and colleagues (2000: 227), "[T]he almost instantaneous response of the fire regime to changes in climate has the potential to overshadow importance of direct effects of global warming on species distribution, migration, substitution and extinction. Thus, fire is a catalyst for vegetation change." Wildfire is a dramatic and well-publicized component of forest disturbance, one that is increasingly affecting both urban and rural communities. This creates an opportunity for education about living with fire, especially in a warmer climate.

## Data Availability

### Length of Records of Dataset

Data on burned area and to some extent fire size are available from some federal lands since 1916, and data on fire severity for all western U.S. lands are available since 1984. Data are sporadic for other public and private lands.

### Stability/Longevity of Dataset and Indicator

Good for burned area and fire size. Continuity of burn severity data after 2010 is uncertain.

### Notes About the Data (Recent Changes in Analysis or Collection Methods)

The early part of the dataset for burned area must be adjusted to account for inadequate reporting of fire from remote locations. Littell et al. (2009) made these adjustments at the state level for the 11 western states.

### Spatial and Temporal Scalability

Spatial and temporal scaling should be possible, but characteristics such as wildfire size and severity differ greatly between regions of the United States.

## Details About the Indicator

### Type of Indicator (Current, Leading, Both)

All are current indicators.

### Approach

Burned area is a simple summation for a given area and time period. Fire size can be determined by summing occurrence at different threshold sizes. Severity typically is a quantification of canopy mortality caused by fire for a particular location; it can be expressed as area with a particular magnitude of severity.

### Metadata

Historical data on burned area and fire sizes are available from the National Interagency Fire Center (www.nifc.gov). Data on fire severity are available from the Monitoring Trends in Burn Severity data archive (www.mtbs.gov).

### Composition and Methodology

Each wildland fire that occurs on federal and tribal lands and most fires greater than about 100 acres (40 ha) on state and private lands are recorded by the National Interagency Fire Center.

### Scientific Validity of Indicator

Underlying data will meet Information Quality Act requirements. Wildfire-burned area, and, to some extent, fire size, has been associated with climate variability and change in the peer-reviewed scientific literature. Fire severity is well documented at the MTBS Web site (www.mtbs.gov) and has been used in the peer-reviewed literature for several applications.

### What Are the Plans for Further Development of the Indicator?

The indicator is operational and used extensively throughout the United States to support predictive services that are responsible for providing information that wildland fire response organizations use to determine resource allocation for wildland firefighting resources. Future development is focused on finer grained generalizations of fuel characteristics, denser networks of weather stations, enhanced technology for interpolating between reporting stations, and more consistent and high-resolution historical observed weather datasets.

## Considerations for Selection of Indicator

### Advantages

1) Burned area and fire size are straightforward and easily understood, and will presumably be collected in perpetuity.
2) Because a small number of fires make up the majority of burned area, there is little opportunity for error even if some small fires on private land are not reported.
3) Fire severity data are available online to all users.

### Disadvantages

1) Fire severity data are not available before 1984 and may not be available after 2010.

## Literature Cited

Flannigan, M.; Stocks, B.; Wotton, B. 2000. **Climate change and forest fires.** Science of the Total Environment. 262(3): 221–229.

Littell, J.S.; McKenzie, D.; Peterson, D.L.; Westerling, A.L. 2009. **Climate and wildfire area burned in western U.S. ecoprovinces, 1916–2003.** Ecological Applications. 19: 1003–1021.

Monitoring Trends in Burn Survey [MTBS]. 2013. **Home page.** Available at www.mtbs.gov. [Date accessed unknown]. [Images of all metrics derived from MTBS can be found by year between 1984 and 2011 at this Web site. In addition to the conterminous United States, images are often available for Alaska, Hawaii, and Puerto Rico. However, the images show wildfires (above a certain minimum size) on all lands, not just forests. To show only wildfires in forests, maps would have to be overlaid.]

## Other Resources

Major contact: National Interagency Fire Center (NIFC), Boise, ID; National Wildland Fire Coordinating Group

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## DISTURBANCE INDICATOR: FOREST INSECT AND DISEASE DAMAGE

Metrics: Area affected by insects and diseases

### Summary

Area affected by insects and diseases (Table 13) is identified and reported by insect or disease type and tree species by the U.S. Forest Service, which conducts annual aerial surveys of insect- and disease-caused tree damage. Affected area is available at fine (polygon) and coarse (national) scales for summarizing as national totals for each disturbance agent as well as for producing maps. This indicator will focus on insects and diseases that damage trees over large areas. Units are number of acres (hectares) affected by a particular insect or disease.

These metrics are available, but more work is needed to use them as an indicator, and to fully interpret results in the context of climate.

### What Is the Link to Climate Variability and Change or Relevance?

Climate affects insects and diseases directly through effects on development rates and life cycles and range limitation. In addition, the indirect effects of high temperatures and low precipitation increase stress in host trees, which then are typically more susceptible to attack by biotic disturbance agents. Recent warming and drought have been linked to extensive tree damage caused by multiple outbreaks of insects and diseases (Weed et al. 2013).

**Table 13.—Decision criteria for Disturbance indicator: Forest insect and disease damage**

| Decision criterion | Ranking | Justification |
|---|---|---|
| **Link to conceptual framework** | Sufficient to best | Direct link indicated by Disturbance effects attribute and Structure attribute |
| **Defined relationship to climate, feedbacks, or impacts** | Best | Climate affects insects and diseases directly as well as affecting host tree susceptibility. Because of the extensive damage, trees affected by insects and diseases have impacts on climate through changes in carbon sequestration, energy, and water fluxes. |
| **Spatial scalability** | Best | Fine-scale polygons available to be summarized at different spatial scales |
| **Temporal scalability** | Sufficient to best | Annual datasets available. Life cycles for many major biotic disturbance agents are 1 year, suggesting that annual resolution is sufficient. Other agents have multiple life cycles per year, and thus an annual observation does not resolve the time of year of tree damage. |
| **Of national (not necessarily nationwide) significance? Should link to the conceptual model** | Sufficient to best | Yes, extensive areas of forest damage are of national significance, especially because they can lead to increased fire risk, and issues in other sectors including the human economy. |
| **Relevance to management decisions** | Best | Healthy forests and ecosystems are important for a sustainable planet and a sustainable human society. |
| **Usefulness for educational purposes** | Best | Extensive damage can be visible indicators to the public and policy makers; strong for education opportunities in climate, biology, and ecosystems, including the fact that insects and disease have a natural place in forests. |
| **Is it a leading indicator?** | Not applicable | Not currently proposed as a leading indicator |
| **Builds on existing data sources** | Best | Aerial surveys are conducted annually by the U.S. Forest Service. |
| **Builds on existing indicator products** | Best | Aerial surveys are conducted annually by the U.S. Forest Service, and summarized at the national scale in annual “Forest Insect and Disease Condition” reports. |
| **If new indicator proposed, likelihood of development and testing within 1 year given existing funding sources** | This is not necessarily new, but would be new in this context. | There are many different species of insects and diseases. Some may be more indicative of climate impacts than others. Additional research could prove fruitful. |
| **Stability/Longevity of dataset** | Best | U.S. Forest Service maintains these datasets. |
| **Stability/Longevity of indicator** | Best | U.S. Forest Service maintains these datasets. |
| **Scientific validity of indicator** | Sufficient to best | The subjective nature of the aerial surveys confers uncertainty about the consistency and accuracy of the product. |
| **Data publicly available and transparent** | Best | Yes |
| **Indicator methods fully transparent and documented** | Sufficient | Methods are documented, but more research to understand the information that the indicator provides in a climate context, and to make that information clear and easily understandable, would be useful. |

### What Are the Drivers of This Indicator, and What Are Their Impacts?

In addition to climate, drivers of insect and disease outbreaks include factors related to distribution of hosts (of which only one or a few species may be attacked by a particular insect or disease) and host stress (older trees and resource limitations associated with site conditions or stand structure). Impacts include changes in timber yield, wildlife habitat, carbon sequestration, and energy and water fluxes (Chan-McLeod 2006, Edburg et al. 2012, Hicke et al. 2012, Pugh and Gordon 2012). Large outbreaks causing tree mortality have had substantial impacts at watershed and broader scales (Bethlahmy 1974, Kurz et al. 2008).

### Has This Indicator Been Used as an Indicator by Anyone Else; If So, by Whom, and How Was It Used and When Was It Initiated?

Indicator 3.15 of Forest Sustainability was discussed by the U.S. Forest Service (2011).

### Relevance to Management Decisions

Tree damage (reduced growth or mortality, or a combination thereof) caused by insects and diseases is relevant to forest managers because of its impacts to forest ecosystems and its widespread extent.

### Other Indicators Considered But Not Recommended at This Time

Mortality area, which is the canopy area of live trees (Meddens et al. 2012); not recommended because of lack of funding to produce this annually.

ForWarn, from the U.S. Forest Service's Eastern Forest Environmental Threat Assessment Center, which produces near real-time maps of potential forest threats; not recommended at this time because of the lack of maturity of the product, including lack of explicit identification of insect and disease outbreaks.

The following tabulation summarizes other disturbance indicators that we considered but did not choose:

| Disturbance type | Indicator | Indicator source | Notes |
|---|---|---|---|
| Invasive plants | Range, populations | U.S. Forest Service, Forest Health Monitoring | Less related to climate change |
| Drought | Tree mortality | U.S. Forest Service, Forest Inventory and Analysis | Difficult to ascribe cause–effect relationships |
| Storms | Tree damage and mortality | Unsure | Good potential indicator if time series of data can be developed |
| Effects of abiotic agents (e.g., fire, storms, land clearance) beyond reference conditions | Area affected | Unsure | Covered by above indicators |

### Usefulness for Educational Purposes

Tree damage from insect and disease outbreaks, especially bark beetle-caused tree mortality, is an indicator of climate change that is clearly visible to the public.

## Data Availability

### Length of Records of Dataset

National, consistent datasets of insect- and disease-affected area are available electronically back to 1997. Some regions of the United States have earlier electronic datasets (e.g., back to 1980 in Washington and Oregon). Earlier hardcopy versions are also available in some regions, and earlier national summaries are available as well (e.g., for mountain pine beetle; Man 2012).

### Stability/Longevity of Dataset and Indicator

The U.S. Forest Service maintains these electronic datasets. Major forest insect and disease conditions are surveyed and reported on annually, beginning in 1940 or earlier. Any changes to protocols are documented, and made available to the public. The datasets are stable and continued collection is expected.

### Notes About the Data (Recent Changes In Analysis or Collection Methods)

Aerial surveys report affected area, which is the area of polygons drawn by observers in airplanes in locations affected by tree damage. These polygons include both live and damaged trees. Not all forest areas are surveyed every year by the U.S. Forest Service. For instance, wilderness areas and national parks are not typically included.

### Spatial and Temporal Scalability

This indicator is spatially scalable because the aerial survey polygons are available and can be summarized by political and ecological units.

This indicator is temporally scalable because the aerial survey polygons are available for each year of the period of record.

## Details About the Indicator

### Type of Indicator (Current, Leading, Both)

Current

### Approach

Observers in planes fly over forest areas annually, drawing polygons in locations affected by tree damage. Observers record damage causal agent (insect or disease) and tree species, and sometimes include levels of damage (e.g., number of trees killed by bark beetles or defoliation severity).

This indicator will focus on insects and diseases that damage trees over large areas: 1) bark beetles, including mountain pine beetle, western pine beetle, spruce beetle, pinyon ips, Douglas-fir beetle, and southern pine beetle; 2) defoliating insects, such as spruce budworms; 3) pathogens, including *Dothistroma* needle blight, Swiss needle cast, and *Phytophthora* root disease; 4) declines, including sudden aspen decline and yellow-cedar decline; and 5) invasive insects and diseases that have a connection with climate, such as sudden oak death, emerald ash borer, gypsy moth, and woolly adelgids.

Affected area polygons will be summarized at the national scale for each of these disturbance agents and across agents. In addition, maps of new infestations and cumulative infestations will be produced for each agent as well as summed across agents.

### Metadata

Aerial surveys and their results are described by:

Man, G., comp. 2012. **Major forest insect and disease conditions in the United States: 2010 update.** FS-988. Washington, DC: U.S. Department of Agriculture, Forest Service. 32 p.

U.S. Forest Service. 2005. **Aerial survey geographic information system handbook: sketchmaps to digital geographic information.** Forest Health Monitoring Program and State and Private Forestry Forest Health Protection. 88 p. Available at http://www.fs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb5361666.pdf (last accessed 21 July 2015).

### Composition and Methodology

See above for description of approach.

### Scientific Validity of Indicator

Aerial surveys are conducted by observers in planes. Some accuracy assessments have been performed (Backsen and Howell 2013, Johnson and Ross 2008). However, variations in observer skill and experience and flying conditions confer uncertainty in accuracy and consistency in the aerial survey datasets. Not all forest areas are flown over every year. Given these issues, this indicator is best considered at larger spatial scales.

### What Are the Plans for Further Development of the Indicator?

Expected to continue being implemented by the U.S. Forest Service.

## Considerations for Selection of Indicator

### Advantages

1) This indicator quantifies the extent of affected area and type of tree damage caused by insects and diseases.
2) Aerial surveys have been conducted for many years, and the program is currently active within the U.S. Forest Service.
3) The U.S. Forest Service prepares the survey data, produces the electronic database, and summarizes information annually about forest insects and diseases.

### Disadvantages

1) Aerial surveys are conducted subjectively, and not all forest areas are flown over every year.
2) Electronic datasets are available nationally only back to 1997, thus lacking the capacity to provide a longer term evaluation of changes in insect and disease activity.

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Meddens, A.J.H.; Hicke, J.A.; Ferguson, C.A. 2012. **Spatiotemporal patterns of observed bark beetle-caused tree mortality in British Columbia and the western United States.** Ecological Applications. 22: 1876–1891.

Pugh, E.; Gordon, E. 2012. **A conceptual model of water yield effects from beetle-induced tree death in snow-dominated lodgepole pine forests.** Hydrologic Processes.

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## Other Resources

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## BIOPHYSICAL INDICATOR: WATER BALANCE DEFICIT— AN INDICATOR OF "PLANT-RELEVANT" DROUGHT

Metric: Water balance deficit (calculated as a difference)

### Summary

Water balance deficit is the difference between potential evapotranspiration (PET) and actual evapotranspiration (AET), and is a measure of "plant-relevant" drought (Stephenson 1990). Units are millimeters or equivalent.

More research would be needed to make this metric operational.

### Additional Descriptive Text

Most methods of determining water balance deficit (Table 14) are based at least on surface climate observations (e.g., temperature and precipitation) and to varying degrees incorporate specific characteristics of soil (e.g., field capacity, infiltration, declining availability) and vegetation (e.g., aerodynamics, vegetation-specific resistance, stomatal conductance). Methods for estimating PET include Hamon, Thornthwaite, Penman-Monteith, and Priestly-Taylor. Data products from the Department of the Interior, Bureau of Reclamation (2015) and from the University of Washington, Climate Impacts Group (2015) use Penman-Monteith with specific soil and vegetation characteristics. The data product from the University of Delaware (2015) uses a modified version of Thornthwaite (Willmott et al. 1985). Abatzoglou et al. (2014) define a related variable, climatic water deficit, as the unmet atmospheric demand, or the difference between growing season reference evapotranspiration for a reference crop and actual evapotranspiration.

### What Is the Link to Climate Variability and Change or Relevance?

Water balance deficit varies with weather conditions and climate variability on timescales of days to centuries because it is partially determined by both temperature (via the contribution to PET) and precipitation (via the contribution to AET). Moreover, the seasonal demand for and availability of water during the growing season in combination determine the consequences for plant responses, so the role of storage in snowpack, for example, is key. Climate variability on timescales of years to decades influences water balance deficit in ways similar to more familiar drought metrics (such as Palmer Drought Severity Index [PDSI]; Palmer 1965) but also accounts for the type of vegetation more explicitly. Therefore, from decades to centuries, as the vegetation responds to the limiting or facilitating effects of climate, the consequences of a certain deficit can change too. Climate variation thus affects water deficit directly in the short term to mid-term (seasons to decades), and also indirectly over longer periods via cumulative effects on vegetation through controls on disturbance and succession.

**Table 14.—Decision criteria for Biophysical indicator: Water balance deficit—an indicator of “plant-relevant” drought**

| Decision criterion | Ranking | Justification |
|---|---|---|
| **Link to conceptual framework** | Sufficient to best | Links to arrows 6, 7, and 9. Deficit integrates some of the Other Environmental physical drivers with Climate Domain physical drivers and forest responses. |
| **Defined relationship to climate, feedbacks, or impacts** | Best | The estimation of the components of deficit is well defined in the hydrologic and climate literature. There is an evolving literature specific to water balance deficit effects on forests; see Introduction. |
| **Spatial scalability** | Sufficient to best | As fine-scale as vegetation, soil, and climate can be estimated. Soils and vegetation data are limiting, and interpolation of climate variables is limited at fine timescales. |
| **Temporal scalability** | Best | Same as spatial scalability, though vegetation and soil can be considered static if needed and sub-daily variation can be modeled. |
| **Of national (not necessarily nationwide) significance? Should link to the conceptual model** | Sufficient | Best developed in the Western United States; could be developed further for effects on ecosystems in the Eastern United States and Pacific Islands. |
| **Relevance to management decisions** | Sufficient | Future projections of water balance deficit give a quick estimate of forest vulnerability in the future because deficit has been related specifically to tree performance, vegetation distribution, and disturbance. |
| **Usefulness for educational purposes** | Sufficient | Deficit is a good way to explain the interaction between physical climatology, hydrology, and ecological variations and can be done in terms of a systems approach. |
| **Is it a leading indicator?** | Not applicable | Not being proposed as a leading indicator |
| **Builds on existing data sources** | Needs improvement | Existing distributed hydrologic modeling, gridded and interpolated climatologies, and forest responses can be mined for responses and impacts. |
| **Builds on existing indicator products** | Best | This builds on existing indicator products in the sense that we have recommended other teams consider the Palmer Drought Severity Index, which is especially limited for vegetation in mountainous areas. If carried by other teams, this approach can be more appropriately applied to forests. |
| **If new indicator proposed, likelihood of development and testing within 1 year given existing funding sources** | This is not necessarily new, but it is relatively new in this context. | Some development may occur, but dedicated funding is not available. |
| **Stability/Longevity of dataset** | Sufficient | Dedicated funding is needed for stability. |
| **Stability/Longevity of indicator** | Sufficient | Indicator has much promise and may have longevity. Some research is needed, and some funding may be needed for development to stabilize indicator. |
| **Scientific validity of indicator** | Best | Has been peer reviewed |
| **Data publicly available and transparent** | Sufficient | Available, but technical expertise required for use |
| **Indicator methods fully transparent and documented** | Best | Peer-reviewed papers and funding reports on development exist. More information in the popular literature is needed, as well as additional technology transfer to help convince users of advantages of using this approach. |

### What Are the Drivers of This Indicator, and What Are Their Impacts?

Water balance deficit is controlled by drivers that influence both potential and actual evapotranspiration, which include climatic (physical) controls, hydrologic controls, and ecological controls. The most inclusive estimates of PET (e.g., Penman-Monteith or Priestly-Taylor) incorporate more controls than simpler versions (e.g., Hamon or Thornthwaite), and are superior, provided appropriate data can be used. Most important in long-term estimates is to consider the role of changing vegetation and, separately, changing relative humidity in addition to climate variables such as temperature, precipitation, and snowpack.

Currently, the largest drivers of change in water deficit are assumed to be changes in temperature and precipitation, in that order. However, land use clearly has a role in that changes in vegetation affect both the amount and timing of evapotranspiration from the vegetation and also the relative humidity.

### Has This Indicator Been Used as an Indicator by Anyone Else; If So, by Whom, and How Was It Used and When Was It Initiated?

The information presented here has a record of more than 20 years in the ecological literature, but we know of no cases where it has been used as an indicator. The argument we present, however, is that if PDSI and related variables have such disparate consequences for the same value of indicator from place to place, a more overarching suite of variables—such as water balance deficit—should be used.

### Other Indicators Considered But Not Recommended at This Time

We considered PDSI, but it has several issues that make it less desirable than water balance deficit specifically for forests. First, deficit is hydrologically consistent: it is measured in millimeters of water and is therefore directly comparable from place to place, whereas PDSI is an index that ranges, often, from -6 to +6 with the meaning of that index varying. A “-2” drought in Tucson, AZ, for March to May of a given year is different from a “-2” drought in Bozeman, MT, for the same timeframe. But in both locations the water deficit might be 100 mm, a meaningful measurement to ecologists and one on which they could base discussion of probable consequences for productivity and summer fire activity. Second, deficit is at least as well correlated with functional responses in forests (from fire disturbance to radial growth). Third, projection of future deficit has a mechanistic linkage to the physical, hydrologic, and ecological controls on it, which are more difficult with PDSI. Fourth, PDSI, which is closely related to the Thornthwaite approximation for deficit, does not consider the physical and ecophysiological limitations of vegetation as directly as deficit; regional parameterization of PDSI is required (Heim 2002). From a plant and ecosystem perspective, therefore, there are sound reasons that deficit is a better choice. However, the two can be complementary, as human socioeconomic consequences (e.g., farming subsidies during drought) correspond to PDSI. Another approach by Peters et al. (2014) was brought to our attention during the review process, but that publication was not available to use during our writing and discussion phase.

## Data Availability

### Length of Records of Dataset

The length of records differs among the four methods used to calculate water balance deficit. Data for variable infiltration capacity are available for 1950 through 1999 at 12 km, monthly or daily, from the Bureau of Reclamation (2015) or for the Western United States for 1916 through 2006 at 6 km monthly (University of Washington, Climate Impacts Group 2015). Global data are available for 1900 through 2010 at 5° latitude/longitude from the University of Delaware (2015), or for 2000 through 2012 at 1 km monthly for the MERRA/MODIS satellite record from the University of Montana (2015).

### Stability/Longevity of Dataset and Indicator

The Bureau of Reclamation and University of Washington sources are being updated on an as-needed and as-funded basis. The information for the Bureau of Reclamation will probably be updated, but it is not known whether the information for the University of Washington, Climate Impacts Group will continue to be updated.

### Models/Scenarios (If Leading Indicator or Based on Model Output)

Data products from the Bureau of Reclamation and from the University of Washington are based on Variable Infiltration Capacity (VIC) hydrologic model output, and the approach to evapotranspiration is described in Elsner et al. (2010). The VIC model is a spatially explicit hydrologic model that uses observed daily or inferred sub-daily weather observations of temperature and precipitation in conjunction with land surface characteristics (soil, vegetation, topography) and empirical relationships to derive hydrologic fluxes, including PET and AET. The VIC model uses several different PET algorithms for standard crops, realistic vegetation, and other attributes.

### What Are the Plans for Further Development of the Indicator?

Progress continues to be made on the development of the measure.

## Considerations for Selection of Indicator

### Advantages

The advantages of water balance deficit over other indicators of drought (soil moisture, PDSI) are: 1) it is vegetation specific; 2) it is more explicitly related to both the energetic and hydrologic processes of plant performance, response, and disturbance; and 3) it better accommodates winter and spring relationships between snowpack and the growing season water budget.

### Disadvantages

Disadvantages include lack of measurement or verification (shared with PDSI) and lack of real-time network of observations and updates. Another disadvantage is that there are both simple and complex approaches to calculating the components of deficit (PET and AET) and also possible confusion with “climatic water deficit,” which is PET minus precipitation. See “Drivers” section for description of different approaches. We recommend the more complicated Penman-Monteith approach because it includes the capacity for differential changes in deficit due to vegetation changes (e.g., stomatal resistance, surface roughness, and albedo).

### Type of Indicator (Current, Leading, Both; If Both, Need to Describe Data/Models and Methods Separately Because of Different Approaches)

There currently exist no real-time updates of the indicator. At best, water balance deficit is calculated after the fact from observations of climate and weather.

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## Other Resources

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[1] As of the writing of this publication, these are the years of data available; more years of data are expected.

## EXTENT/SOCIOECONOMIC INDICATOR: AREA AND POPULATION OF THE U.S. WILDLAND-URBAN INTERFACE

Metrics: Area of forest wildland-urban interface, Population residing in forest wildland-urban interface

Although we present this indicator (Table 15) as covering all wildlands, we as the forest team can only recommend that this indicator be adopted as a cross-cutting indicator for land uses other than forest.

### Additional Descriptive Text

Because of the way the National Land Cover Database identifies vegetation from remote sensing, highly urbanized areas may not be included as wildland-urban interface (WUI) if the areas retain enough vegetation cover at the 30-m pixel scale to be classified as wildland. The population residing in the WUI is the number of people residing in areas determined to be in a WUI. This value is calculated from U.S. Census data, after the WUI is mapped.

**Table 15.—Decision criteria for Extent/Socioeconomic indicator: Area and population of the U.S. wildland-urban interface**

| Decision criterion | Ranking | Justification |
|---|---|---|
| **Link to conceptual framework** | Sufficient | This is a context indicator that is arguably a result of adaptation to fire risk. Links most directly from interactions of the Human Domain with Forest, Other Land Use, and Other Environmental Domains, particularly arrows 8 and 12. |
| **Defined relationship to climate, feedbacks, or impacts** | Sufficient | This indicator identifies where greater climate impacts to people and wildland are expected. |
| **Spatial scalability** | Best | Scalable to national, regional, state and local levels |
| **Temporal scalability** | Sufficient | No vegetation or housing data are currently available on an annual basis at this spatial scale. |
| **Of national (not necessarily nationwide) significance? Should link to the conceptual model** | Best for context | Need to identify these areas for mitigation or adaptation responses |
| **Relevance to management decisions** | Best | The current WUI population as well as ongoing growth expected in the WUI will magnify the social impacts of global climate change effects on wildland landscapes. |
| **Usefulness for educational purposes** | Yes | The designation of the WUI targets the audience that especially needs to be educated about fire. |
| **Is it a leading indicator?** | Not applicable | Not applicable |
| **Builds on existing data sources** | Yes | Datasets are updated every 10 years. |
| **Builds on existing indicator products** | Best | This indicator appears to be gaining use in the fire community. |
| **If new indicator proposed, likelihood of development and testing within 1 year given existing funding sources** | Could be viewed as new in this context | Could possibly be more useful if updated more often than every 10 years. Research on how informative it can be for climate purposes would be useful. |
| **Stability/Longevity of dataset** | Needs improvement | Existing datasets are well archived. Future funding is not guaranteed. |
| **Stability/Longevity of indicator** | Needs improvement | The dataset is being updated every 10 years. Now have 3 decennial censuses' worth of data. |
| **Scientific validity of indicator** | Needs improvement | Could use additional investigation in terms of use in climate effects |
| **Data publicly available and transparent** | Best | Widely available and well-documented |
| **Indicator methods fully transparent and documented** | Sufficient | Methods are documented, but more research to understand the information that the indicator provides in a climate context would be useful. |

In the final decade of the 20th century, the WUI expanded throughout the United States. By 2039, the WUI is expected to grow by an additional 10 percent nationally (Theobald and Romme 2007) and by 17 percent around national forests, national parks, and wilderness areas (Radeloff et al. 2010).

### What Is the Link to Climate Variability and Change or Relevance?

Increases in the area and human population of the WUI are associated with processes that will affect forest and rangeland contributions and responses to climate change, such as degradation of wildland vegetation, altered hydrology, increasing impervious surface, and introduction of exotic species of both flora and fauna (Fall et al. 2009; Radeloff et al. 2005, 2010). In addition, as the WUI grows, so too will society's experience of the effects of climate change on natural systems, potentially degrading recreation experiences, exacerbating fire problems, and increasing the demand for government remediation of or protection from forest degradation. Expected ongoing housing growth in the WUI and expansion of the WUI will magnify the social impacts generated by climate change effects on wildland vegetation.

### What Are the Drivers of This Indicator, and What Are Their Impacts?

Expansion of the WUI is caused by residential development (housing above 15.98 housing units per square mile, or 6.17 housing units per square kilometer) in areas that retain wildland vegetation. The WUI has been expanding in the United States in the past several decades, driven by reasons including Americans' preference for rural areas with natural amenities, small towns, and a lower cost of living; and technological innovations such as reliable cars and extensive highway networks, air conditioning, telecommunication, and Internet service. All of these advances have made these regions attractive to home buyers and businesses.

The ecological impacts of WUI expansion encompass all the effects of humans living in or near wildland and modifying their property, and thereby the landscape as a whole. Human activity is responsible for the majority of wildland fire ignitions. Development (e.g., roads, houses, and infrastructure) fragments habitat. Landscaping introduces exotic and invasive species. Wildlife is harassed by traffic and pets. Light and noise levels increase. As a result of all of this human activity, biodiversity declines and ecosystem function is altered. Environmental impacts of increased housing result not only from the larger number of houses, but from their density and distribution on the landscape. The low-density residential growth found in the WUI is of particular environmental concern, because houses are dispersed through previously undeveloped areas and on larger lots, spreading the impacts of each house over a larger area and maximizing the cumulative footprint of each housing development.

### Has This Indicator Been Used as an Indicator by Anyone Else; If So, by Whom, and How Was It Used and When Was It Initiated?

This indicator is used by the National Wildfire Coordinating Group (see http://www.nwcg.gov/var/data-standards/wildland-urban-interface-indicator) to determine whether the presence of WUI increases the cost or management complexity of a wildfire. It is used in the National Cohesive Wildland Fire Management Strategy to characterize wildfire problems and policy responses (http://www.forestsandrangelands.gov/strategy/).

### Relevance to Management Decisions

The WUI data and maps are used by national-level policy makers assessing the scope and growth of the WUI across the country, and by regional and state policy makers for allocating funds to support wildland fire mitigation.

### Other Indicators Considered But Not Recommended at This Time

This is a context indicator to pinpoint areas where the social impacts of climate change effects on forests are expected to be magnified, in comparison to more rural forests. Response strategies to climate variability or change will probably be different in these areas. We considered using the urban forest area, but that is not as well defined and is likely to be a heterogeneous area.

## Data Availability

### Length of Records of Dataset

Dataset is updated every 10 years, with decennial census. Data from 1990, 2000, and 2010 are available.

### Metadata

The WUI is the area where houses meet or intermingle with undeveloped wildland vegetation. By using geographic information systems (GIS), researchers integrate U.S. Census and National Land Cover data (MRLC 2014) to map the WUI in accordance with the Federal Register definition (U.S. Department of the Interior and U.S. Department of Agriculture 2001). These data are useful within a GIS for mapping and analysis at national, state, and local levels.

### Stability/Longevity of Dataset and Indicator

Data are updated with each 10-year census. Researchers process the data with GIS so that the WUI can be tracked over different censuses, as the shape changes between censuses. Researchers provide datasets that facilitate direct comparison of decadal WUI products. Data for changes between 1990 and 2000 are available, and change data for 2000–2010 will be released in 2015.

### Notes About the Data (Recent Changes in Analysis or Collection Methods)

The current version of the WUI uses a nationwide map of “protected areas with no housing units.” These areas were derived from the Public Areas Database (Conservation Biology Institute 2010) and included all publicly owned areas—federal, state, regional, and local government-owned lands—where housing cannot occur.

### Spatial and Temporal Scalability

Data are available for the conterminous 48 states, at the level of the census block. Because WUI data rely on housing counts, the dataset is updated every 10 years with the decennial census.

## Details About the Indicator

### Type of Indicator (Current, Leading, Both)

Current

### Geographic Scope and Scale of Analysis

Conterminous United States

### Approach of Indicator (e.g., Single Measure, Composite)

Data are generated by combining information on housing, land cover, and protected areas. See “Metadata” and “Composition and Methodology” for more information.

### Purposes and Conceptual Framework

The WUI data and maps were created to provide a nationwide assessment of the wildland-urban interface specific to fire management and policy. The WUI concept originates in wildland fire management and policy and was codified (U.S. Department of the Interior and U.S. Department of Agriculture 2001) following passage of the National Fire Plan in 2001. Thus, the WUI concept is arguably a need that resulted from societal adaptation to fire risk. The indicator results more directly from interactions of the Human Domain, and Forest, Other Land Use, and Other Environmental Domains, in particular, arrows 8 and 12.

### Composition and Methodology

**Method to determine area of WUI**—Occasionally the datasets showed housing units within protected area boundaries, where housing units would not normally occur by definition. This location was thought to be in error. We relabeled these units as belonging to neighboring privately owned blocks with the same block identification label. If the same block had no private areas, then houses remained within the protected land boundary (unmoved).

**Housing data**—Bureau of Census housing data were used at the block level, along with the Public Areas Database (Conservation Biology Institute 2010), to refine census blocks so that the area in each census block could be used to calculate housing density. These data occur only on privately owned land.

**Land cover data**—The National Land Cover Dataset is used to determine the density and location of wildland vegetation.

**Processing—**

1) Working in GIS, we calculate housing density and exclude blocks with less than 15.98 housing units per square mile (6.17 housing units per square km).
2) In remaining blocks, we determine where wildland vegetation density is greater than 50 percent. Those blocks with >15.98 housing units per square mile (6.17 housing units per square km) and >50 percent wildland vegetation are intermix WUI.
3) We estimate where wildland vegetation is greater than 75 percent, and for remaining blocks that meet the housing density minimum, any block or portion of a block that falls within 1.5 miles (approximating how far a firebrand can fly), these areas are interface WUI.

**Process for estimating WUI population**—Population residing in the WUI is estimated from the Census of Population at the block level. The steps are:

1) Determine which blocks are entirely within WUI and sum the population census counts for those blocks.
2) Determine which blocks are partly in WUI and what proportion are within the WUI. Use the proportion of census population counts to represent their populations. Sum these and add to above.

### Scientific Validity of Indicator

Social validity is indicated by the number and variety of uses made of the WUI map by policy makers and resource managers. Biophysical validity of the data as an indicator of where homes are at risk of fire has been assessed for western states. In an analysis of 2006 fires in the West, 93 percent of homes within 1 mile of fire perimeters were classified as WUI; within 10 miles of fire perimeters, 73 percent of homes were classified as WUI (Stewart et al. 2007).

### What Are the Plans for Further Development of the Indicator?

The U.S. Forest Service has supported research on the WUI under the National Fire Plan since 2001. The U.S. Forest Service has an extensive program of research which updates and maintains the WUI data, and uses the data to understand the social and ecological dynamics of fire in the WUI, and of human impacts on ecosystems more generally. See also Pellegrino et al. (2013).

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**Reanalysis.** International Journal of Climatology. 30: 1980–1993.

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Theobald, D.M.; Romme, W.H. 2007. **Expansion of the US wildland-urban interface.** Landscape and Urban Planning. 83: 340-354.

U.S. Department of the Interior and U.S. Department of Agriculture. 2001. **Urban wildland interface communities within the vicinity of Federal lands that are at high risk from wildfire.** 66 Fed. Reg. 751. January 4. pp. 751–777. Available at https://federalregister.gov/a/01-52. (Last accessed 13 July 2015).

## Other Resources

Major contacts: SILVIS Lab at the University of Wisconsin – Madison. [Manages and maintains WUI data and maps. All are available to the public at http://silvis.forest.wisc.edu/maps/wui_main. This page also provides more information about the WUI methods.] Contact: Volker Radeloff (University of Wisconsin, Forest Ecology/SILVIS Lab). Others involved in research supported by the National Fire Plan include: Roger Hammer (Oregon State University, Sociology Department), Susan Stewart (former U.S. Forest Service, Northern Research Station research social scientist), and Miranda Mockrin (U.S. Forest Service, Rocky Mountain Research Station research ecologist).

Bar Massada, A.; Radeloff, V.C.; Stewart; S.I. 2011. **Allocating fuel breaks for optimal protection of structures in the wildland-urban interface.** International Journal of Wildland Fire. 20: 59–68. [Especially contains information about developing a method for mapping the WUI by using

structure location data.]

Bar Massada, A.; Syphard, A.D.; Radeloff, V.C.; Hawbaker, T.J.; Stewart, S.I. 2011. **Effects of ignition models on the spatial patterns of simulated wildfires.** Environmental Modelling and Software. 26(5): 538–592. [Discusses modeling the relationship between WUI housing density and location, and wildland fire occurrence.]

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Radeloff, V.C.; Hammer, R.B.; Stewart, S.I. 2005. **Rural and suburban sprawl in the U.S. Midwest from 1940 to 2000 and its relation to forest fragmentation.** Conservation Biology. 19(3): 793–805. [Analyzes housing growth at the sub-county scale.]

Radeloff, V.C.; Stewart, S.I.; Hawbaker, T.J.; Gimmi, U.; Pidgeon, A.M.; Flather, C.H.; Hammer, R.B.; Helmers, D. 2010. **Housing growth in and near United States' protected areas limits their conservation value.** Proceedings of the National Academy of Sciences. 107(2): 940–945. [Analyzes housing growth in and around national parks, national forests, and wilderness areas.]

Stewart, S.I.; Wilmer, B.; Hammer, R.B.; Aplet, G.H.; Hawbaker, T.J.; Miller, C.; Radeloff, V.C. 2009. **Wildland-Urban Interface maps vary with purpose and context. Journal of Forestry.** 107(2): 78–83. [Contains information on mapping the WUI in 1990 and 2000 across the United States.]

Syphard, A.D.; Stewart, S.I.; McKeefry, J.; Hammer, R.B.; Fried, J.; Holcomb, S.S.; Radeloff, V.C. 2009. **Assessing housing growth when census boundaries change.** International Journal of Geographical Information Science. 23(7): 859–876. [Contains information on mapping the WUI in 1990 and 2000 across the United States.]

## CLIMATE IMPACTS ON HUMAN DOMAIN VIA FOREST: COST TO MITIGATE WILDFIRE RISK

Metrics: Expenditures on fire suppression activity, Expenditures on forest treatments to mitigate fire risk, Total payments for insurance premiums for policies against damage from forest fire. Units are inflation-adjusted dollars per year by category and (if available) by geographic region.

### Summary

Expenditures on fire suppression activity are compiled on an annual basis from federal, state, and local sources.

Expenditures on forest treatments to mitigate fire risk would be compiled on an annual basis from federal, state, and local sources.

Total payments for insurance premiums for policies against damage from forest fire would be compiled from insurance companies on an annual basis.

More research is needed on this indicator (Table 16), but the feasibility of providing metrics for this indicator is medium to high.

### What Is the Link to Climate Variability and Change or Relevance?

Owing to anticipated increases in temperature and moisture deficits, climate change is expected to increase wildfire frequency and intensity. The biophysical impacts can be measured by indicators of fire extent, frequency, and intensity. The socioeconomic impacts, however, can take many different forms, ranging from loss of life and property to aesthetic impacts. Mitigation costs (suppression, fuels reduction treatments, and insurance) are one such measure.

### What Are the Drivers of This Indicator, and What Are Their Impacts?

Temperature and moisture are major drivers of fire ignition, spread, and intensity, and they likewise help determine vegetative growth and thereby available fuels for wildfires. Fire activity will influence suppression costs. Fire risk will influence levels of forest treatment activity and insurance premiums. Note that several confounding factors will also affect each of these expenditure categories: general federal and state budgetary considerations will influence availability of funds and thereby suppression and treatment expenditures, and development in the WUI will influence demand for insurance against wildland fire risk.

### Has This Indicator Been Used as an Indicator by Anyone Else; If So, by Whom, and How Was It Used and When Was It Initiated?

Not to our knowledge. At the federal level, budget allocations by the U.S. Forest Service and Department of the Interior for wildfire control and management are reported through various channels. These allocations and related measures of wildfire costs are analyzed by various entities and in various contexts (e.g., see Gorte 2011). In this sense, these data serve a similar role as “indicators,” but

**Table 16.—Decision criteria for Climate impacts on Human Domain via Forest: Cost to mitigate wildfire risk**

| Decision criterion | Ranking | Justification |
|---|---|---|
| **Link to conceptual framework** | Best | Links directly (arrow 1) |
| **Defined relationship to climate, feedbacks, or impacts** | Sufficient | Strong causal link to climate change but confounding factors also present |
| **Spatial scalability** | Best | Scalable to national, regional, and state levels |
| **Temporal scalability** | Sufficient | Federal suppression costs available in annual time series from 1985 |
| **Of national (not necessarily nationwide) significance? Should link to the conceptual model** | Best | Potentially significant impact of climate change on human populations, with strong implications for national and local management activities |
| **Relevance to management decisions** | Best | Fire expenditure is a major budget category for land management agencies. Addressing fire will be a major challenge facing these agencies in the coming decades. |
| **Usefulness for educational purposes** | Sufficient | Budget allocations may not be a very exciting topic, but they do reveal an important cost imposed on society by climate change. |
| **Is it a leading indicator?** | Not applicable | Not proposed as a leading indicator |
| **Builds on existing data sources** | Sufficient | Federal fire suppression costs are readily available. Other cost categories will require varying levels of development. |
| **Builds on existing indicator products** | Needs improvement | Builds on existing reporting categories, but not indicators per se |
| **If new indicator proposed, likelihood of development and testing within 1 year given existing funding sources** | Sufficient | Federal suppression costs can be reported easily. Other indicator components are not likely to be produced in 1-year timeframe with available resources. |
| **Stability/Longevity of dataset** | Sufficient | Federal suppression costs are well established. Other categories will require development. |
| **Stability/Longevity of indicator** | Sufficient | This indicator needs more work, but some information is likely to be available. |
| **Scientific validity of indicator** | Sufficient | Budgetary expenditures are not subject to the same level of analysis as biophysical indicators. Causal links are not explicitly defined; more research would be useful. |
| **Data publicly available and transparent** | Sufficient | Federal suppression costs are available and reasonably transparent. |
| **Indicator methods fully transparent and documented** | Sufficient | Federal budget reporting conventions are well established, but meaning is sometimes obscure. More research on the information that this indicator provides in a research context would be useful. |

they do not appear to be formally integrated into well-known sustainable forest management indicator sets. Insurance premiums associated with wildland fire risk are commonly cited as an interesting avenue for future research, but they have not yet been compiled and are therefore merely potential candidates for future development.

### Relevance to Management Decisions

Wildfire control and management costs have many implications for management, ranging from the spatial and temporal allocation of resources to more general calculations of the costs of climate change. To the extent that wildfire increases in the coming decades as a response to climate change (in combination with other factors), wildfire management will be a major challenge for natural resource managers and a major drain on their budgets, thus requiring focused planning. Insurance premiums related to wildfire will act as a direct market indicator of perceived risk—high premiums will indicate high risk, and low premiums low risk—that may then be used to allocate resources for fuels reduction and fire preparedness.

### Other Indicators Considered But Not Recommended at This Time

The following indicators were also considered: number of lives lost to wildfire, number of structures lost to wildfire, number of structures and lives lost to wildfire, and the value of structures and other improvements lost to wildfire.

### Usefulness for Educational Purposes

This indicator will aid society in understanding, in explicit terms, one dimension of the costs imposed by climate change.

## Data Availability

### Length of Records of Dataset

Federal wildfire suppression costs: 1985–present
Federal fuels reduction treatment costs will require compilation:
likely 2000–present
State-level activities require compilation; length of record unknown.
Wildfire-related insurance costs need compilation; length of record unknown.

### Data Sources

Tabulation of federal, state, and local suppression/avoidance costs: See National Interagency Fire Center at www.nifc.gov/fireInfo/fireInfo_statistics.html; consult National Association of Insurance Commissioners and allied groups.

### Notes About the Data (Recent Changes in Analysis or Collection Methods)

As is true with most time series compiled from various sources, collection methods and reporting conventions are subject to change. Federal wildfire suppression costs appear to have an established time series with consistent reporting. Other federal wildfire control and treatment costs will be subject to changing budget categories, definitions, and other reporting conventions.

### Models/Scenarios (If Leading Indicator or Based on Model Output)

Not proposed as a leading indicator. Fire incidence is modeled at various scales, and federal agencies incorporate anticipated fire activity in budgets of future years, but this does not constitute an integrated or consistent modeling projection framework.

## Details About the Indicator

### Type of Indicator (Current, Leading, Both)

Current

### Geographic Scope and Scale of Analysis

National, regional, state

### Approach of Indicator (e.g., Single Measure, Composite)

Composite indicator with discrete display for component parts. Federal fire suppression costs are the most likely candidate for initial development.

### Purposes and Conceptual Framework

Applies directly to “Climate impacts on Human Domain via Forest” (arrow 1 in current conceptual model). Fuels reduction activities would apply to “Human Domain influences on Climate Domain via Forest” (arrow 2 in current conceptual model).

### Composition and Methodology

Compilation of budget allocation and expenditure documents. Display in simple aggregate by category. Insurance premiums, if developed, would involve census, if possible; otherwise statistical sampling may be needed.

### What Are the Plans for Further Development of the Indicator?

Initial focus on display of federal suppression costs, followed by compilation of similar data and display for state-level suppression costs, and then incorporation of fuels treatment and mitigation costs (federal and state). Insurance premiums are a candidate for future research and development as feasible and appropriate.

## Considerations for Selection of Indicator

### Advantages

1) Measures major category of impact on humans via forest
2) Provides data that is useful in many contexts (especially if state and local tabulations are available)
3) Amenable to quantitative measurement

### Disadvantages

1) Insurance premiums may confound value at risk with probability of fire.
2) Attribution of fire, and thereby costs, to climate change as opposed to other causes will call for external analysis.
3) Accounting definitions may be problematic (e.g., distinction between "wildland" and "forest" fire, or "forest restoration" and "fuels treatment").
4) Data compilation for state-level costs may be a tedious exercise.

### Literature Cited

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### Other Resources

Major contact: National Interagency Fire Center (http://www.nifc.gov/fireInfo/fireInfo_statistics.html)

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Lynch, D.L. 2004. **What do forest fires really cost?** Journal of Forestry. 102(6): 42–49.

## HUMAN INFLUENCE ON CLIMATE DOMAIN VIA FOREST: ENERGY PRODUCED FROM FOREST-BASED BIOMASS

Metric: Energy produced, domestically or in export markets, from biomass harvested from U.S. forests

### Summary

Energy produced, domestically or in export markets, from biomass harvested from U.S. forests. Data readily exist to populate most of the indicator. More work and data are needed on the export market information.

Units are British thermal units (Btu) per year, which is a traditional and common measure of energy and, if possible, $CO_2$ equivalent assuming appropriate conversion (e.g., national electricity generation average ratio of carbon to Btu).

The Decision Criteria table for this indicator is shown in the main text (see Table 1 on page 6) to provide a clear description of the methods. To reduce duplication, we are not including it here.

### Additional Descriptive Text

Wood exports for foreign energy generation are not currently tracked in the U.S. Forest Service indicator, but estimates of export volumes may be developed from U.S. International Trade Commission (ITC) trade data. This process, however, will involve some form of modeling as explicit North American Industry Classification System (NAICS) codes for wood pellets and related wood-based fuels do not exist.

### Metadata

The U.S. Department of Energy (2013); U.S. Forest Service FIA Timber Products Output Database; U.S. International Trade Commission ITC Database. Indicator prototype available as Indicator 5.24 in National Report on Sustainable Forests—2010 (U.S. Forest Service 2011), specifically at http://www.fs.fed.us/research/sustain/criteria-indicators/indicators/indicator-524.php.

### What Is the Link to Climate Variability and Change or Relevance?

This indicator is proposed as a measure of human impact on atmospheric carbon concentrations via the forest sector and, more generally, as an indicator of social response to global climate change (arrow 2 in the current conceptual model). Through carbon sequestration and bioenergy production, forests and forest management provide positive opportunities for human action to mitigate climate change. Moreover, industrial-scale bioenergy production will potentially result in significant impacts to forest ecosystems and thus represent a channel through which climate-driven policy decisions can affect forests.

### What Are the Drivers of This Indicator, and What Are Their Impacts?

Climate change-related drivers include perceived risk resulting from climate variability, which then drives policy responses favoring forest-based bioenergy production. Forest-based bioenergy production will occur in the context of broader energy markets, and energy prices determined by factors both related to climate change and not related to climate change (e.g., relative scarcity of alternative fuels). Technology innovations in areas such as cellulosic ethanol, or for competing nonwood energy sources, will likewise influence uptake and dispersion of forest-based bioenergy production.

Impacts include changes in atmospheric carbon concentrations (per full life-cycle analysis) and changes in forest characteristics resulting from bioenergy management activities.

### Has This Indicator Been Used as an Indicator by Anyone Else; If So, by Whom, and How Was It Used and When Was It Initiated?

A similar indicator, “Avoided Fossil Fuel Carbon Emissions by Using Forest Biomass for Energy,” is included in the Montreal Process Criteria and Indicators for Sustainable Forest Management (Indicator 5.c, http://www.montrealprocess.org/). A U.S. domestic-only version (omitting exports used for foreign energy production) has been incorporated in the two editions of the U.S. National Report on Sustainable Forests published to date (indicator 5.24, U.S. Forest Service 2004 and 2011). The estimation of forest biomass energy production was the primary component of the indicator, and the avoided emissions component was calculated by simply scaling forest biomass energy production by a fixed ratio of carbon to Btu (e.g., the average ratio pertaining to coal energy production). This approach ignores many of the complexities of a full carbon accounting based on life-cycle analysis. For this reason, we are proposing an energy measure as opposed to the avoided carbon emissions used by the Montreal Process. Conversion to carbon measures could easily be provided, but sufficient caveats accompanying the estimates are necessary.

### Relevance to Management Decisions

Changes in carbon emissions and sequestration as a result of forest biomass energy production could serve as inputs to national carbon accounting efforts. Identification of growing energy applications in the forest sector could help managers target future investments and mitigation measures.

### Other Indicators Considered But Not Recommended at This Time

The other indicators considered were: volume and value of forest-based carbon credits exchanged in relevant markets; amount of carbon sequestered by forest management activities explicitly aimed at increasing in situ forest carbon stocks; number of structures or lives, or both, lost to wildfire; and value of structures and other improvements lost to wildfire.

### Usefulness for Educational Purposes

This indicator could help inform the public about a little-known source of energy. Periodic updates would allow for tracking of activity and identification of nascent opportunities for industrial development.

## Data Availability

### Length of Records of Dataset

Domestic energy production from forest biomass: 1990–present, though compilation is needed for each new iteration of the time series (i.e., it is not routinely published as a survey or census statistic).

Exports of forest biomass for energy production: compilation/estimation needed.

### Stability/Longevity of Dataset and Indicator

The domestic component is dependent upon Department of Energy reporting activities. It is unclear whether the department will continue to publish estimates in this area. The U.S. Forest Service, however, is committed to producing an estimate for this indicator on a 5-year cycle as part of its responsibility to the Montreal Process.

### Notes About the Data (Recent Changes in Analysis or Collection Methods)

Presentation, data transformation, and estimation protocols would follow those presented in the U.S. Forest Service report (U.S. Forest Service 2011), though modifications could be incorporated as appropriate. Protocols for collection of export data need to be developed.

### Spatial and Temporal Scalability

May be scalable to regional and state levels, but this is primarily a national-level indicator.

## Details About the Indicator

### Type of Indicator (Current, Leading, Both)

Current

### Geographic Scope and Scale of Analysis

The scope is national to international (depending on incorporation of export markets). For carbon accounting purposes, scale of analysis is national (i.e., nation is the primary unit of analysis). Regional display may be warranted to ascertain location of impacts to forest ecosystems.

### Approach of Indicator (e.g., Single Measure, Composite)

Composite of different energy categories (i.e., fuelwood, wood pellets, wood products industry cogeneration, liquid biofuels, other)

### Purposes and Conceptual Framework

Applies directly to “Human Domain influences on Climate Domain via Forest” (arrow 2 in the current conceptual model). Additionally, to the extent that forest bioenergy development is driven by climate response policy, the indicator would help track “Climate impacts on Human Domain via Forest” (arrow 1). The purpose is to track changes in forest-based energy production, allowing for associated estimation of carbon stocks and fluxes, and impacts of energy development on forest ecosystems.

### Composition and Methodology

Composite indicator compiled from multiple reporting streams estimating forest-based energy production/consumption.

### Scientific Validity of Indicator

U.S. National Report on Sustainable Forests (U.S. Forest Service 2011) indicator 5.24 has been subject to peer review. Given data and analysis issues associated with compilation of disparate data streams, the validity of the indicator is not as strong as a statistical estimate based on a consistent sample or census.

### What Are the Plans for Further Development of the Indicator?

Incorporation of export volumes. Development of consistent protocols for compilation, analysis, and reporting.

## Considerations for Selection of Indicator

### Advantages

1) Conceptually straightforward and amenable to quantitative measurement
2) Good data availability
3) Key measure linking forests, climate change, and human activity if forest-based bioenergy emerges as major industry

### Disadvantages

1) Ambiguous in terms of implications for atmospheric carbon concentrations (long-term carbon neutrality vs. short-term emissions)
2) Lack of variance or significant levels in historical record (relevance is predicated on emergence of new energy uses)
3) Tracking export volumes for energy usage may be problematic.

## Literature Cited

U.S. Energy Information Administration. 2013. Electricity: detailed state data. U.S. Department of Energy. Available at http://www.eia.doe.gov/cneaf/electricity/epa/epa_sprdshts.html. (Last accessed 18 July 2015). [State-level utility data.]

U.S. Forest Service. 2004. **National report on sustainable forests—2003.** FS-766. Washington, DC: U.S. Department of Agriculture, Forest Service. 139 p.

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U.S. Forest Service. 2015. **Forest sustainability reporting in the United States, Indicator 5.24: avoided fossil fuel carbon emissions by using forest biomass for energy.** Available at http://www.fs.fed.us/research/sustain/criteria-indicators/indicators/indicator-524.php. (Accessed 15 March 2015). [An alternative display of this indicator in a nationally summarized form over time.]

Zerbe, J.I. 2006. **Thermal energy, electricity, and transportation fuels from wood.** Forest Products Journal. 56: 6–14.

## SOCIOECONOMIC INDICATOR: DEVELOPED AND CROSS-COUNTRY SKIING

Metrics: Number of U.S. ski/snowboarder visits, Revenues of ski area, Participation days in cross-country skiing

### Summary

Socioeconomic activities that are forest- and snow-dependent such as downhill skiing, snowboarding, and cross-country skiing are expected to be influenced by climate. More work is needed to ensure datasets are consistent for the indicators, and to understand the links between climate variability and these metrics. See Table 17 for a summary of the justifications for choosing this specific indicator and metrics.

#### What Is the Link to Climate Variability and Change or Relevance?

Winter skiing and snowboarding are dependent on snow and on temperature conditions that support snow. The effect of climate variability on these activities is clear, although developed skiing is less affected by climate, given that resorts can manufacture snow. Some regions are more affected than others by climate variability due to the nature of the skiing visits (Irland et al. 2001).

#### What Are the Drivers of This Indicator, and What Are Their Impacts?

Economic conditions, income, demographics, and climate variability are all drivers of this indicator (e.g., see Bowker et al. 2012).

#### Has This Indicator Been Used as an Indicator by Anyone Else; If So, by Whom, and How Was It Used and When Was It Initiated?

Cross-country skiing and number of snow skiing facilities on public land were included as part of an indicator on visits attributed to recreation and tourism and related to facilities available for forest sustainability (U.S. Forest Service 2012).

#### Relevance to Management Decisions

Developed ski areas are major investments, and often occur on or in conjunction with public land. Their development and planning is costly and long-term. This indicator would inform these decisions. Cross-country skiing could also benefit for similar reasons, although the infrastructure investment is usually not as large.

#### Other Indicators Considered But Not Recommended at This Time

Significant socioeconomic variables such as employment in the forestry sector and revenues from production of wood products were considered. These will also be affected by climate variability, but there are many drivers affecting them, and they are available in other indicator compilations (see U.S. Forest Service 2012). This indicator is perceived to be strongly related to climate. Nearly all Americans enjoy some form of outdoor recreation, and choosing a major form of recreation clearly related to climate was deemed more relevant and useful to this set of proposed indicators.

**Table 17.—Decision criteria for Socioeconomic indicator: Developed and cross-country skiing**

| Decision criterion | Ranking | Justification |
|---|---|---|
| **Link to conceptual framework** | Sufficient | Example of a complex impact, involving all domains, but focused on the Human and Forest Domains, and arrows 3, 4, 5, 6, 8, 12, and 13 |
| **Defined relationship to climate, feedbacks, or impacts** | Sufficient | Climate directly influences activity, which directly affects forest extent, is an ecosystem good, and can affect forest structure. |
| **Spatial scalability** | Sufficient | National to regional to county. Some datasets are tied only to participation, not to location. Work is needed to monitor local participation. |
| **Temporal scalability** | Best | Annual data are available. |
| **Of national (not necessarily nationwide) significance? Should link to the conceptual model** | Sufficient | This is more important in some regions than others, but nationally it is of interest owing to the United States' tradition of having ski areas. |
| **Relevance to management decisions** | Best | Relevant to policy-level decisionmaking and long-term planning |
| **Usefulness for educational purposes** | | Skiing is perceived as being tied to climate, and is popular across age groups. It has a wide appeal and is therefore useful for educational purposes. |
| **Is it a leading indicator?** | No | Not applicable |
| **Builds on existing data sources** | Sufficient | Some data sources from industry are available for purchase. |
| **Builds on existing indicator products** | Not applicable | No current indicator products |
| **If new indicator proposed, likelihood of development and testing within 1 year given existing funding sources** | Needs improvement | Although the data are not new, and some have been used as indicators previously, more work is needed to ensure indicators are based on consistent datasets. |
| **Stability/Longevity of dataset** | Needs improvement | Some data are proprietary; other datasets are available and research could prove them useful. |
| **Stability/Longevity of indicator** | Sufficient | This indicator could be reported; however, more work is needed to ensure consistency with longevity. |
| **Scientific validity of indicator** | Sufficient | More research is needed, especially to understand the information that the indicator provides in a climate context. |
| **Data publicly available and transparent** | Needs improvement | Some data are proprietary. More work is needed. |
| **Indicator methods fully transparent and documented** | Needs improvement | Methods are documented, but more research to understand the information that the indicator provides in a climate context would be useful. |

### Usefulness for Educational Purposes

This indicator can be reported on an annual basis, and the immediate obvious relationship between this indicator and climate creates a strong educational opportunity for all age groups.

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National Ski Areas Association. 2014. **Kottke national end of season survey 2012/13: preliminary report.** Available at http://www.snowsports.org/Retailers/Research/SnowSportsFactSheet. (Accessed 9 January 2014).

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## Other Resources

Bowker, J.M.; Askew, A.E.; Poudyal, N.; Zarnoch, S.J.; Seymour, L.; Cordell, H.K. 2014. **Climate change and outdoor recreation participation in the southern United States.** In: Vose, J.M.; Klepzig, K.D., eds. Climate change adaptation and mitigation management options: a guide for natural resource managers in southern forest ecosystems. Boca Raton, FL: CRC Press: 421–450.

Cordell, H.K. 2012. **Outdoor recreation trends and futures: a technical document supporting the Forest Service 2010 RPA Assessment.** Gen. Tech. Rep. SRS-150. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 167 p.

# APPENDIX 2: Forest Indicators Technical Team Research Memo[1]

This material is being included in this appendix for full transparency of our deliberations. We were asked to provide information about research gaps on the recommended indicators, as well as indicators that appear promising but which would probably need more than 1 year of research to be ready for use in an operational system. Some information presented here is also in the main text. We have worked to reduce duplication, yet make the entire publication as easy to read and understand as possible.

## INTRODUCTION

This memo has three main sections: 1) general concerns, 2) research gaps for selected recommended indicators, and 3) recommended potential indicators and metrics. Most of the 11 recommended indicators need technical work to make them ready to be included on a Web site available to the public. For these, we briefly describe the work that is needed. For the potential indicators, we provide a more extensive description of each potential indicator, possible metrics, and needed research. The potential indicators are not a comprehensive list. They were determined by team members, and other scientists who expressed an interest in championing an indicator for forests.

## GENERAL CONCERNS

### Direct Link to Climate Impacts

For more than a decade, indicators have been used for forest conditions and their sustainability in the United States (e.g., see U.S. Forest Service 2011). The interaction of forests, climate change, and bioenergy as a crucial overarching issue has already been identified as an area needing more attention (U.S. Forest

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[1] Slightly updated from version dated December 18, 2014.

Service 2011). Studies that are focused on the explicit links between climate and the forest indicators, interpretation, and implications are needed.

## Links With Other Teams

Similar indicators for different teams also require additional thought in the forest indicator effort. Additional research or discussion would help to ensure that similar indicators for different teams are either shared or made appropriately consistent. For example, teams may prefer different indicators of drought. The agriculture team may prefer the Palmer Drought Severity Index, whereas the forest team is suggesting a newer indicator that is proving to be more appropriate for forests.

## Protocols for Determining When New Approaches Are Better

A third issue is related to the perceptions (or realities) that new technologies can provide more accurate, effective estimates for recommended or potential indicators. Indicators for sustainability have a rich history in a forest context (e.g., U.S. Forest Service 2011), and a notable number of these indicators may be of core importance for climate change impacts in forests. Indicators for other land uses or land covers may not have the same level of data availability or history of use as do indicators for forests. Scientists or traditional stakeholders may consider the approaches to data collection in other land uses to be less accurate than those for existing forests. Disagreement over accuracy provides an additional level of complexity and even uncertainty when interpreting and explaining these indicators. Research is needed to determine when new technologies are ready to be implemented, or to clarify interpretation of indicators during the major transitions of approaches and technologies. A topic of much discussion is statistical and other quantitative approaches for detecting change. There are many techniques for time series and change detection, and different scientists or practitioners may have different opinions on which is best. Questions to consider are: Does a parsimonious set of techniques exist that would pass peer review? Should the approach be consistent across different indicators?

### Sensitivity and Risk

A final yet very important issue is about responses to impacts. Will the indicators be sensitive to response activities so that the effect of response activities will be detected? In addition, a concept often discussed in relation to response is that of risk. Even if probabilities are known that a result will occur, how decisionmakers choose to act based on that knowledge will probably differ. If the idea of risk is important to convey, how can risk be best conveyed through indicators? Research is needed to determine the importance of risk, and, if it is important, how to best convey the idea of risk through indicators.

# RESEARCH GAPS FOR SELECTED RECOMMENDED INDICATORS

## Ecosystem Services Indicator: Trends in Diversity/Abundance of Forest-associated Floral and Faunal Species

The primary indicator that we recommend for monitoring trends in faunal species diversity/abundance is the Breeding Bird Survey (BBS) of the Department of the Interior, U.S. Geological Survey (USGS). This indicator is fairly comprehensive in terms of spatial and temporal coverage. The dataset, both in raw and analyzed form, is readily available through USGS (2015). However, deficiencies are present that may limit the usefulness of the data as a robust climate change indicator. First, the BBS focuses only on a single taxon (birds) and does not encompass the broad spectrum of forest-associated faunal species. Efforts are underway to collect similar, national-level data on a variety of other taxa (e.g., USGS North American Amphibian Monitoring Program, National Ecological Observatory Network [NEON]). To date, those fledgling datasets are not as comprehensive or uniform. If the efforts continue, the resulting databases would serve well to document trends in forest-associated species.

Second, more work is needed to link trends in faunal diversity/abundance to the effects of climate change. Data from the BBS have been used to document population trends associated with a variety of factors including habitat loss/fragmentation (Herkert 1994) and, more recently, climate change (Hitch and Leberg 2007). Additional studies are needed to determine how to tease apart these various factors. Third, known biases exist in the BBS dataset such as observer differences (Sauer et al. 1994), roadside survey bias (Keller and Scallan 1999), and limitations for certain species (e.g., raptors, nocturnal birds). Numerous studies have worked to address some of these biases, but caution should be used when applying this dataset as an indicator for certain species or for certain regions until additional research is conducted to address these issues fully.

For our primary indicator of trends in forest-associated floral biodiversity, we recommend monitoring change over time in forest tree diversity across Forest Inventory and Analysis (FIA) plots maintained by the U.S. Forest Service. The advantages of this indicator include its broad spatial extent (about 130,000 plots across the conterminous United States and southeast Alaska); a nationally consistent sampling protocol across all forest ownerships, based on a rigorous statistical design; the regular remeasurement of plots across time; and the public availability of the FIA data online. Additionally, the FIA plot system allows for aggregation to larger spatial scales, such as ecoregions and counties.

However, two issues present challenges for the use of the FIA data for this indicator, at least in the short term. First, FIA data have been collected in a systematic fashion nationally since only about 2000; data are available from before that, but are problematic to use. Second, options for time-series analyses in the Western United States will be limited for some time, as each plot in the region is visited only once every 10 years. At the same time, the number of 5-year remeasurement cycles in the Eastern United States may not yet be adequate to assess biodiversity change associated with climate change.

In addition, work is necessary to determine the extent to which change in forest tree seedling diversity represents a leading indicator of climate change effects on overall forest biodiversity because of seedlings' additional sensitivity to environmental conditions. A recent study using FIA data in the Eastern United States detected weak broad-scale patterns of change in tree seedling diversity that are consistent with expected early effects of climate change (Potter and Woodall 2012). However, other factors may be affecting changes in seedling diversity over time. Additional research is also needed to establish whether simple measures of biodiversity are sufficient in such a context, or whether biodiversity metrics that account for the evolutionary relationships among species also have utility (e.g., Potter and Woodall 2014).

### Climate Impacts on Human Domain via Forest: Cost to Mitigate Wildfire Risk

Federal suppression costs are the most easily accessible data element for this indicator and can be relatively easily compiled for display. Federal expenditures for fuels treatments and related mitigation activities can likewise be accessed from federal budget reports, but measures in this area may call for additional development. Many forest restoration activities aim to improve multiple aspects of forest condition (including fire susceptibility and resilience) even if they are categorized directly under fuels treatments. Extension of these reporting activities to the state level will probably involve tallying expenditures for individual states and may be labor-intensive.

Insurance premiums and related measures require additional exploration and conceptual development. Whereas insurance markets have the benefit of representing actual market transactions and may thereby reveal new information about fire risk and expense, the use and interpretation of statistics in this area need careful consideration.

### Human Influence on Climate Domain via Forest: Energy Produced from Forest-based Biomass

Major components of this indicator have already been developed by the U.S. Forest Service (2011). However, exports of forest biomass for energy production, notably the growing volume of wood pellets being shipped overseas to help fulfill renewable energy goals, are not included in current statistics. A full accounting of wood-based energy production should include exports, though mapping product reporting categories into specific energy usages may be challenging.

Additional improvements to the indicator may be obtained by further consolidating and developing statistics in the domestic energy production sector. Wood energy from industrial installations, particularly as a byproduct of wood products manufacturing, is well reported and responsible for a major proportion of wood energy generation. Residential use and other diffuse energy production activities are less well reported, and estimates for them may require additional refinement. This is especially true in the presence of emerging technologies or shifting markets.

### Socioeconomic/Ecosystem Service: Outdoor Recreation (Developed Skiing and Cross-Country Skiing)

Mining additional available datasets could improve this indicator, especially in conjunction with local ski area monitoring, to more strongly tie participation in developed skiing to location.

## RECOMMENDED POTENTIAL INDICATORS AND METRICS

The forest team recommends six high-priority areas for further indicator research (Table 18). Several of these may be more appropriately housed within other teams, but we included them here due to their perceived importance as well as the interest of our team's scientists.

**Table 18.—High-priority potential indicator areas and metrics**

| Area for additional indicator research | Potential indicator metrics |
|---|---|
| Tribes and climate change | 1) Number of Native coastal communities relocated or needing to relocate in the next decade as a result of sea level rise or permafrost thaw, 2) Number of tribes developing climate change adaptation plans, 3) Number of tribes and Native communities engaged with Climate Science Center/Landscape Conservation Cooperatives |
| Recreation | 1) Mean high water, 2) Net internal rural migration rate, 3) Number of participants and days of participation in hiking |
| Permafrost | Extent and distribution of permafrost and peatland and associated changes in the depth of the active layer within boreal forests and tundra |
| Diversity of lichens | Lichen biodiversity status and trends, Lichen functional group state and trends |
| Ground layer (of moss/lichen mats) | Biomass, Elemental content (carbon, nitrogen), and Functional groups of moss/lichen mats which form ground layer (in Alaska and Pacific Northwest) |
| Relationship of ozone to climate change | Ozone concentrations in natural ecosystems |

## Indicator: Tribes and Climate Change

Major contributor: Marla R. Emery

Metrics: Number of Native coastal communities relocated or needing to relocate in the next decade as a result of sea level rise or permafrost thaw, Number of tribes developing climate change adaptation plans, Number of tribes and Native communities engaged with Climate Science Center/ Landscape Conservation Cooperatives

### General Description of What Is Being Measured

As forest- and natural resource-dependent communities with centuries-to-millennia in place, Native peoples are among the first to be directly affected by accelerating climate change (Fig. 14). Native peoples also have a wealth of experience adapting to past changes. Three high-priority research areas address the impacts of climate change on indigenous peoples in the United States and the potential contributions of Native peoples to adaptation planning for their communities and the larger world. We considered using the metric Proportion of communities or tribes affected, but chose Number of tribes and Native communities because obtaining data for this metric is more feasible. Additionally, "number of" provides a core metric that can be used to calculate other values such as financial resources needed to address this pressing humanitarian need.

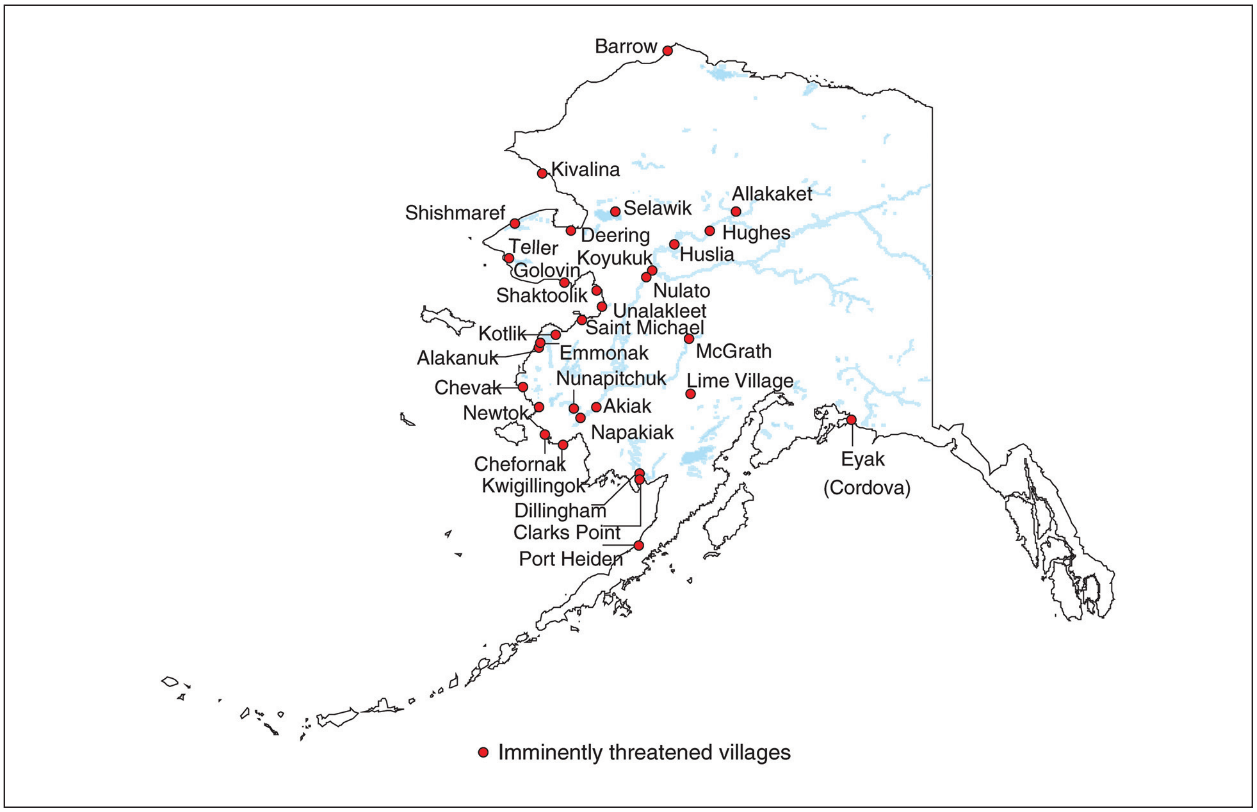


Figure 14.—Map of Alaska showing the locations of the 31 Alaska Native villages that the U.S. Government Accountability Office (2009) identified as "imminently threatened." Map source: U.S. Government Accountability Office (2009: 18).

### Number of Native Coastal Communities Relocated or Needing to Relocate by 2025 and Beyond

As stated in Bennett et al. (2014), the impacts of climate change on tribal lands and resources, such as accelerated sea level rise, erosion, permafrost thaw, and increased intensity of weather events, are resulting in current and potential future relocation of indigenous communities in Alaska, Louisiana, the Pacific Islands, and other coastal locations. These relocations are already causing a loss of community and culture, health impacts, and economic decline. At present, no lead agency is responsible for assessing, tracking, or assisting Native coastal communities needing to relocate as a result of climate change-related impacts (Bennett et al. 2014). Making this a high-priority research need would provide base information to focus attention on this escalating impact.

**Relevance to policy and management decisions**—In addition to humanitarian concerns, sea level rise and relocation of Native communities may challenge federal and state capacities to comply with treaty obligations, the American Indian Religious Freedom Act (AIRFA 1978), and other bodies of law.

**Has this been used as an indicator by anyone else?**—This issue is raised as a key message in the Third National Climate Assessment's chapter on indigenous peoples, land, and resources (Bennett et al. 2014). However, we are not aware of a U.S. or international effort in which this was used as an indicator.

**Needs for indicator development**—A formal process is needed to compile local and regional data and fill in data gaps. U.S. federal agencies tracking sea level include the U.S. Environmental Protection Agency (EPA), National Aeronautics and Space Administration, and National Oceanic and Atmospheric Administration (NOAA). Organizations with the capacity to conduct or facilitate research incorporating Native peoples in the United States and its island protectorates include:

- Pacific Northwest Tribal Climate Change Project, University of Oregon: http://tribalclimate.uoregon.edu/
- Institute for Tribal Environmental Professionals, Northern Arizona University:
  www7.nau.edu/itep/main/home (accessed 25 September 2015)
- American Indian and Alaska Native Climate Change Working Group, Haskell Indian Nations University:
  http://www.haskell.edu/climate/
- Pacific Islands Climate Change Cooperative:
  http://hawaiiconservation.org/activities/pacific-islands-climate-changecooperative

### Number of Tribes and Native Communities Developing Climate Change Adaptation Plans

Tribes across the country are becoming actively engaged in developing climate change adaptation plans and other climate initiatives (e.g., Swinomish Climate Change Initiative). These efforts address, among other topics, the likely impacts of climate change on health, culture, and the built and natural environments, as well as actions that could be taken to counteract these impacts. Though focused first and foremost on the communities that implement these programs and the resources (including forests) on which they depend, actions often also encompass planning and cooperation with surrounding communities and local, state, and federal governments. Such plans would provide a window into fine-scale climate change effects of particular concern to resource-dependent communities.

**Relevance to policy and management decisions**—An understanding of U.S. Native peoples' climate change initiatives would support:

- Incorporation of traditional ecological knowledge (TEK) into climate change adaptation and mitigation in a manner that is culturally appropriate and honors tribal sovereignty
- Anticipation of and planning for compliance with legal guarantees to U.S. Native peoples that may be compromised by climate change
- Identification of opportunities for partnerships to benefit U.S. Native peoples and others.

**Has this been used as an indicator by anyone else?**—No.

**Needs for indicator development**—Native peoples actively resist the notion that they are hapless victims of climate change. Rather, their cultures have millennia of experience adapting to a wide variety of environmental and other changes; they wish to be active players in devising solutions for their own communities and humanity at large. Currently, there is no clearinghouse or other single source of information on climate change initiatives by U.S. Native peoples. Preliminary information about tribal climate change adaptation plans is available through sources including:

- Institute for Tribal Environmental Professionals: www7.nau.edu/itep/main/climatechange/ (accessed 25 September 2015)
- Pacific Northwest Tribal Climate Change Project: http://tribalclimate.uoregon.edu/
- Northern Institute of Applied Climate Science: www.mtu.edu/forest/research/partnerships/niacs.html

### Number of Tribes and Native Communities Engaged With Climate Science Center/Landscape Conservation Cooperatives

U.S. Department of the Interior Secretarial Order 3289 of 2009 (amended 2010), “Addressing the Impacts of Climate Change on America’s Water, Land, and Other Natural and Cultural Resources,” resulted in the establishment of partner-based Climate Science Centers (CSCs) and Landscape Conservation Cooperatives (LCCs) with the mandate for CSCs and LCCs to apply “scientific tools to increase understanding of climate change and to coordinate an effective response to its impacts on tribes and on the land, water, ocean, fish and wildlife, and cultural heritage resources that the Department manages.” As a result, CSCs and LCCs are focal points for engaging U.S. Native peoples in collaborative climate change efforts.

**Relevance to policy and management decisions**—Preparedness and adaptation activities are of increasing importance to decisionmakers. This indicator provides information useful for targeting such efforts to protect the interests of Native communities, particularly for determining what is to be protected, why, and how.

**Has this been used as an indicator by anyone else?**—No.

**Needs for indicator development**—Climate Science Centers and Landscape Conservation Cooperatives support substantive participation by tribes in deliberations on climate-related mechanisms, agreements, and rules and regulations. Understanding these efforts will enhance national capacity to plan for climate change adaptation and mitigation for all communities. Potential sources of data include:

- U.S. Institute for Environmental Conflict Resolution survey of tribal engagement in Landscape Conservation Cooperatives: http://www.ecr.gov/; Sarah Palmer, federal-tribal engagement, palmer@ecr.gov
- Climate Science Centers: http://www.doi.gov/csc/index.cfm
- Landscape Conservation Cooperatives: http://www.fws.gov/landscape-conservation/lcc.html
- College of Menominee Nation, Sustainable Development Institute: http://sustainabledevelopmentinstitute.org/

Some additional selected literature on the impact of climate change on tribal communities can be found in Alexander et al. (2012), Bronen (2013), Malconado et al. (2013), and Salick and Ross (2010).

## Indicator: Outdoor Recreation and Amenities

Major contributor: Linda S. Heath, with major input from H. Kenneth Cordell
Metrics: Access to coastal land, Amenities, Hiking

### General Description of What Is Being Measured

Climate change impacts on forests naturally include impacts on rural communities and people linked to forests (Melillo et al. 2014). The term “outdoor recreation” covers a wide range of activities such as walking on the beach, hiking, bird-watching, hunting, canoeing, skiing, and camping. Many of these activities may be affected by climate variability and change, but the response effect is complex and the outcome may be unexpected (e.g., Irland et al. 2001). Research has investigated the relation of specific types of outdoor recreation to climate broadly, as well as the relationship of amenities to climate (Bowker et al. 2014; Cordell et al. 2011, 2012).

An amenity is “an attribute that enhances a location as a place of residence” (McGranahan 1999). In the United States, people prefer rural areas that include a mix of forestland, and mild winters and cool summers. Research has shown that because of this preference, amenities are strongly linked to climate (Cordell et al. 2011). If a location is rich in amenities, people want to move there; this consequence is confirmed by data which show net internal migration rates are positive to amenity-rich locations. We include the following as potential indicators.

**Access to coastal land (Mean high water)**—In most coastal states, recreational access is granted to the public under the Public Trust Doctrine. This access (ordinarily) is afforded the public between mean low tide up through the “soft sand” beach areas to the vegetation line. As climate grows warmer, sea level will rise and the public’s opportunities for using this outdoor recreation resource will change. Additional research is needed to understand how well this indicator relates to climate impacts on outdoor recreation. Another possible metric is the area of land between mean lower low tide and mean higher high tide. These tide-level data are all standard NOAA measures (see NOAA 2015). Some research highlighting the use of these coastal areas for outdoor recreation, linked with a metric from NOAA data, could prove fruitful.

**Amenities: Net internal rural migration rate**—Net internal migration rate is an amenity metric. It is the difference between domestic in-migration to an area and out-migration from the same area during a set time period. Domestic in- and out-migration consist of moves where both the origin and the destination are within the United States, excluding Puerto Rico. The rate expresses net domestic migration during a time period as a proportion of an area’s population at the midpoint of the time period. Rates are expressed per 1,000 people. Research has shown this rate to be climate-sensitive (Cordell et al. 2011) at a scale as fine as the county level.

**Number of participants and Days of participation in hiking**—Hiking is a popular activity in the United States, with 1.2 billion activity days of day hiking in 2007–2008 (U.S. Forest Service 2011). Number of participants and days of participation in hiking have been shown to be linked to warm-season climate. These variables are available as regional current estimates and as projections. Projections will be updated as new underlying information becomes available. Local and state-level projections are not currently available. Research indicates that day hiking would be negatively affected under several of the currently used climate change projections (Bowker et al. 2014). Additional research is needed to use climate impacts on hiking as an indicator.

## Indicator: Permafrost

Major contributor: Bethany K. Schulz
Metrics: Extent and distribution of permafrost and peatland, Associated changes in the depth of the active layer within boreal forests and tundra

Boreal forest and woodland occur across landscapes that include nonforest ecosystems. Collectively, the landscape response to disturbance, succession, and climate change is linked to the distribution of permafrost, soil types, and the dynamics of the layer of soil that thaws during the growing season. Our ability to predict how climate change may affect these boreal systems hinges on our knowledge of the extent and distribution of permafrost and peatland and the changes in depth of the active-layer.

Boreal landscape of a mix of forest and nonforest in Alaska. U.S. Forest Service photo by Jon Williams.

## General Description of What Is Being Measured

**Extent and distribution of permafrost**—Permafrost, which is permanently frozen ground, is a major feature of arctic and subarctic biomes, affecting ecosystem function as well as engineering of human infrastructure. At the highest latitudes, it may be continuous over vast landscapes. Where permafrost becomes discontinuous, it is difficult to map over scales meaningful to ecological processes or infrastructure planning. Permafrost is responding to changing temperature regimes, but it is unclear how changes in climate will affect near-surface processes in the long term (Abraham 2011). The extent of permafrost in Alaska is shown in Figure 15.

**Extent and distribution of peatlands**—Peatlands feature deep organic soils associated with live, dead, and decaying peat mosses. Although all peatlands store abundant amounts of carbon, boreal peatland is of special interest when it coincides with permafrost. Boreal peatland is generally insulated from air temperatures by thick layers of sphagnum moss (*Sphagnum* spp.) (Chapin et al. 2010, Krankina et al. 2008).

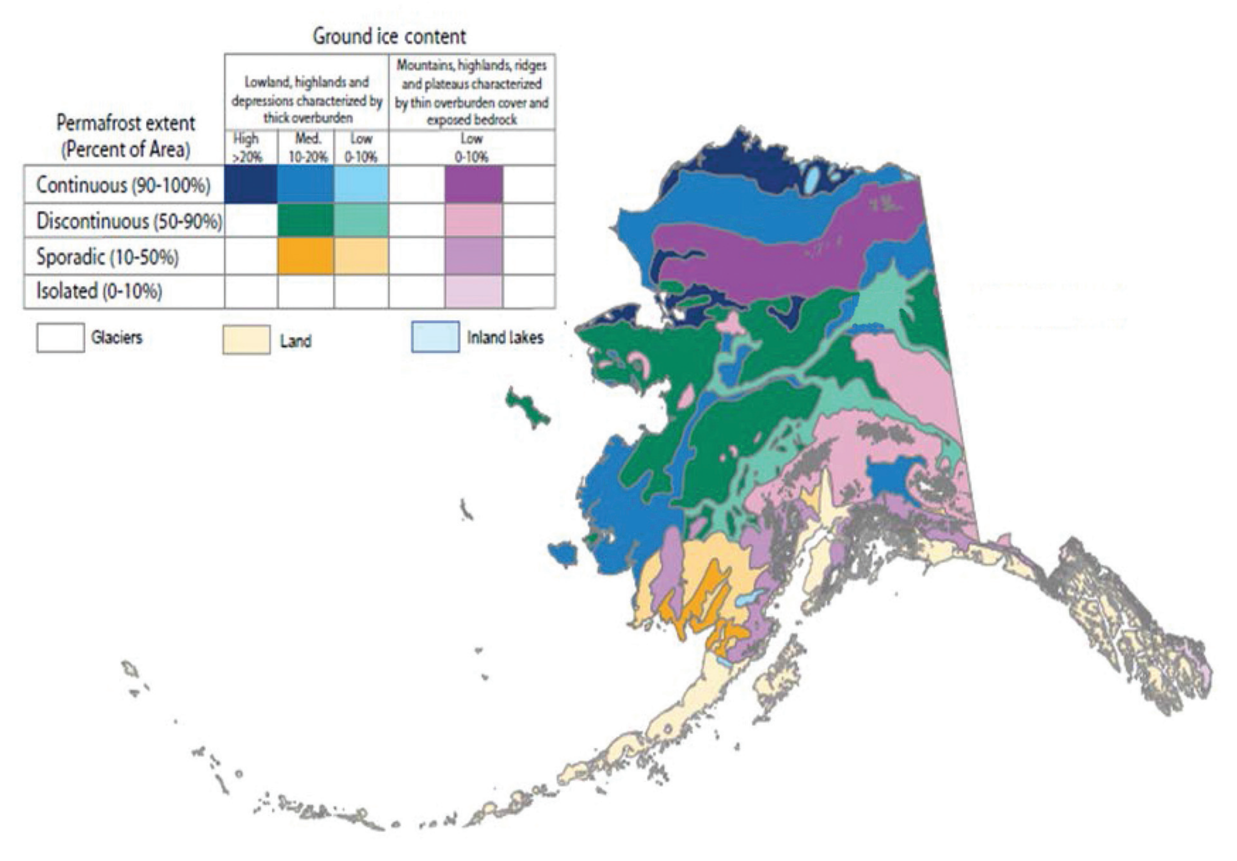


Figure 15.—Map of the permafrost extent in Alaska (Brown et al. 1998).

**Changes in the depth of the active layer**—The active layer is the portion of the soil horizon that melts in the growing season; it supports plant growth and soil respiration, and is subject to decomposition. In general, the active layer responds to air temperature on an interannual basis. In areas with tree cover, however, thaw depth is associated with snow cover (or lack thereof), forest canopy, and ground surface vegetation layers (Brown et al. 2000).

**What is the link to climate variability and change or relevance?**—Permafrost represents a large reservoir of stored carbon. These soils are subject to the changing global climate (Zimov et al. 2006) and their distribution is predicted to decrease in response to climate warming (Stendel and Christensen 2002). A better understanding of the dynamic distribution and physical properties of permafrost, continuous and discontinuous, will provide knowledge of how the permafrost environment may change in the future and help inform engineering and natural resource response strategies (Abraham 2011).

Mapping the distribution and extent of peatland, where permafrost is insulated by thick moss mats, provides a basis for calibration of estimates of carbon loss, which is expected due to temperature changes. Even in warming conditions, peat-dominated communities can continue to store carbon (Chapin et al. 2010). Once degraded, however, they can quickly become sources of atmospheric carbon. Knowing the distribution and extent of these lands is critical for understanding how continued warming may tip the balance of carbon sequestration in the boreal zone.

Vegetation shifts are directed in different trajectories according to the substrates and underlying permafrost conditions. Where water accumulates, peatland may expand; if water drains away, shrubs and trees may encroach into wetland (Pitkänen et al. 2013). Tracking the changes in the depth of the active layer in relation to permafrost and peatland distribution will aid our understanding of ecosystem response to a changing climate.

**Relevance to management decisions**—A better understanding of the extent and distribution of permafrost, peatland, and the changes to the active layer can inform engineers tasked with building roads, pipelines, and infrastructure. This indicator would help resource managers predict shifts in vegetation that might influence tree growth, wildlife habitat, or wildfire activity as well as the ways that specific management activities may affect carbon storage or release. The carbon stored in permafrost is highly decomposable (Waldrop et al. 2010) once exposed to warming temperatures. However, permafrost under peatland is protected by thick moss layers which may continue to act as a carbon sink even as air temperatures rise. These lands provide an enormous reservoir of carbon storage, and would provide a valuable ecosystem service if managed accordingly.

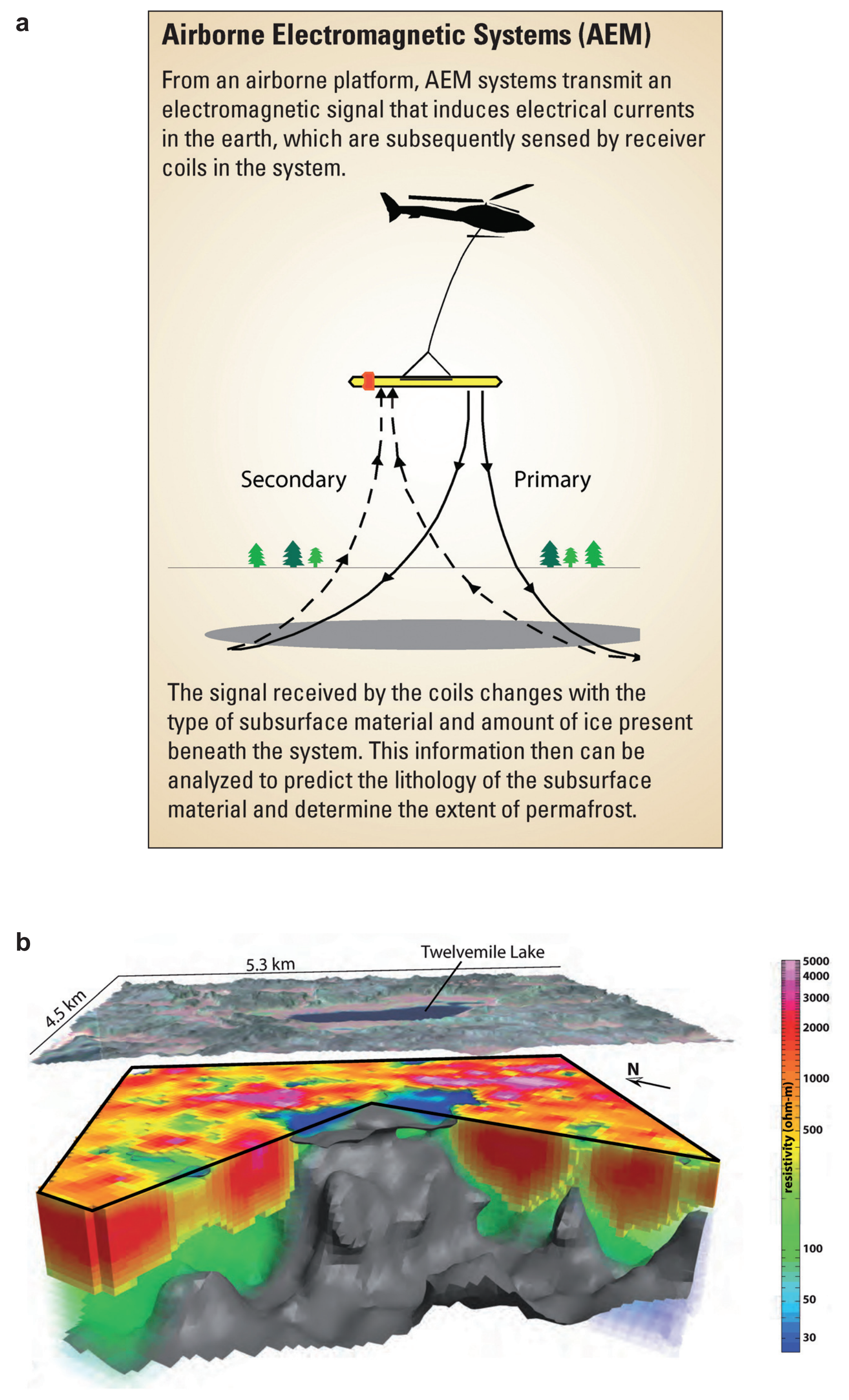
Understanding the dynamics of carbon storage and release in boreal systems is critical for accurate estimation of the terrestrial contribution to the global carbon cycle. Underscoring the continued need for carbon emission reductions at the global level, Zimov et al. (2006) conclude with a stern warning: “Factors inducing high-latitude climate warming should be mitigated to minimize the risk of a potentially large carbon release that would further increase climate warming.”

**Has this indicator been used as an indicator by anyone else?**—Remote sensing techniques for mapping permafrost features have been developed to provide information for groundwater models of the Yukon River Basin; the implications for engineering infrastructure and natural resource management are acknowledged (Abraham 2011). However, metrics for this indicator and techniques to provide measurements need additional development.

**Needs for indicator development**—Peatland mapping techniques have been developed, but are less reliable when tree cover is present (Krankina et al. 2008). This difficulty emphasizes the need for ground measurements of moss and lichen mats and measurements of the active layer (see “Ground layer indicator” later in this appendix). Changes in the depth of the active layer have long been recognized as an important factor for predicting the changing dynamics of carbon storage. The Circumpolar Active Layer Monitoring (CALM) Network has established more than 200 sites in the last two decades to measure active-layer thickness and observe soil temperatures (Brown et al. 2000, CALM Network 2015). Even with data from these sites, however, active layer characteristics are difficult to assess over large regions without additional specialized techniques.

Indeed, advances in remote sensing techniques in recent years have provided promising new methods for mapping permafrost features (Fig. 16) (Abraham 2011) and peatlands (Krankina et al. 2008, Torbick et al. 2012). The CALM Network’s sites are invaluable, but remote sensing techniques could bridge the gap between in situ point measurements and areal averages to provide information at regional scales.

The joint development of remote sensing methods with ground-based measurements (see “Ground layer indicator,” later in this appendix) to calibrate and verify remotely sensed results is critical. The extent and distribution of permafrost and peatland, along with the dynamics of the active layer, provide for a meaningful indicator for climate assessments. Given recent advances in technology, estimates for this indicator appear within reach. Solutions derived from multi-agency efforts, with a focused implementation, would facilitate data sharing for larger regional assessments.



**Airborne Electromagnetic Systems (AEM)**

From an airborne platform, AEM systems transmit an electromagnetic signal that induces electrical currents in the earth, which are subsequently sensed by receiver coils in the system.

The signal received by the coils changes with the type of subsurface material and amount of ice present beneath the system. This information then can be analyzed to predict the lithology of the subsurface material and determine the extent of permafrost.

Figure 16.—(a) Description of airborne electromagnetic systems, a promising tool for subsurface permafrost mapping (source: Abraham 2011); (b) three-dimensional cutout view showing results for the resistivity model for an example in Alaska. The gray isosurface is the interpreted base of the permafrost in the subsurface (source: Abraham 2011).

## Indicator: Lichen Biodiversity

Major contributor: Sarah Jovan
Metrics: Lichen biodiversity status and trends, Lichen functional group status and trends

### General Description of What Is Being Measured

Lichens are a large component of biodiversity in North American forests. To date, 5,355 species of lichens and allied fungi are known to inhabit the continental United States and Canada (Esslinger 2012). Under optimal conditions, epiphytic (i.e., living on tree surfaces) lichen biomass may exceed 0.83 tons per acre (1.87 metric tons per ha) (McCune 1993). The role of this epiphytic layer in regulating water and nutrient cycling in forest ecosystems is not widely recognized. Lichens increase capture of rain and nutrients from the atmosphere; captured nutrients are slowly released to the canopy and forest floor through leaching and decomposition of lichen litter (Pike 1978).

Lichens are highly climate-sensitive because they lack roots and are unable to retain water. As a result, basic metabolic processes and fitness are closely tied to ambient temperature and moisture. In some ways this life strategy is beneficial—for instance, by allowing species to grow independently of the soil (e.g., epiphytically or on rocks and leaves) and for short-term endurance of drought and other unfavorable conditions whereupon lichens dry out and go “dormant.” However, dependence on atmospheric conditions becomes a liability with longer term climate changes, which may damage tissue directly or unbalance photosynthesis and respiration rates.

We propose that a climate indicator be developed using the FIA Lichen communities indicator (U.S. Forest Service 2015a). A dataset already exists of more than 8,000 epiphytic lichen surveys (1998–2013) collected by FIA and the U.S. Forest Service, Region 6 Air Management Program, including many repeat measurements (Fig. 17). Use of these data for climate assessment has so far been cursory (but see Root et al. 2014, 2015).

### What Is the Link to Climate Variability and Change or Relevance?

Optimal levels of moisture, temperature, and nutrient availability differ widely by lichen species as does stress tolerance to suboptimal conditions. Sustained shifts in any of these drivers cause changes in lichen community composition, which affect species that use lichens directly or depend upon the ecological services they provide.

Some of the most climate-sensitive lichens have specialized functions. One example is the bearded alectorioid lichens. This functional group serves as nesting material and critical winter forage for a variety of wildlife species in the temperate and boreal forest biomes. (For example, see “Lichen Use by Wildlife in North America” at http://www.lichen.com/fauna.html.) Another example of

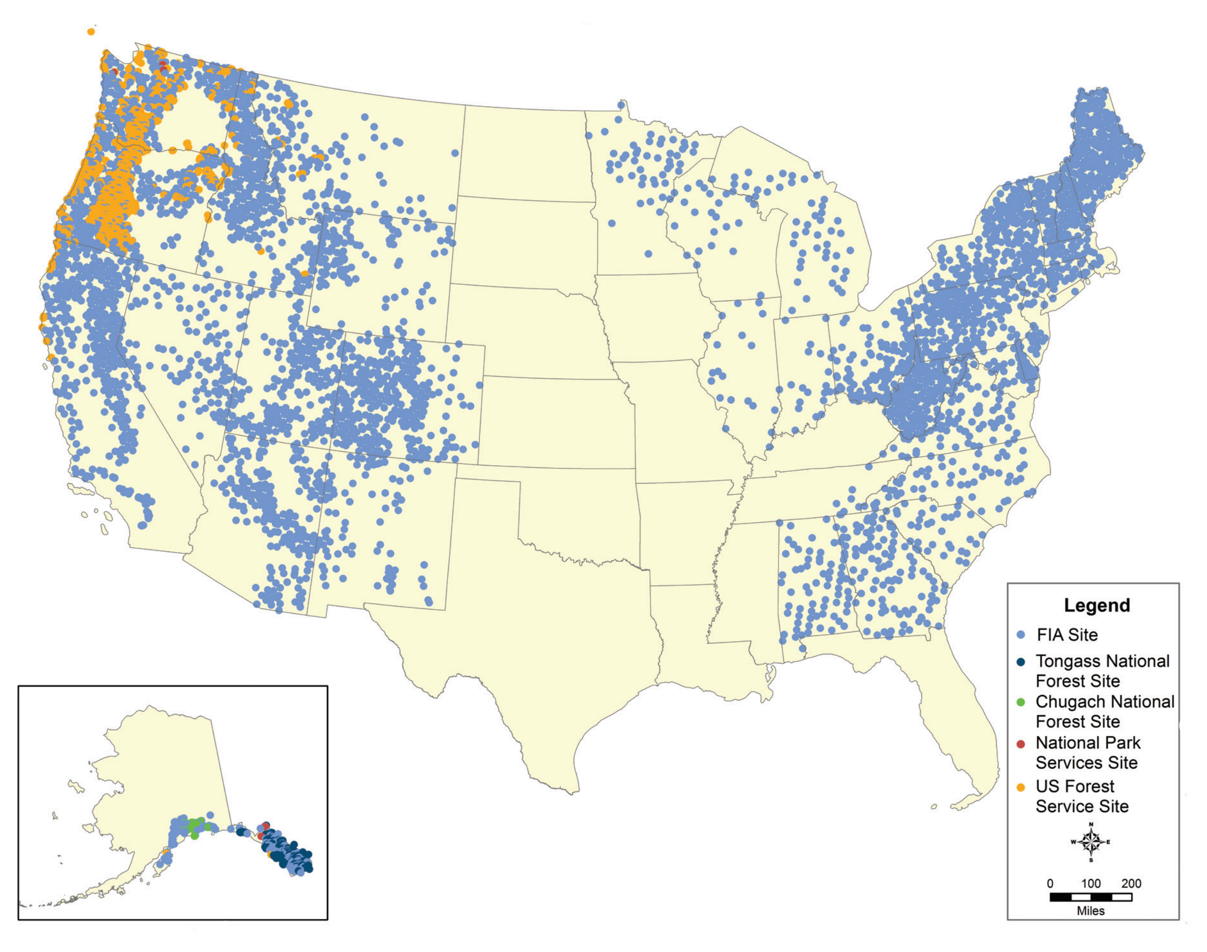


Figure 17.—Sites surveyed for epiphytic lichen communities by the U.S. Forest Service, Forest Inventory and Analysis and partner agencies. Some of these data have been only recently released. Used with permission from Jennifer Phelan, RTI International.

a lichen group highly sensitive to climate is the cyanolichens, a group that fixes atmospheric nitrogen (N) into a form that is usable by plants. Under favorable conditions, a single species (*Lobaria oregana*) can fix as much as 14.2 pounds N per acre per year (16 kg N per ha per year) (Antoine 2004), and total biomass of cyanolichen may exceed 892 pounds per acre (1,000 Kg per ha) (McCune 1993). This group is distributed in patches across the landscape and requires a relatively narrow range of moisture and temperature.

Community-level and species-level responses to climate have been demonstrated in several studies (Ellis 2013, Ellis et al. 2007), and we are starting to understand effects at the physiological level (Song et al. 2012). However, few studies investigate changes over time, and little work has been done for U.S. forest ecosystems.

### Has This Indicator Been Used as an Indicator by Anyone Else?

The U.S. Forest Service uses the Lichen communities indicator extensively for indicating air quality effects on forests. Studies stemming from that effort also document strong community patterns relating to spatial temperature and moisture gradients. Describing these results and following them over time has not been a high priority, however.

### Needs for Indicator Development

In the summer of 2014 we collected baseline data on community composition and health of lichen transplants at the U.S. Forest Service Marcell Experimental Forest in Minnesota, as part of the Spruce and Peatland Responses Under Climatic and Environmental Change (SPRUCE) project (http://mnspruce.ornl.gov/), a state-of-the-art open-topped chamber warming experiment. We are seeking support for periodic remeasurements and for a graduate research assistant to conduct research on the dataset of 9,000 lichen surveys for use as indicator species and response indices, as well as to work on estimates of change by using remeasured data.

## Indicator: Ground Layer

Major contributors: Robert J. Smith and Sarah Jovan
Metrics: Ground layer moss/lichen biomass, Ground layer moss/lichen elemental content, and Ground layer moss/lichen functional group status and trends

### General Description of What Is Being Measured

Mosses and lichens extensively carpet boreal regions with thick “ground layers” which are responsible for stabilizing and cooling soils, halting permafrost thaw, regulating water tables, slowing decomposition rates, and building deep deposits of peat (Turetsky et al. 2012). Peatlands sequester one-third of the global soil carbon budget (Yu et al. 2011), and carbon release from peatlands is highly sensitive to changes in climate and fire regimes (Turetsky et al. 2011). Until recently, however, we have lacked reliable tools for quantifying terrestrial carbon and ecosystem functions in ground layers at landscape scales.

To address such gaps, we are testing a Ground layer indicator with metrics that evaluate biomass, elemental content (i.e., carbon and nitrogen content), and functional group status and trends in moss and lichen ground layers (Smith et al. 2015). The indicator is based on the premise that simple measurements of the depth and area covered by mosses and lichens can be scaled into landscape-level estimates of biomass and elemental content based on prior calibrations. Ground layer moss/lichen biomass is the amount of biomass by dry weight of mosses/lichens. A separate ground layer moss/lichen elemental content metric allows for

Boreal peatland deeply carpeted with mosses and peat. Peatlands represent vast stores of global carbon, yet they are increasingly vulnerable to climate fluctuations and land use changes. Photo by Robert J. Smith, Oregon State University, used with permission.

tracking changing carbon and nitrogen content in this layer. Ground layer moss/lichen functional group status and trends is a measure of functional importance, which is assigned to nine easily recognizable morphological groups, examples of which are soil stabilizers, nitrogen fixers, water regulators, and wildlife forage groups. The lichens in this indicator are independent of and not related to the epiphytic lichens in the Lichen biodiversity indicator.

### What Is the Link to Climate Variability and Change or Relevance?

Changing climate has the potential to shift species ranges, resulting in the gain or loss of major functional groups in ground layers. For example, a warming and drying climate can promote shrub expansion into boreal tundra that excludes forage lichens (Heggberget et al. 2002). Similarly, increasing aerial nitrogen deposits are associated with the loss of tundra and boreal forest lichens, which are indicators of air quality (Pardo et al. 2011). In wetland, lowered water tables coupled with more severe wildfires can eliminate both critical peat deposits and the Sphagnum mosses which form them (Turetsky et al. 2011).

Climatic change also affects carbon cycling between ground layers and the atmosphere. If boreal climates warm as expected, decomposition of peat liberated from degraded permafrost may release methane ($CH_4$)and carbon dioxide ($CO_2$) in a feedback loop that would amplify additional carbon losses (McGuire et al.

2009). However, longer and warmer growing seasons might alternatively promote the expansion of peat-forming mosses that raise water tables, which would enhance soil cooling, permafrost retention, and decomposition rates (Chapin et al. 2010). The wide range of uncertainty among possible outcomes highlights the importance of monitoring ground layers as vital contributors to ecosystem functioning and global carbon budgets.

### What Are the Drivers of This Indicator and What Are its Impacts?

The Ground layer indicator arose from the need to make status and trend information available to researchers, resource managers, and policy makers. It represents not only an inventory of current ground layer conditions, but also the launching point for process-based studies that seek to understand the causes and consequences of environmental change and resulting regime shifts. However, the utility of the indicator extends beyond academics and specialists because it can guide policy makers and educators. Likewise, the indicator is not constrained to any geographical region; its simplicity means that the indicator has the flexibility to be implemented not only in high-latitude terrestrial systems, but also in forest, steppe, grassland, and wetland habitats throughout all regions. It is also readily scaled from plot to landscape levels.

Sphagnum peat-moss, a desirable keystone species responsible for regulating water levels, soil temperature, and rates of decomposition. Photo by Bernd Haynold, under Creative Commons license.

### Relevance to Management Decisions

Land management (or decisions which may result in land use change) such as wildfire prescription/suppression, invasive species control, and groundwater use entails impacts to ground layers (both positive and negative) which managers must understand if they are to retain the suite of ecosystem services that ground layers provide. The Ground layer indicator will give resource managers baseline information useful for gauging how land use changes and environmental alterations may affect the provision of ecosystem functions and carbon budgets in boreal forests and beyond.

### Has This Indicator Been Used as an Indicator by Anyone Else?

No previous indicator has attempted to quantify the biomass, elemental content, and functional importance of the ground layer. To date, the Ground layer indicator has undergone extensive field trials throughout interior Alaska and the U.S. Pacific Northwest (Smith et al. 2015).

### Needs for Indicator Development

The protocol in Smith et al. (2015) is still flexible enough to be modified where local needs dictate (e.g., some regional locations may have different plant functional groups not found elsewhere). It would be fruitful to extend the work to different habitat types and to explore and test methods for deep peat sampling.

Portion of the ground layer in Alaska tundra. A 6-inch portion can fulfill many functional roles, such as fixing nitrogen, stabilizing soils, and providing winter forage for wildlife. Photo by Robert J. Smith, Oregon State University, used with permission.

## Indicator: Ozone: Relationship of Ozone to Climate Change

Major contributors: Robert Musselman and Andrzej Bytnerowicz
Metric: Ozone concentrations in natural ecosystems

### General Description of What Is Being Measured: Ozone

We propose the development of a climate indicator using ambient ozone in forests. Many forest areas already exceed the current National Ambient Air Quality Standard (40 CFR part 50) for ozone (Fig. 18) assessed by U.S. EPA. Ozone ($O_3$) is a pollutant produced in the atmosphere by chemical reaction of precursor chemicals, which are produced by burning fossil fuels. Climate change is expected to result in additional ozone and increased plant stress. Higher temperatures may increase the amount of chemical precursors for $O_3$ formation, the rate of chemical reactions creating $O_3$, and the sensitivity of plant species from new climate-induced stress not previously encountered.

### What Is the Link to Climate Variability and Change or Relevance?

Ozone is a greenhouse gas that plays an important role in the energy budget of the atmosphere. It features the third largest positive radiative forcing among the atmospheric greenhouse gases (Gauss et al. 2003). Because $O_3$ is a precursor for

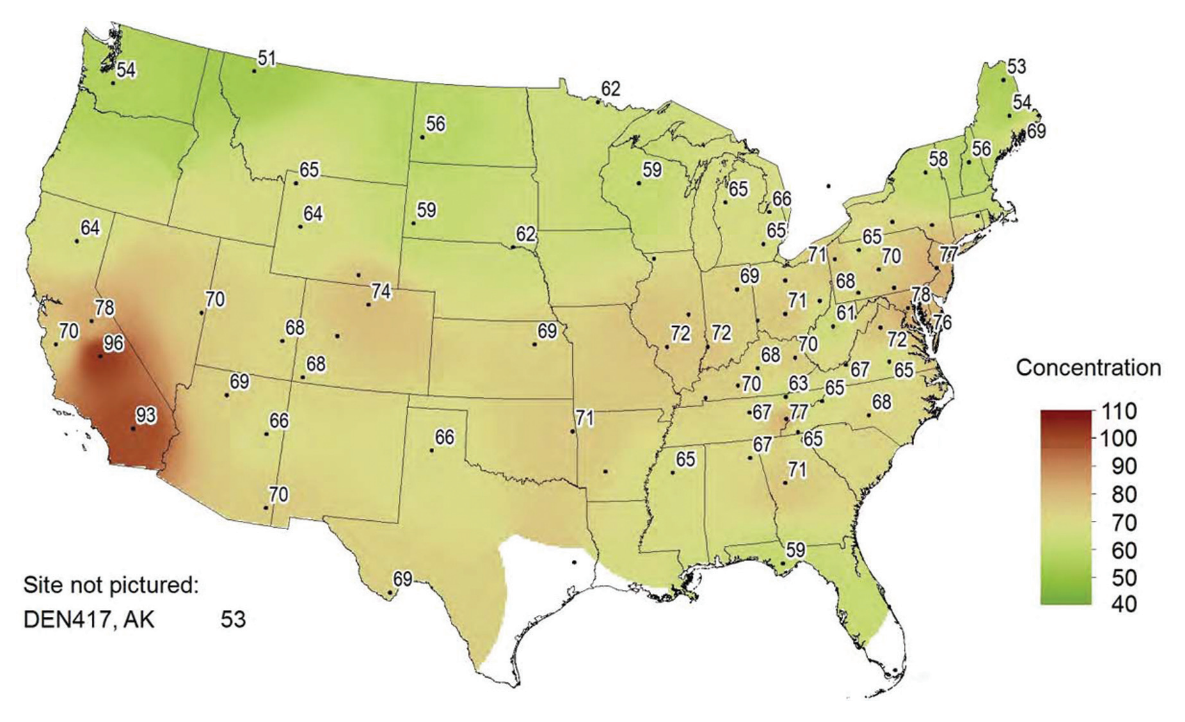


Figure 18.—Concentration of ozone (parts per billion) in the United States in terms of the 3-year average of the fourth highest daily maximum 8-hour average for 2009 through 2011 (AMEC Environment & Infrastructure, Inc. 2013).

oxidizing reactions, it strongly influences the lifetime of other greenhouse gases such as methane and hydrofluorocarbons (HFCSs), which in turn affects radiative forcing (Gauss et al. 2006). In addition, it also indirectly affects climate by limiting sequestration of $CO_2$ by vegetation (Sitch et al. 2007).

Modeling the link between climate change and ozone is only in its early phases (U.S. EPA 2009), but most models predict a link between climate change and increased $O_3$. For example, emissions of the $O_3$ precursor volatile organic compounds (VOCs) and nitrogen oxides ($NO_x$ ) are expected to increase, with a significant contribution of those generated in southeast Asia (Doherty et al. 2013). Increases in summertime peak $O_3$ concentrations are particularly evident in model results (U.S. EPA 2009). Lengthening of the summertime high-$O_3$ season is also expected concurrent with an increase in the length of the growing season (U.S. EPA 2009).

Vegetation is very sensitive to high $O_3$ concentrations. Ozone already exceeds the current standard in some forested mountain areas of the Rocky Mountains (Musselman and Korfmacher 2014), and U.S. EPA has proposed strengthening the ozone standard to protect vegetation and trees (U.S. EPA 2004). Therefore, the importance of $O_3$ to management is expected to continue to grow. Interactions of increases in $CO_2$ and increases in $O_3$ will likely cause genetic changes in plant populations (Moran and Kubiske 2013). Increased $O_3$ effects on ecosystems will most likely cause changes in ecosystem function such as carbon sequestration and in distribution, quality, and quantity of streamwater (Bytnerowicz et al. 2013a, McLaughlin et al. 2007). Recent years have shown increases in the number of wildfires in U.S. forests, partially a result of climate-increased ambient temperatures and increased weather extremes, such as drought. A direct link between wildfires and increased $O_3$ has been reported (Bytnerowicz et al. 2013b).

### Has This Indicator Been Used as an Indicator by Anyone Else?

The Ozone indicator has been used by the U.S. Forest Service’s Forest Health Monitoring program to indicate sensitivity of plant species in forests to ambient $O_3$ (U.S. Forest Service 2015b). However, the explicit link to climate has not been made.

### Needs for Indicator Development

The model results linking ozone to climate change differ greatly by region (U.S. EPA 2009). Additional research on the interaction of increased $CO_2$ , temperatures, and $O_3$ effects on individual forest tree species is needed. Little is known about the interaction of longer growing season, increased levels of summertime $O_3$ , and increased climate-induced vegetation stress, such as drought, on vegetation or ecosystem response. The relationship between climate change and emissions of $O_3$ precursors needs additional study. Finally, determining the metric that will most clearly convey the impact of ozone on climate and forests needs additional work.

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The Third National Climate Assessment (NCA) process for the United States focused in part on developing a system of indicators to communicate key aspects of the physical climate, climate impacts, vulnerabilities, and preparedness to inform decisionmakers and the public. Initially, 13 active teams were formed to recommend indicators in a range of categories, including forest, agriculture, grassland, phenology, mitigation, and physical climate. This publication describes the work of the Forest Indicators Technical Team. We briefly describe the NCA indicator system effort, propose and explain our conceptual model for the forest system, present our methods, and discuss our recommendations. Climate is only one driver of changes in U.S. forests; other drivers include socioeconomic drivers such as population and culture, and other environmental drivers such as nutrients, light, and disturbance. We offer additional details of our work for transparency and to inform an NCA indicator Web portal. We recommend metrics for 11 indicators of climate impacts on forest, spanning the range of important aspects of forest as an ecological type and as a sector. Some indicators can be reported in a Web portal now; others need additional work for reporting in the near future. Indicators such as budburst, which are important to forest but more relevant to other NCA indicator teams, are identified. Potential indicators that need more research are also presented.

KEY WORDS: forest extent indicator, forest biomass indicator, wildfire indicator,
forest insect and disease damage indicator,
water balance deficit indicator, WUI indicator, fire risk cost indicator,
biomass energy indicator, forest growth indicator,
biodiversity indicator, skiing indicator, NCA indicator system

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