Climatic Change (2021) 165:13
https://doi.org/10.1007/s10584-021-02993-6

Developing a set of indicators to identify, monitor, and track impacts and change in forests of the United States

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Received: 15 December 2016 / Accepted: 6 January 2021/Published online: 10 March 2021

Abstract
United States forestland is an important ecosystem type, land cover, land use, and economic resource that is facing several drivers of change including climatic. Because of its significance, forestland was identified through the National Climate Assessment (NCA) as a key sector and system of concern to be included in a system of climate indicators as part of a sustained assessment effort. Here, we describe 11 informative core indicators of forests and climate change impacts with metrics available or nearly available for use in the NCA efforts. The recommended indicators are based on a comprehensive conceptual model which recognizes forests as a land use, an ecosystem, and an economic sector. The indicators cover major forest attributes such as extent, structural components such as biomass, functions such as growth and productivity, and ecosystem services such as biodiversity and outdoor recreation. Interactions between humans and forests are represented through indicators focused on the wildland-urban interface, cost to mitigate wildfire risk, and energy produced from forest-based biomass. Selected indicators also include drought and disturbance from both wildfires and biotic agents. The forest indicators presented are an initial set that will need further refinement in coordination with other NCA indicator teams. Our effort ideally will initiate the collection of critical measurements and observations and lead to additional research on forest-climate indicators.

Keywords US forests · Forest indicators · Climate change indicators · Global change

This article is part of a topical collection on "National Indicators of Climate Changes, Impacts, and Vulnerability" edited by Anthony C. Janetos and Melissa A. Kenney.

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1 Introduction

Forests are important ecologically, economically, socially, and culturally, and in the United States, they account for about one-third of the total land base (Oswalt et al. 2019; Williamson and Edwards 2014). They are a major land use, ecosystem type, and economic sector (forestry) that provide ecosystem services, economic value, and other resources (Burton et al. 2010; Gauthier et al. 2014). Ecosystem goods and services provided by forests include: habitat for more than 200,000 plant and animal species, freshwater supplies, protection of soil from erosion, accumulation of organic matter, air quality improvements, a significant terrestrial carbon sink, and human health benefits (Stein et al. 2000; Collins and Larry 2007; Friedlingstein et al. 2019). Economically, they contribute an estimated 2.8 million jobs, $102 billion in payroll, $262 billion in annual sales of manufactured and wholesale forest products, and 6.7% of total manufacturing revenue (U.S. Forest Service 2012; Wan and Fiery 2013). Forests provide livelihood resources outside of market exchange such as a direct source of food, medicine, and utilitarian materials for subsistence and personal use (Emery and Pierce 2005), and they also enhance quality of life through numerous recreational opportunities including viewing, photography, backcountry activities, and hunting (Cordell 2012).

The significance of forests makes them crucial to understanding climate change and its impacts on the global biophysical system and society. Climate change exacerbates the risks faced by forests and the resources they provide from both biotic (e.g., disease, insects, and invasive species) and abiotic (e.g., fire and drought) stressors and disturbances (Dale et al. 2001; Seidl et al. 2017). It increases the frequency, severity, and/or duration of many disturbances while also affecting growth, shifting species distributions, and disrupting ecosystem composition, structure, and function (Littell et al. 2010; Seidl et al. 2017; Anderegg et al. 2020).

Climate change affects forests, and forests also provide a major avenue for human response to climate change. Responses could mitigate climate change through carbon sequestration on forested land, or they could amplify climate change through deforestation (Solomon et al. 2007). In recent decades, US forests sequestered substantial amounts of carbon, annually offsetting 10 to 20% of US fossil fuel emissions (Heath et al. 2011). As a setting for ecosystem-based adaptation strategies, forests offer low-cost options for climate mitigation while also providing additional environmental and social benefits (Fargione et al. 2018). However, forests can switch from a carbon sink to source through continued warming stress that drives respiration to outpace photosynthesis or through uncharacteristic disturbances (Cai et al. 2010; Anderegg et al. 2020). Another climate mitigation approach is increased use of renewable energy, and forests can provide renewable resources such as woody biomass, which accounts for 20% of renewable energy consumption in the United States (US Energy Information Administratrion 2013).

The importance and vulnerability of forests and forest resources have long made them the focus of efforts to monitor their status and track change at national and global scales (Liknes et al. 2013). In 1874, the US Department of the Interior established the Commissionership of Forestry, and within 2 years, legislation was passed to conduct a forest survey with additional assessments called for in the ensuing years (LaBau et al. 2007). In 1928, Congress passed the McSweeney-McNary Act, tasking US Department of Agriculture (USDA) to conduct periodic inventories of the Federal, State, and private forest lands and to report the results to Congress, leading to the development of the USDA Forest Service's Forest Inventory and Analysis (FIA) and Forest Health Monitoring programs (Fedkiw 1998; LaBau et al. 2007; Oswalt et al. 2019; EPA 2016). Monitoring impacts and changes to forests was recognized as a global-scale endeavor in the late twentieth century with United Nations Conference on Environment and

Development in Rio de Janeiro in 1992 and the formation of the Montréal Process Working Group, in which the United States participates (Montreal Process 1995; Linser et al. 2018). Following the lead established in the early 1990s by the International Tropical Timber Organization's (ITTO) development of criteria and indicators for sustainable tropical forest management, the Montréal Process established the first international guide to sustainable temperate forest management (Montreal Process 2015; ITTO 2016). Both the Montréal Process and the Intergovernmental Panel on Climate Change (IPCC) recognize the necessity for sustainable forest management to mitigate and adapt to climate change (IPCC 2007; Montreal Process 2015). International work has spurred national scale efforts such as those in Canada to address sustainable forest management under climate change (Gauthier et al. 2014; Williamson and Edwards 2014; Lorente et al. 2018; Natural Resources Canada 2020). Monitoring remains crucial as forests are managed across large areas and continue to face new and evolving stressors and threats including land-use/land-cover conversion, air and water pollution, increased disturbance, wildland fire, and climate change (IPCC 2007; Gauthier et al. 2015; Lugo 2015; Millar and Stephenson 2015; Montreal Process 2015; Abatzoglou and Williams 2016).

International and national scale efforts to develop indicators and monitor forests provide a strong foundation from which to build and identify indicators for a US effort to track climate change impacts across sectors and systems of concern, including forests. A National Climate Indicator System (NCIS) is one goal of the sustained National Climate Assessment (NCA), an effort to allow continual input into the climate change assessment mandated by the 1990 Global Change Research Act (Kenney et al. 2014; Kenney et al. 2018). The NCIS would serve as a "system of physical, natural, and social indicators that communicate and inform decisions about key aspects of the physical climate, climate impacts, vulnerabilities, and preparedness" (Buizer et al. 2013; Kenney et al. 2016). The effort to design the NCIS defines indicators as "reference tools that can be used to regularly update status, rates of change, or trends of a phenomenon using measured data, modeled data, or an index to assess or advance scientific understanding, to communicate, to inform decision-making, or to denote progress in achieving management objectives" (Kenney et al. 2016). As part of this effort, we focus on indicators related directly to forest ecosystems and associated social and economic systems as they relate to climate change detection and monitoring for impacts from a changing climate. Building on prior efforts, we focus on aspects unique to US forests, approach indicators with a climate change lens, and concentrate on areas of interest for sustained NCA efforts. Our three objectives are to (1) develop a conceptual model of the forest-climate system, (2) utilize the conceptual model in identifying indicators of climate impacts on forests, and (3) identify areas of future research on forest indicators.

2 Process to identify recommended indicators

To make recommendations for the NCIS, the sustained NCA established the Indicator Working Group (Kenney et al. 2018). The Working Group organized 13 technical teams to identify and select indicators and provided them overarching decision criteria and guidance (Janetos et al. 2012; Kenney et al. 2014). The criteria defined indicators to (1) be scientifically defensible, (2) link to a conceptual framework, (3) have a defined (not necessarily cause–effect) relationship to climate, (4) be nationally important and scalable if possible, (5) build on existing efforts, and (6) include both current and leading indicators (Kenney et al. 2014). Current indicators describe status, trends, or conditions while leading indicators provide information and insight into future conditions, serving as a type of “canary in the coal mine” (Janetos et al. 2012).

The Forest Indicator Technical Team, of which we are members, was one of the 13 teams established. Because forests can be defined as a land use, a land cover, an economic sector, and an ecosystem, it was important to clearly define and identify forested lands. We adopted the definition of forestland used by the FIA program, which by mandate, provides a census of the nation's forests (Oswalt et al. 2019). The FIA defines forests as “land at least 120 feet wide and 1 acre (0.4 hectare) 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…Forestland does not include land that is predominantly under agricultural or urban land use.” This definition clarifies areas we recognize as forests even as we understand forests from ecological, economic, social, and cultural perspectives.

We also adopted a broad definition of an indicator as a description of an item, process, or concept of interest with the actual measurement or dataset of the indicator being defined as a metric. Some indicators could be based on several metrics or datasets, each with different advantages and disadvantages. For example, we considered the National Resources Inventory (NRCS 2017) for forest cover information; however, it only addresses non-federal land whereas FIA provides forest cover information for all forested lands regardless of ownership. Often the attributes that make one metric more useful than another are a combination of specific characteristics, various stakeholders' needs, and the perceived maturity of a metric methodology. Our approach allowed identifying major concepts of interest while avoiding debates between metrics, specific data sets, and their collection methodologies.

We began by identifying major attributes of forest systems followed by potential indicators depicting those attributes and then subsequent data sources that could support the indicator. Nearly 70 different candidate indicators were identified from a range of prior national scale monitoring programs, indicator efforts, and studies. The team vetted these for data availability, scientific validity, operability, relevance to management, and ease of communication. Guiding the identification of attributes and candidate indicators was a conceptual model that recognized the major drivers of change relevant to forests within the broader context of the Earth system and the relationships and feedbacks affecting forests within a multi-stressor context (Fig. 1). Developing the conceptual model served as a brainstorming mechanism and helped to connect the different areas of expertise among team members. It created a common framework and shared understanding of forests from multiple perspectives brought by different team members. We agreed that the recommended set of indicators would strive to cover the scope of our conceptual model to capture the full system from end-to-end, a requirement of the larger NCIS effort (Kenney et al. 2018). To recommend a reasonable number of indicators, this required tradeoffs between selecting indicators rated highly across all criteria and those that provided end-to-end coverage of the forest system. For some attributes, practical issues such as data availability and tractability determined indicator selection, and for others, tradeoffs related to scope along with professional judgment drove the selection process.

The result of our work is a forest indicator set designed to be updated as new information, research, and data become available, rather than to exist as a permanent collection of datasets, although we do propose datasets for each indicator identified. Our recommendations include indicators both based on established data sources and from sources with recognized potential that require more development and data collection. Kenney et al. (2016) provide further details on the broader process, and Heath et al. (2015) provide specifics on each indicator selected (see also Electronic Online Resources 1 and 2). No leading indicators were identified, but with more

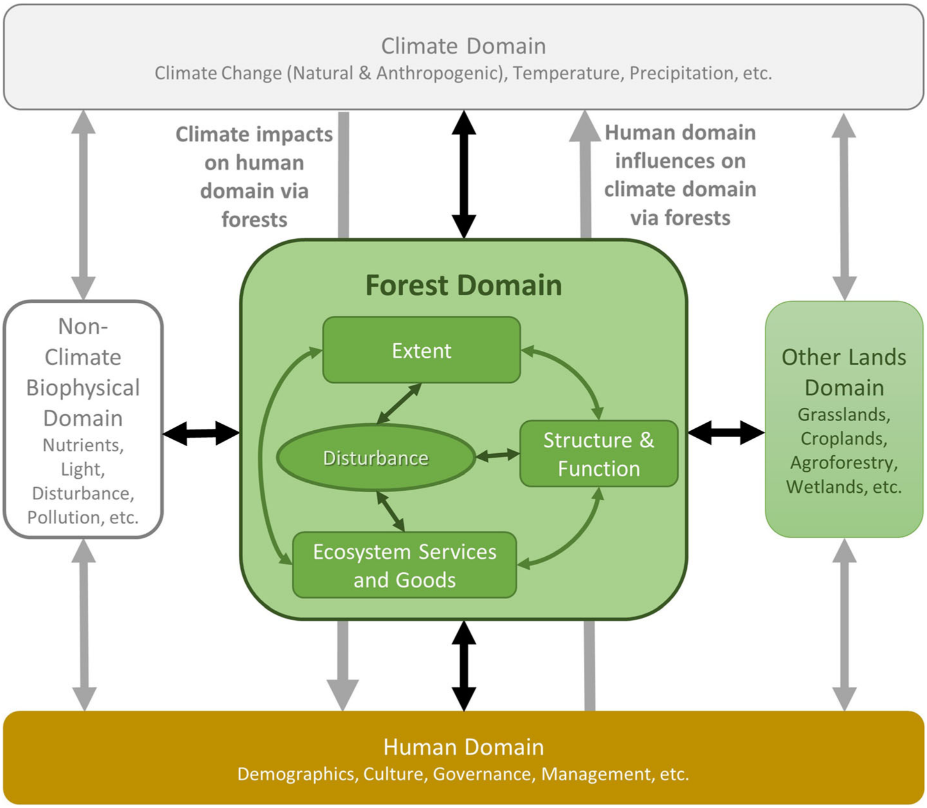

Fig. 1 The conceptual model places forests at the center and attempts to capture direct interactions and drivers of change through black arrows and indirect interactions and feedbacks with gray arrows. Forests interact with other major components of the Earth system, recognized by the four boxes surrounding forest and described here as domains: Climate, Other Lands, Non-Climate Biophysical, and Human. Forests are also complex systems in and of themselves. We identified three major attributes within the forest system: Extent, Structure & Function, and Ecosystem Services and Products. Disturbance can alter and affect all attributes within the Forest Domain.

research, some of the candidate indicators may serve this role. As work to identify and develop forest indicators proceeded, we recognized that some ecological, social, or climatic processes important to forests were more relevant to other technical teams. To ensure these aspects were not overlooked, we identified seven indicators for consideration by other teams.

3 Conceptual model of forests and climate

The conceptual model recognizes the major drivers of change in forest systems and identifies categories to which our initial recommended set of indicators can be assigned (Fig. 1). The model uses a generic design to be adaptable to the wide variety of forest types and ecosystems in the United States and to processes occurring at different scales. We describe forests with the term "domain" to be inclusive of forests as a land type, an ecosystem, and an economic resource. Our conceptual model recognizes four other domains that are major components of the Earth system interacting with and driving change in the Forest Domain: (1) Climate, (2) Other Lands, (3) Non-Climate Biophysical, and (4) Human (Fig. 1). Arrows define interactions, relationships, and feedbacks among domains and their components, distinguishing between direct (black arrows) and indirect (gray arrows) interactions with the Forest Domain. Within the Forest Domain, attributes are the major components that define or constitute a forested ecosystem, that can differentiate one type of forest from another, and that capture internal dynamics within forests. Discussing individual activities when using this conceptual model may involve several arrows, domains, and attributes in the Forest Domain. The examples used below are intended only to illustrate how the model can be used to think about a particular forest system or interaction, and they are not intended to be inclusive of all possible systems, relationships, or scenarios where the model could be applied.

The Forest Domain interacts with all other domains. Interactions with Other Lands Domain result in conversion from or to forest, and they subsequently change the major attributes within the Forest Domain and ultimately the ecosystem services and goods provided (U.S. Forest Service 2001; MacCleery 2011; U.S. Forest Service 2011). The other three domains each have major drivers of change that affect the Forest Domain. Climate drivers include changes in variability and extremes of temperature and precipitation; non-climate biophysical drivers include nutrients, light, disturbance, and pollution; and human drivers include demographics, culture, governance, and management including adaptation and mitigation strategies although these may exert an effect through other domains. Because forests also affect other domains, the arrows between forests and other domains are more than one-way interactions, hence two-headed arrows. For example, climate drivers such as changes in temperature, precipitation, and atmospheric conditions initiate feedbacks from the Forest Domain to the Climate Domain by affecting evapotranspiration, trace gas fluxes, and albedo (Melillo et al. 2014; Lewis et al. 2015; Schlesinger et al. 2015).

All the domains and drivers of change can affect the Forest Domain directly or indirectly through interactions with other elements in the model. Thus, feedbacks from each driver are implicit in the conceptual model by connecting multiple arrows through different model elements. For example, nitrogen deposition leads to fertilization, acidification, or eutrophication within forest systems depending on local factors and deposition amounts (Aber et al. 2003; Davidson et al. 2012). The Human Domain drives most changes in nitrogen emissions with the resulting deposition affecting forest structure, function, and ecosystem goods and services (Pardo et al. 2011). Nitrogen deposition also modifies greenhouse gas emissions with resulting climate impacts (Pinder et al. 2012; Porter et al. 2013). This Non-Climate Biophysical Domain driver illustrates the multi-stressor context of forests and the potential for interactions and feedback loops among all domains.

Relationships exist among the other domains that are expressed in the Forest Domain. For example, climate events with major effects on the Human Domain include the increased incidence of heat waves (Horton et al. 2015). Increases in heat waves directly affect the Human Domain by increasing heat-related fatalities and indirectly affect the Human Domain through impacts on aspects of forest ecosystem structure, function, and services such as increased tree mortality (Gauthier et al. 2014; Hansen et al. 2014). Tree mortality reduces carbon sequestration, increases fuel for wildfires, and reduces the value of timber with implications for the Human Domain. The Forest Domain also facilitates the influence of the Human Domain on the Climate Domain. Examples of this include management and policy decisions such as those associated with deforestation (feedback loop that increases CO_2 emissions; Bala et al. 2007; Bonan 2008; Le Quéré et al. 2014; Alkama and Cescatti 2016) or using harvested wood to produce bioenergy and renewable materials (feedback loop that mitigates CO_2 emissions over the long-term; Woodbury et al. 2007; Geng et al. 2017). These types of decisions are made in the Human Domain of our conceptual model, carried out in the Forest Domain, and result in impacts to the Climate Domain.

Within the Forest Domain, forest extent, structure and function, ecosystem services and goods, and disturbance are major attributes of forestland, interacting over time and across the landscape. Extent defines the area designated as forestland, which is dynamic and can change to and from other land use and/or land cover types. Structure and function are core characteristics of forestland such as the number and size of trees and growth, recruitment, and mortality rates. Ecosystem services and goods are recognized environmental and social benefits provided by forests. Disturbances such as storms, wildfires, or outbreaks of biotic agents permeate the Forest Domain, and they affect all the other attributes: extent, structure and function, and ecosystem services and goods. One example of the interconnectedness of attributes within the domain is that of a strong storm (disturbance) that blows down or breaks off the tops of many trees (structure), some of which are harvested (goods), thereby affecting forest growth (function), carbon sequestration (service), and biomass of dead wood (structure). Some of the disturbed forest area may be cleared and developed, reducing forest area (extent, Xi and Peet 2011, Fischer et al. 2013). These attributes encapsulate major aspects, relationships, and characteristics of forest systems that are and will be affected by environmental change including climate change.

4 Indicator selections and their context within the conceptual model

In total, the Forest Indicator Team recommends 11 forest indicators and provides at least one potential metric for each indicator (Table 1, Online Resource 1, Online Resource 2). Detailed descriptions of each indicator are found in Heath et al. (2015). Our recommended indicators represent major processes, concepts, and interactions within the conceptual model and cover interactions between the Forest Domain and other domains, major attributes of forests, and disturbance within the Forest Domain. They were rated by experts as best across the different criteria outlined by the Indicator Working Group. We also attempted to select the best available metric for each indicator given the decision criteria, scale, and scope of this effort. The selection of proposed metrics utilized existing data sources and data collections efforts. However, we recognize that each indicator could have multiple metrics, and depending on the audience, some metrics for a given forest indicator may work better than others.

The conceptual model illustrates how forests interact with the other components of the Earth system, and four of the 11 indicators explicitly capture these types of interactions. Two indicators are devoted to major interactions between the Climate and Human Domains that influence and affect forests. *Cost to Mitigate Wildfire Risk* is an indicator of how the Climate Domain can impact the Human Domain and captures how climate's influence on wildfire and managing wildfire risk has tangible financial impacts to society (Gorte 2011). The Human Domain's Influence on the Climate Domain arrow (Fig. 1) is represented by the *Energy Produced from Forest-based Biomass* indicator, which captures a societal response to climate change. Utilizing forest-based biomass for energy provides an alternative to fossil fuels and can serve as a mitigation measure against climate change over long timeframes, assuming regeneration of forest lands or reduction in carbon emissions from the disposal of waste wood (US Forest Service 2011). The third indicator captures interactions among the Other Lands, Human, and Forest Domains by tracking the area and human population of the wildland-urban

Table 1 The 11 recommended indicators are listed along with the major process or concept to which they are linked in the conceptual model, recommended metric(s), and recommended dataset(s)

Indicator	Link to conceptual model	Metric(s) selected	Proposed dataset
Forestland Area and Extent	Forest extent	•Forestland area by land use •Forest area based on forest cover only	FIA and NLCD
Forest Biomass Density	Structure and function	•Aboveground live tree biomass per unit area •Dead wood mass per unit area	FIA
Diversity/Abundance of Forest-associated Floral and Faunal Species	Ecosystem services	•Forest tree biodiversity status and trends •Forest fauna biodiversity status and trends	Floral: FIA Fauna: USGS Breeding Bird Survey
Forest Growth/Productivity	Structure and function	•Net annual forest growth •Forest net primary productivity (NPP)	Forest Growth: FIA NPP: MODIS
Wildfire Effects	Disturbance	•Burned area •Number of large fires •Fire severity	MTBS and NIFC
Forest Insect and Disease Damage	Disturbance	•Area affected by insects and diseases	ForWarn; Forest Health Protection
Water Balance Deficit—An Indicator of "Plant--Relevant" Drought	Biophysical indicator	•Water balance deficit (calculated as a difference between potential and actual evapotranspiration)	gridMET
US Wildland-Urban Interface	Extent and human domain indicator	•Area of wildland-urban interface •Population residing in wildland-urban interface	Integration of US Census and NLCD according to Federal Register definition
Cost to Mitigate Wildfire Risk	Climate impacts on human domain via forests	•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	NIFC
Energy Produced from Forest-based Biomass	Human domain influences on climate domain via forest	•Energy produced, domestically or in export markets, from biomass harvested from US forests	US DOE, USFS FIA Timber Products Output Database, and US International Trade Commission
Outdoor Recreation	Human domain and ecosystem services	•Number of US ski/snowboarder visits •Revenue of ski areas •Participation days in cross-country skiing	National Ski Areas Association and others[a]

More detail on specific indicators is provided in Online Resource 1 and Online Resource 2.

Abbreviations: FIA, Forest Inventory and Analysis; NLCD, National Land Cover Dataset; USGS, US Geological Survey; MODIS, Moderate Resolution Imaging Spectroradiometer; MTBS, Monitoring Trends in Burn Severity; NIFC, National Interagency Fire Center; US DOE, United States Department of Energy; USFS, United States Forest Service.

[a] Other data sources are available and may show different estimates or trends (e.g., Cordell 2012).

interface (WUI). The *WUI* indicator is not driven by climate change, but it is impacted by and responds to climate change impacts, especially as it relates to wildfire (Radeloff et al. 2005). The fourth indicator capturing interactions among domains is the *Water Balance Deficit* indicator (also knowns as Climatic Water Deficit), which focuses on the feedbacks among the Non-Climate Biophysical, Climate, and Forest Domains as they relate to drought and was selected as an ecologically relevant measure of drought (Stephenson 1990; Littell et al. 2016).

Five of the 11 indicators represent the major attributes of forests identified in the conceptual model. Extent is captured in the *Forestland Area and Extent* indicator, a key indicator for tracking changes in forest area as a result of climate change impacts and human management (U.S. Forest Service 2011). Structure and Function are captured with the *Forest Biomass Density* indicator and *Forest Growth/Productivity* indicator. *Forest Biomass Density* provides an indication of climate mitigation in terms of forest stocks and potential biomass for bioenergy while *Forest Growth/Productivity* provides an indicator of forest function and how it is changing (U.S. Forest Service 2011; Oswalt et al. 2019). Ecosystem Goods and Services are represented by the *Diversity/Abundance of Forest-associated Floral and Faunal Species* indicator and the *Outdoor Recreation* indicator. Forest biodiversity has been related to ecosystem resilience while outdoor recreation relates to cultural ecosystem services (Winter et al. 2018; Balvanera et al. 2006; USDA Forest Service 2016; Liang et al. 2016).

The remaining two indicators cover disturbance, which permeates forests, affecting all their major attributes. Disturbance indicators include the *Wildfire Effects* indicator and the *Forest Insect and Disease Damage* indicator. Disturbance from wildfire is increasing with a well-recognized link to climate change (Littell et al. 2009; Dennison et al. 2014; Abatzoglou and Williams 2016). Climate is also an important factor influencing outbreaks of both insects and diseases which merits the inclusion of *Forest Insect and Disease Damage* as a disturbance indicator in this effort (Bentz et al. 2010; Sturrock et al. 2011; Potter and Conkling 2020).

Beyond the 11 recommended indicators, we identified other indicators important to forests but more relevant to other teams who we encouraged to consider including (Online Resource 3). These included indicators related to the physical climate (temperature, precipitation, and wind), water cycle (drought), human health (health impacts related to forests such as asthma or Lyme disease), and phenology (senescence and budburst). Additionally, we identified multiple important links and areas of overlap between forests and land-uses/sectors represented by other teams. For example, wildfire indicators are relevant to forests, grasslands, and phenology. Currently, we and the Phenology Team have identified different metrics for a wildfire indicator to meet different stakeholders' needs (Weltzin et al. this issue). We and the Grassland Team share interests in indicators of primary ecosystem productivity (Ojima et al. this issue; Jones et al. 2018). Drought indicators are important to forests and to agriculture, physical climate, and water cycle (Kenney et al. 2014; Hatfield et al. 2018; Peters-Liddard et al. this issue). Several indicators from the Physical Climate team are highly important to forests, such as temperature and precipitation (Kenney et al. 2014). Also, the Forest and the Mitigation and Greenhouse Gas Sources and Sinks Teams could collaborate on indicators of terrestrial greenhouse gas sources and sinks (Bruhwiler et al. this issue). Given the breadth of the NCIS, identifying overlaps is critical for developing an integrated system and indicators useful to a broad range of stakeholders and decision-makers (Kenney et al. 2018).

5 Research priorities

Several of the recommended indicators have recognized research gaps. Specific research gaps or data needs were noted for four of the 11 recommended indicators; these gaps and needs shared several common themes (Table 2). Research gaps related to data source and data collection were noted for three indicators: *Diversity/Abundance of Forest-associated Species*, *Cost to Mitigate Wildfire Risk*, and *Outdoor Recreation*. Improvements in the methodologies were identified for three indicators: *Diversity/Abundance of Forest-associated Species*, *Energy Produced from Forest-based Biomass*, and *Outdoor Recreation*. Research on trends is needed for two indicators to better articulate their links to climate change: *Diversity/Abundance of Forest-associated Species* and *Outdoor Recreation*. Other research needs exist, but they were deemed not as pressing as these.

We did not identify any leading indicators. Developing the indicators listed here or others as leading indicators is a research priority. Some of the recommended indicators, such as *Diversity/Abundance of Forest-associated Species* indicator, could become leading indicators with additional research and development. The state of these indicators, however, allows them to be effective as current indicators, and thus they were recommended as such.

We also identified and described six areas for additional indicator research and development related to forests: Native American tribes and climate change; outdoor recreation and amenities; tropospheric ozone; lichen biodiversity; ground layer of lichens and mosses; and permafrost (Online Resource 4). Several of these additional research areas highlight the need to understand interactions between forests and other domains (Fig. 1). Recognizing the unique ways climate change may impact Native American tribes and tribal communities makes clear the importance of additional research between the Forest and Human Domains (Norton-Smith et al. 2016). Additionally, there is a need to better understand and incorporate traditional ecological knowledge in mitigation and adaptation efforts as we strive to better understand forested and other ecosystems (Vinyeta and Lynn 2013). An ozone indicator would provide further insight into interactions between Forest and Non-Climate Biophysical Domains. These additional indicator concepts also highlight the need for further research related to the Forest Domain itself. Lichen biodiversity and the ground layer of lichens and mosses candidate indicators both expand on ecosystem goods and services, with the ground layer indicator also contributing to our ability to track forest structure and function. Additional subject areas, such as permafrost, are not strictly focused on forestland, and we list them here because of their role as potential drivers of change in the Forest Domain or as being driven by change in the Forest Domain.

We also identified four broad areas of research that would benefit all recommendations for the broader NCIS. First, more research is needed on direct links of indicators to climate, and on interpretation of those indicators. Specifically, studies are needed that explicitly investigate the connections, interpretation, and implications between climate and forest indicators. Second, we identified indicators that are useful to forests but more relevant to other teams; discussing such linkages among relevant teams is crucial to developing continuity within the larger indicator system. Third, guidance on how to decide between data collection methods and approaches for metrics is needed to keep choices objective and to determine when new approaches are better than existing approaches. Some users may prefer a newer approach, but newer approaches often have greater uncertainty and shorter data collection records. Fourth, sensitivity of an indicator's response to perturbation and the risk of impacts that this sensitivity conveys are interacting concepts that need further exploration.

Our indicators currently do not include urban trees or trees growing on agricultural lands, but we recognize these resources constitute notable and growing gaps in understanding the US landscape (U.S. Forest Service 2016; Westfall et al. 2018). In 2000, urban areas covered 3.1% of land area in the conterminous United States and are projected to grow to 8.1% of the land base by 2050, with a considerable amount of this increase occurring on current forestland

Table 2 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	•Possible deficiencies in US 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. •More work is needed to link trends to climate change effects. •Additional work is needed on the relation of faunal populations to influential factors other than climate.
Diversity/Abundance of Forest-associated Floral Species	•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 US data, which collected on a 10-year cycle; data series in the Eastern United States may not be long enough yet to assess biodiversity change associated with climate change. •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. •Research is needed to establish whether simple measures of biodiversity are sufficient or whether biodiversity metrics that account for functional diversity or evolutionary relationships among species would be needed.
Climate impacts on Human Domain via Forest: Cost to mitigate wildfire risk	•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. •Design of reporting activities for forest restoration activities will probably involve tallying expenditures to the state level and may be labor-intensive. •Insurance premiums and related measures require additional exploration and conceptual development.
Human influence on Climate Domain via Forest: Energy Produced from Forest-based Biomass	•A method or methods are needed to determine and include exports of forest biomass for energy production in current statistics. •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.

(Nowak and Crane 2002). Trees on agricultural lands or in agroforestry systems provide forest-derived services that support agricultural operations and landscapes that are productive and more climate resilient (Schoeneberger et al. 2012). However, little information is routinely collected about the extent and type of agroforestry practices in the United States because they generally occur on land not designated as forest and are not included in operational forest inventories. These systems of increasing human–forest and human–tree interactions and their associated climate change impacts warrant additional attention.

6 Conclusions

The earth is changing at an unprecedented rate with every year post-2013 warmer than all others dating back to the start of the meteorological record (Blunden and Arndt 2020). Understanding this level of change and its impacts requires well-designed systems to track and monitor. Identifying critical elements in an end-to-end system allows recognizing how climate impacts permeate through ecological and social systems. Additionally, it takes time to recognize the cascade of impacts, underscoring the importance of indicator identification now and continuing data collection and monitoring into the future. The power of a comprehensive system with long-term records not only informs decision-making but also allows detecting responses as patterns emerge over time.

This paper relies on a multidisciplinary approach to identify possible indicators describing forest systems and their relation to climate change. Taken together, these indicators comprise an explicit, albeit incomplete, framework for gathering and displaying information—an essential first step supporting policy, management applications, and hypothesis testing focused on forests and climate change. Our effort is envisioned as the first step in an ongoing process of indicator identification, development, and refinement. A comprehensive conceptual model placing forests and climate within a multi-stressor context is useful to inform users of the entire system's diverse aspects that need consideration. It facilitates thinking about forests in a multi-faceted way as a land use, ecological type, and part of an economic sector simultaneously while also serving as a tool to facilitate communication. The conceptual model guided the selection of 11 current indicators for the NCIS. It captures the impacts, vulnerabilities, and responses of forests to climate change. In the future, we recommend revisiting the partitioning of the land base for NCIS development and ensuring continuity among indicators identified for different land cover types. As experience and understanding in the use of indicators deepens, the next set of NCIS indicators should show a marked advance in sophistication and cross-indicator team integration.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10584-021-02993-6.

Acknowledgments The authors acknowledge the support provided by A.C. Janetos, chair of the Indicator Work Group under the National Climate Assessment and Development Advisory Committee (NCADAC), and M.A. Kenney, director of the Indicator Research Team. Kenney's research team provided research and coordination support to the technical team, which was supported by National Oceanic and Atmospheric Administration grant NA09NES4400006 and NA14NES4320003 (Cooperative Climate and Satellites-CICS) at the University of Maryland/ESSIC. Members of the Indicators Technical Teams, NCADAC Indicator Work Group, and Kenney's NCIS research team are included in Kenney et al. (2014). The authors also wish to recognize contributions to Heath et al. (2015), which formed the foundation for this article: Andrzej Bytnerowicz (USFS, Pacific Southwest Station), Sarah Jovan (USFS Pacific Northwest Research Station), Miranda Mockrin (USFS, Rocky Mountain Research Station), Robert Musselman (USFS, Rocky Mountain Research Station), Bethany K. Schulz (USFS Pacific Northwest Research Station), Robert J. Smith (Oregon State University), Susan I. Stewart (University of Wisconsin).

Authors' contributions All authors contributed to conceptualization, analysis of datasets, literature, writing, and critical review of the manuscript. Anderson was responsible for primary writing of the article, conceptualizing the conceptual model, and synthesizing input from all team members. Heath was responsible for conceptualization of the whole project and supervised design. Team members also contributed to specific indicators: Heath (Forestland Area and Extent, Forest Biomass and Density, Forest Growth and Productivity, Wildfire Effects, and Outdoor Recreation), Emery (indicators identified as research needs), Hicke (Forest Insect and Disease Damage), Littell (Water Balance Deficit), Lucier (Forestland Area and Extent), Masek (Forest Growth and Productivity), Peterson (Wildfire Effects), Pouyat (conceptual model, coordination with other technical teams), Potter (Diversity/Abundance of Forest-associated Floral Species), Robertson (Cost to Mitigate Wildfire Risk, Energy Produced from Forest-based Biomass), and Sperry (Diversity/Abundance of Forest-associated Faunal Species).

Funding information M.A. Kenney, director of the Indicator Research Team, provided research and coordination support to the technical team, which was supported by National Oceanic and Atmospheric Administration grant NA09NES4400006 and NA14NES4320003 (Cooperative Climate and Satellites-CICS) at the University of Maryland/ESSIC. S.M. Anderson was supported by National Science Foundation grant 0903714 for most of the time spent working on this project.

Declarations

Ethics approval Not applicable.

Conflicts of interest/Competing interests The authors declare no competing interests.

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