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Terrestrial primary productivity indicators for inclusion in the National Climate Indicators System

Matthew O. Jones[1] **· Steven W. Running**[2] **·**
John S. Kimball[2] **· Nathaniel P. Robinson**[1] **·**
Brady W. Allred[1]

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Abstract The National Climate Indicators System (NCIS) aims to provide a suite of systematically updated, easily interpretable, and policy relevant national metrics of key physical, ecological, and societal conditions. The NCIS will distill and communicate complex scientific information to a broad audience as part of sustained National Climate Assessments. The current NCIS has made significant strides in defining its scope, providing an initial suite of indicators, and outlining its future development goals. In line with the scope and aims of the NCIS, we present a set of terrestrial primary productivity indicators that are scientifically defensible, scalable, directly related to climate, nationally important, built on existing agency efforts, and linked to the conceptual framework of the NCIS. The Gross Primary Productivity (GPP) and Net Primary Productivity (NPP) indicators provide seasonal and annual metrics of the growth of all plant material across the contiguous U.S., Alaska, Hawaii, and Puerto Rico. The GPP and NPP products used to produce the indicators have become key carbon measurements of environmental health and ecosystem services, including food, fiber, and fuels supporting national economies, human sustainability, and quality of life. We demonstrate how the proposed GPP and NPP indicators are relevant across indicator system sector topics of Forests, Grassland/Rangelands/Pastures, Agriculture, Wildfire, and Seasonal Timing and Phenology, can be used in concert with existing proposed indicators, and will aid to filling current gaps in the NCIS.

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✉ Matthew O. Jones
matt.jones@ntsg.umt.edu

[1] Numerical Terradynamic Simulation Group, Forest Management, W.A. Franke College of Forestry and Conservation, University of Montana, ISB 419, 32 Campus Dr, Missoula, MT 59812, USA

[2] Numerical Terradynamic Simulation Group, Ecosystem and Conservation Sciences, W.A. Franke College of Forestry and Conservation, University of Montana, Missoula, MT, USA

1 Introduction

Net primary productivity (NPP), the growth of all plant material on the land surface, represents the rate of CO_2 assimilation through photosynthesis and is a fundamental link between the atmosphere and the biosphere. Through NPP, global ecosystems absorb approximately 25% of anthropogenic CO_2 emissions (Pan et al. 2011) yet inter-annual variation is prevalent due to the complex response of ecosystems to climate variability; with the majority of year-to-year variation in the airborne fraction of CO_2 attributable to variability in the land carbon sink. Global estimates of primary productivity are therefore essential for understanding and quantifying the global carbon cycle and serve as key indicators of ecosystem responses to a changing climate and disturbance.

The U.S. National Aeronautics and Space Administration (NASA) Earth Observing System (EOS) currently produces consistent satellite derived global estimates of daily gross primary productivity (GPP) and annual net primary productivity (NPP) over the entire terrestrial earth surface at 1-km spatial resolution (Running et al. 2004; Zhao et al. 2005). The satellite-derived primary productivity estimates are based on three theoretical components. First, NPP is directly related to absorbed solar energy (Field et al. 1995). Second, there is a direct connection between canopy absorbed solar energy and satellite-derived spectral vegetation indices. Third, biophysical constraints limit vegetation photosynthetic efficiency in converting absorbed solar energy to biomass.

In brief, the NPP algorithm implements the fraction of photosynthetically active radiation that is absorbed by the land surface (FPAR), biome specific conversion efficiency parameters which translate the energy absorbed into tissue growth (biomass), and reductions in the conversion efficiency due to temperature and water constraints. This is done by combining spectral vegetation indices derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) aboard the TERRA and AQUA satellite platforms with daily surface meteorology and biome specific vegetation parameters to globally map GPP and NPP at 1-km resolution. GPP, calculated daily and provided as an 8-day product, is the amount of carbon fixed during photosynthesis which is directly affected by temperature, water, and light availability as constraints on theoretical growth potential. NPP is calculated annually from GPP by considering both maintenance and growth respiration costs; the carbon consumed by these processes is subtracted from GPP to obtain annual NPP, including both aboveground and belowground biomass production. For a detailed description of the algorithm and logic, refer to Running et al. (2004) and Running and Zhao (2015).

The MODIS GPP and NPP products (Fig. 1) are continually produced since year 2000 and have provided valuable data for carbon, climate, ecosystem, agriculture, and bioenergy research across environmental, social, and economic sectors. The products have demonstrated drought induced reductions in global NPP (Zhao and Running 2010), informed both global (Le Quéré et al. 2009; Cleveland et al. 2013; Poulter et al. 2014) and regional (Hasenauer et al. 2012; Reeves et al. 2006, 2014) estimates of carbon source/sink dynamics, and displayed response to large-scale ocean-atmosphere circulation modes (Bastos et al. 2013). They have been implemented to track ecosystem disturbances (Bright et al. 2013; Kang et al. 2005), alterations to ecosystem services (Allred et al. 2015; Tallis et al. 2012), and vulnerabilities of societies to changes in primary productivity (Running 2012; Milesi et al. 2003, 2005). Research has also revealed the value of the NPP product to estimate the U.S. bioenergy potential (Smith et al. 2012a), global bioenergy capacity (Smith et al. 2012b), crop yields (Sánchez et al. 2015; Reeves et al. 2006), and the effect of land use conversion to agriculture

(Smith et al. 2014). The scientifically defensible and widely implemented seasonal GPP and annual NPP products have become key carbon measurements of environmental health and ecosystem services, including food, fiber, and fuels supporting national economies, human sustainability, and quality of life. In this manuscript, we demonstrate the potential of MODIS GPP and NPP products in the development of climate indicators for inclusion in the U.S. Global Change Research Program (USGCRP) National Climate Indicators System (NCIS) and future National Climate Assessments.

The National Climate Assessment (NCA) is mandated by the Global Change Research Act of 1990 and carried out by the U.S. Global Change Research Program. New to the third NCA is a recommendation for a sustained assessment that includes foundational products, such as indicators (Buizer et al. 2013) that provide timely relevant assessment information to broadly support decisions. A National Climate Indicator System (NCIS) proposed in this special issue, as discussed by Kenney et al. (2014) and Janetos and Kenney (2015), provides such a foundational product. The NCIS is designed to include easily interpretable, policy relevant national metrics of key physical, ecological, and societal conditions. The inclusion of GPP and NPP indicators support the broad vision of the NCIS, can be used synergistically with existing proposed indicators for improved understanding and applications of ecosystem response to climate, and will aid in filling current system gaps.

The GPP and NPP indicators presented here are directly applicable to many of the system and sector topics outlined including Agriculture (Hatfield et al. this issue), Forests (Anderson et al. this issue), Grasslands-Rangelands-Pastures (Ojima et al. this issue), Seasonal Timing and Phenology (Betancourt et al. this issue), and Water Cycle and Management (Peters-Lidard et al. this issue). The GPP and NPP indicators also meet the selection criteria as they are scientifically defensible, scalable, directly related to climate, nationally important, built on existing agency efforts, and linked to the conceptual framework (Buizer et al. 2013; Kenney et al. 2016). Building on the initial prototypes, here we demonstrate how the GPP and NPP Indicator’s ability to track conditions and trends would be a valuable addition to the NCIS. This is demonstrated by addressing three questions. (1) Do NPP and GPP anomalies across the continental U.S. (CONUS) provide a means to track conditions of annual and seasonal vegetation productivity at CONUS-wide and regional scales. (2) Can the high temporal and spatial resolution of these indicators inform vegetation productivity response to disturbances (such as drought and fire) and changes in growing season length. (3) Do GPP and NPP indicators provide more refined estimates of vegetation productivity within and across forests, grasslands, rangelands, and pastures than those currently available in the NCIS.

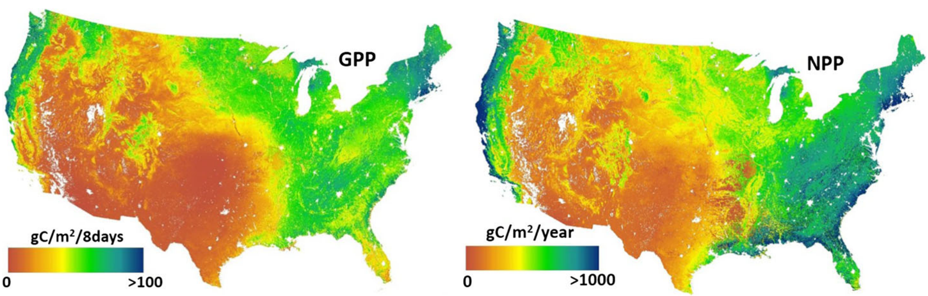

Fig. 1 MODIS GPP and NPP over the contiguous U.S. at 1-km resolution. GPP is the 8-day total over the period July 28–August 4, 2011 and NPP is year 2011 total

2 Methods

As indicators are intended to be easily interpretable and traceable to an established scientific metric, straightforward methods are used in the production of GPP and NPP indicators. The input datasets represent two standard NASA EOS MODIS data products: the 8-day MOD17A2 version 055 GPP and annual MOD17A3 version 055 NPP produced at the end of each calendar year. The global 1-km resolution products are available via the NASA/USGS Land Processes Distributed Active Archive Center as 1200 km by 1200 km tiles in a sinusoidal projection providing coverage of the continental U.S., Alaska, Hawaii, and Puerto Rico. The version 055 product implements preliminary quality assessments (and if necessary gap-filling) of two essential input data sets, the MODIS FPAR and Leaf Area Index products (LAI), and includes a simplified quality control metric. While the version 055 product was used in this investigation, the newly available version 6 provides similar performance and enhanced spatial resolution (500 m), and could be used for any future creation of GPP and NPP indicators.

The GPP and NPP products are calculated from other MODIS products and meteorological data, so separating measurement uncertainty from natural variability is a challenge, particularly considering NPP cannot be measured directly at large scales. Recent research efforts have implemented the MODIS GPP and NPP algorithms to assess global GPP and NPP trends (Smith et al. 2015; Ballantyne et al. 2017) which generated uncertainty bounds across a wide range of parameter combinations and meteorological datasets using a Markov Chain Monte Carlo approach. Results indicated that uncertainties in calculated NPP are well represented by ± 1 temporal standard deviation (SD) of the estimate. Therefore, in this application, any detection of change in NPP within ± 1SD of the long-term mean, on a per-pixel basis, is categorized as "no detectable change". Estimates of GPP however are available via the FLUXNET2015 database providing eddy covariance flux tower derived GPP. We compared MODIS GPP with tier one FLUXNET2015 GPP data from 30 sites (Supplementary Table S1) across a CONUS-wide distribution representing a range of land cover classes using the tower GPP observations as an observational benchmark to gauge relative performance of the MODIS GPP record (Supplementary Methods). Results from all sites displayed strong correlations and relatively low error estimates (r value = 0.89, RMSE = 1.53, Bias = 0.09) with RMSE values by land cover type ranging from 1.04 to 1.8 (mean of 1.44). In production of GPP indicators, we use an easily interpretable value of 1.50 gC/m^2/day where any per-pixel GPP anomaly within ± 1.50 gC/m^2/day is categorized as having "no detectable change".

The GPP and NPP indicators are calculated as temporal anomalies relative to the full data record means for each pixel (i.e., deviations from a "normal" baseline condition). For the annual NPP anomaly, this is done by calculating the full data record mean for each pixel, and then subtracting the mean from the yearly NPP value. For GPP, the data record pixel means are calculated for each 8-day interval of the calendar year. The data record 8-day mean is subtracted from each year's 8-day value to determine the GPP anomaly. The results include yearly maps of annual NPP anomalies, and 46 weekly (8-day) GPP anomaly maps per year. The indicators meet the NCIS specifications by providing deviations from a "normal" or baseline historical state; wall-to-wall national maps at sufficiently fine spatial resolution to allow for inter-comparisons at national, regional, and local scales; and easily interpretable maps and graphs with intuitive common color palettes that provide information on the health of ecosystems relevant to public interests and decision makers.

3 Proposed indicators

3.1 NPP anomaly indicator

The NPP anomalies provide annual indicators of ecosystem health, response to a changing climate, and impacts from disturbances. The NPP indicator is provided in both map and plot formats (Fig. 2). The high-resolution maps highlight the variability of vegetation productivity at the national scale, displaying how changes in climate can have dramatic effects within and across regions, and

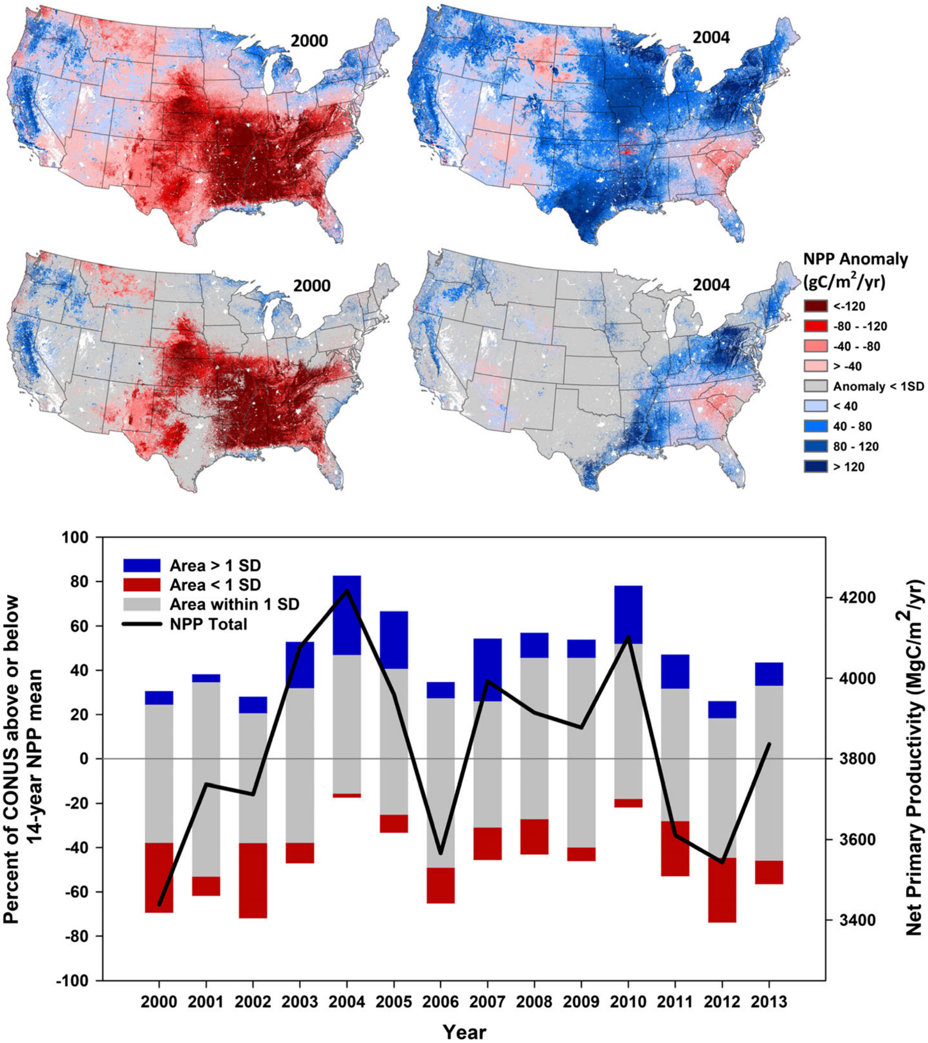

Fig. 2 NPP Anomalies in both map and plot format. Maps in top row are year 2000 and 2004 anomalies from the long-term (2000–2013) mean, and maps in second row display only pixels with anomalies greater or less than 1 SD of the long-term mean; gray areas are anomalies within ± 1 SD and white areas denote where NPP was not calculated (e.g., urban or barren land, water bodies). Plot displays percent of the contiguous U.S. within ± 1 SD of the long-term mean (gray bars), above 1 SD (blue bars), or below 1SD (red bars). Total NPP over the contiguous U.S. is also provided (black line)

allowing for essential regional or local assessments applicable to land managers and decision makers. The time series NPP plot provides a national summary of inter-annual variation, providing both the geographic extent of area above or below the long-term mean (delineated by amount of area above or below 1 SD) and the total national yearly NPP. This summary plot provides a broad overview for rapid assessment of the nation's yearly condition and long-term trends.

Examination of the yearly anomaly maps and plot in Fig. 2 highlights the importance of providing indicators in both geographic and plot summary formats. For example, the bar plot for years 2000–2002 displays a majority (approx. 70%) of the USA below the long-term mean with year 2000 displaying the lowest NPP, yet total NPP for 2001 and 2002 were similar to the 14-year average of 3827 MgC/year. The year 2000 map provides an explanation for this discrepancy where extensive large negative anomalies are apparent in the central and southern U.S. (~20% of CONUS) attributable to pervasive wide-spread drought conditions.

3.2 GPP anomaly indicator

The GPP anomalies provide seasonal indicators of ecosystem health, responses to intra-seasonal variation in climate, and recovery trajectories following disturbances, with the ability to plot GPP anomaly time series over specific locations or summations over defined seasonal periods. Figure 3 demonstrates the summation of 8-day GPP anomalies over seasonal periods (January

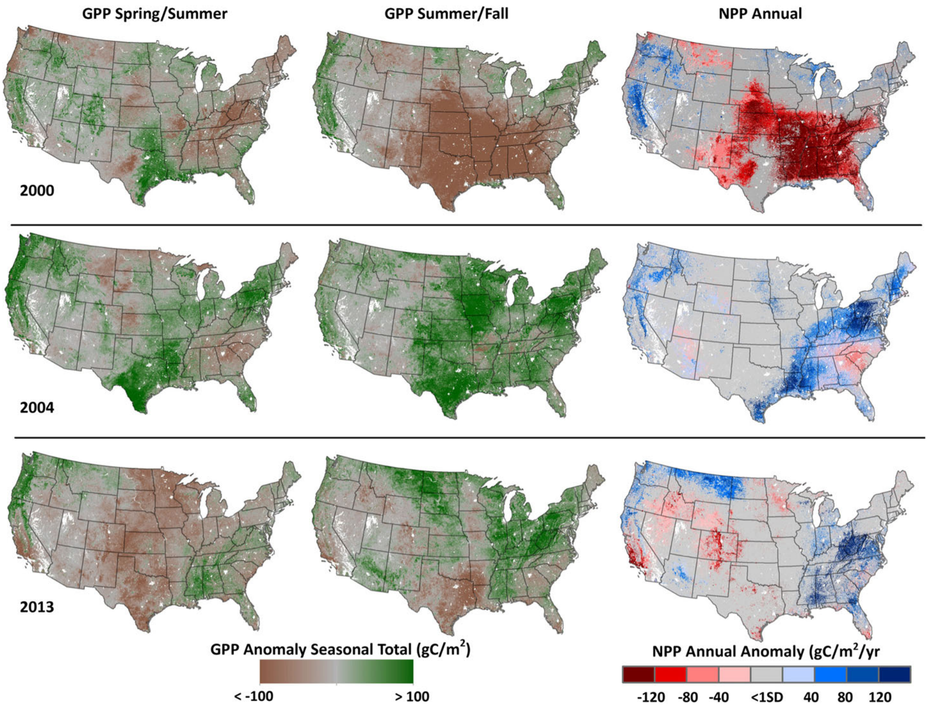

Fig. 3 Sum of GPP anomalies for selected years 2000, 2004, and 2013 from the first half of the year (January 1–June 26; labeled as Spring/Summer) and second half of the year (June 27–December 31; labeled as Summer/Fall). Maps at right display the corresponding year's NPP anomaly with gray areas representing pixels within ± 1SD of the long-term mean. White areas denote pixels where GPP and NPP were not calculated (e.g., urban or barren land, water bodies). Years 2000, 2004, and 2013 represent, respectively, the lowest, highest, and near-average CONUS NPP annual totals

1–June 26 labeled as Spring/Summer, and June 27–December 31 labeled as Summer/Fall) and the resulting NPP anomaly for 2 years of data representing the lowest and highest total NPP (2000 and 2004, respectively) and a third year (2013) that best represents the average NPP across CONUS. This type of visualization provides information on the degree to which respiration costs (included in NPP) outweigh gains in productivity (GPP) on a seasonal basis.

In year 2000, extensive drought conditions resulted in widespread negative GPP anomalies in the summer/fall season, but in some areas (e.g., Oklahoma, east Texas) high positive GPP anomalies in the spring/summer season offset productivity declines, resulting in NPP anomalies within 1SD of the long-term mean. The highest NPP year (2004) is driven by high positive GPP anomalies across CONUS, but in certain regions such as the southeast, positive summer/fall anomalies were insufficient in offsetting negative spring/summer anomalies and resulted in annual NPP anomalies less than 1SD. Year 2013 displays a contrast between the NPP anomalies over forested and non-forested systems (see Fig. 5) and the seasonal GPP anomalies resulting in an overall NPP most similar to the long-term average. The primarily deciduous and mixed forests of the Eastern U.S. display a mix of positive and negative GPP anomalies of relatively low magnitude in the spring/summer season, while areas in the Midwestern U.S. dominated by shrubs, grassland, pasture/hay, and managed croplands display primarily negative anomalies. In the summer/fall the northern Midwest displays increasing productivity, but not enough to result in positive NPP anomalies except in parts of Montana and North Dakota. The eastern forested systems however, display large positive anomalies in the summer/fall season resulting in regions with large positive NPP anomalies for that year.

4 Indicator applications

4.1 GPP anomalies and disturbance

The 8-day fidelity of the GPP indicator allows for delineating intra-seasonal productivity changes in vegetated systems, and is sensitive to regional disturbances including wildfire. Here we examine GPP anomalies pre- and post-wildfire over the year 2004 large-scale Boundary and Pingo wildfires in Alaska, which provide insight on vegetation recovery trajectories following disturbance (Fig. 4). The GPP anomalies over these fires capture the seasonal variability of conditions leading up to the fire year, the fire impact in 2004, and the seasonal recovery trajectory of the vegetation within each fire perimeter. In pre-fire years, the Boundary fire displays annual increments in peak GPP anomalies while the Pingo fire displays the inverse. During the fire year both areas display large positive GPP spring anomalies attributed to the effect of warm spring temperatures, spring snowmelt, and early season water availability, followed by the detrimental effects of fire. While both fires display two post-fire years of highly negative GPP anomalies, the remaining post-fire years provide contrasting recovery trajectories. The Boundary perimeter displays slow positive growth increments in GPP anomalies while the Pingo perimeter displays a rapid recovery to higher than normal GPP in the third year following fire and maintains primarily positive anomalies for the remainder of the data record. The GPP response is likely due to relatively rapid FPAR recovery of secondary herbaceous vegetation, relative to longer succession cycles of forests and woody vegetation (Jones et al. 2013; Goetz et al. 2006) and the difference in recovery rate across fires is attributable to differences in fire severity and proportional vegetation cover loss (Jones et al. 2013). The high temporal fidelity of the GPP anomalies and resulting time series provide intra-

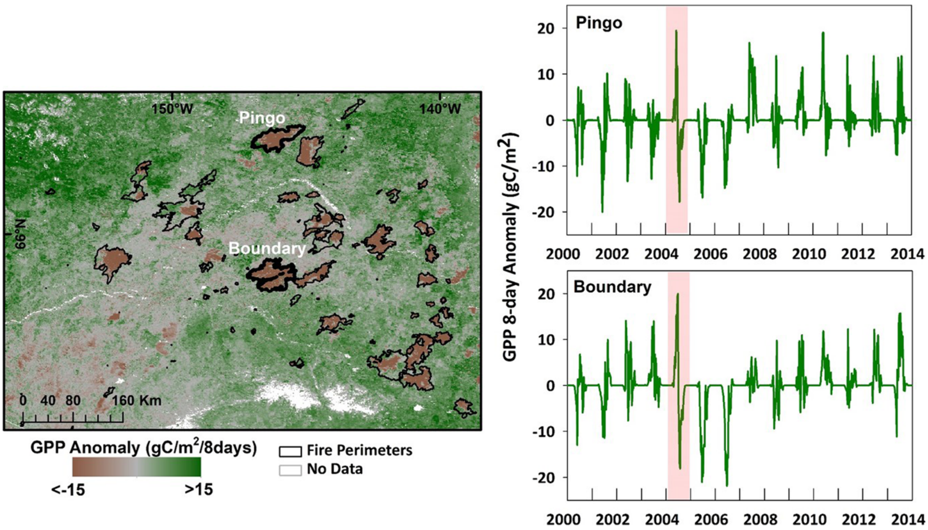

Fig. 4 Map of the MODIS GPP Anomaly for the July 20–27, 2004 period with year 2004 Alaska fire perimeters (black polygons). Time series (8-day) plots of GPP Anomaly means from 2000 to 2013 within the two labeled fire perimeters. Pink bar is year of fire

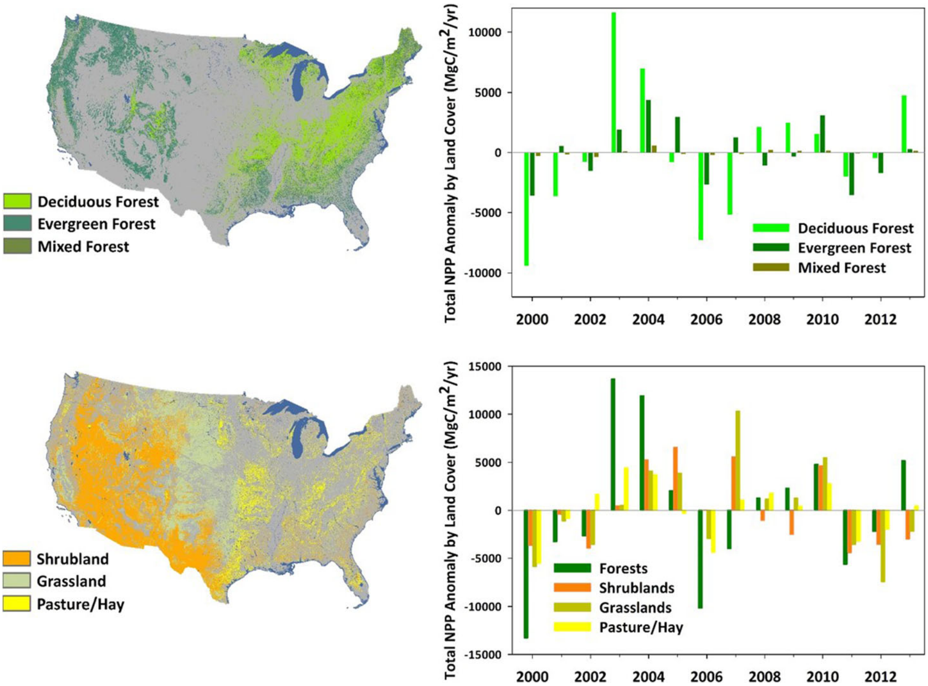

Fig. 5 Top, map of three forest cover types (deciduous, evergreen, and mixed) from the 2011 National Land Cover Database and bar plot of total yearly NPP anomaly by forest type. Bottom, map of shrubland, grassland, and pasture/hay lands from the 2011 National Land Cover Database and bar plot of total yearly NPP anomaly by non-forest land cover type (as shown in map) and total forest yearly NPP anomaly (all forest types, top bar plot)

seasonal conditions of vegetation productivity and valuable insight regarding the influence of spring, summer, and fall growth on the yearly NPP. Integrated with other proposed indicators, such as the forest sector Wildfire Effects-Burned Area indicator, the GPP indicator provides added-value information to land managers for decisions related to the seasonal and longer term effects of prescribed burns or wildfires on ecosystem productivity relative to pre-fire conditions.

4.2 NPP anomalies and phenology

The NPP indicator can be integrated with Phenology sector indicators providing quantitative assessments of vegetation productivity response to climate induced changes in vegetation phenology metrics. We integrate the NPP indicator with the Frost-Free Season indicator (an estimate of the potential vegetation growing season) over National Forests of the U.S. We calculated Pearson correlation coefficients between mean yearly frost-free season anomalies (days/year) and mean yearly NPP Anomalies from every U.S. National Forest in the continental U.S. As expected, a majority (65%) of National Forests displayed positive correlation coefficients, well aligned with numerous studies demonstrating increased NPP with increased growing season length (Piao et al. 2007), yet the remaining 35% of forests displayed negative correlation coefficients. Time series of frost-free season length anomalies and NPP anomalies (Fig. S1) coupled with his type of analysis demonstrates that productivity of a specific forest is responsive to an established climate indicator and in some cases increases in growing season length may have detrimental effects on forest productivity (Kim et al. 2012). The two forests with the highest negative significant correlations (Ozark-St. Francis N.F. and Mark Twain N.F.) are deciduous forests which often display greater productivity sensitivity to variations in phenology metrics (Richardson et al. 2010). Such forests may require more intensive monitoring or alternative management strategies as season length increases with increasing temperatures, especially considering deciduous forests often represent the largest NPP anomalies from year to year (see Fig. 5).

4.3 GPP and NPP indicators to fill indicator system gaps

The continental coverage and yearly fidelity provided by the NPP indicator can be used synergistically with existing indicators to provide higher-order information and fill current gaps in the indicator system framework. The GPP and NPP indicators are directly applicable to the NCIS sector topics of Forests, Grassland/Rangelands/Pastures, Agriculture, and Seasonal Timing and Phenology, providing higher temporal resolution information than some indicators within these sectors, as well as comprehensive spatial coverage across sectors. The Forest Area Extent and Grassland, Shrubland, and Pasture Extent indicators (based on the National Land Cover Database, Homer et al. 2015) measure land cover extents which are affected by both climate and anthropogenic factors. While valuable, these indicators do not provide yearly status information on the health or productivity of these ecosystems or comparisons of productivity across land cover types. Implementing the NPP indicator in concert with these other existing indicators provides more detailed information on specific land cover contributions to regional and national scale productivity.

Extracting yearly NPP anomalies over land cover categories within the Forest Area Extent indicator provides both the relative contribution of each land cover type to the overall national NPP anomaly and the individual ecosystem responses to changes in climate. NPP anomalies from the three forest cover categories of mixed forest, deciduous forest, and evergreen forest (Fig. 5) show that deciduous forests represent approximately 45% of forest cover in the contiguous U.S., yet they contributed over 70% of the yearly national NPP anomaly for 7 of the 14 years examined. A similar analysis incorporating the Grassland, Shrubland, and Pasture Cover indicator (Fig. 5) indicates that NPP anomalies from these three land cover types are occasionally far outweighed by the forest anomalies (2000, 2003, 2004, 2006). However, in some years (2005, 2010, 2011, 2012) individual non-forest land cover types display equitable or greater NPP anomalies, and in other years the anomalies are inverse to forested systems (2007, 2013). These results provide critical information applicable to the NCIS goals of allowing an inter-comparison of changes between different regions and environments, and assessing the impacts on, and vulnerabilities of, ecosystems to changing climate.

Within the Forest sector the Forest Growth/Productivity indicator does provide estimates of net annual growth from USDA Forest Service Forest Inventory and Analysis (FIA) data, but due to the low temporal fidelity (plots are generally measured no less than 5-years apart) changes are reported as averages over the period and are not easily attributable to any given year. The estimates are also calculated over a range of geographic scales (national, subnational, state, ecologic unit) and decreases in the geographic extent of estimates results in larger estimate uncertainty. The most recent USDA Forest Service Resources Planning Act (RPA) Assessment (Oswalt et al. 2014) provides estimates of forest growth over the history of the FIA program, but the temporal fidelity of estimates is limited (1952, 1976, 1986, 1996, 2006, and 2011). The NPP indicator provides higher-order information on the inter-annual variability of forest growth and a more detailed understanding of forest response to short and long-term climate variability. We calculated the timber forest net annual growth (Oswalt et al. 2014) anomaly as the percent change from the long-term mean (calculated from the six reported years) across the four ecoclimatic zones and assessment regions of the RPA; North, South, Rocky Mountain, and Pacific Coast. Those anomalies are plotted (excluding year 1952) with the mean NPP indicator anomalies from the four regions; converted to percent change from the regional long-term term mean for consistency (Fig. S2). Although these values are not directly comparable (NPP is inclusive of all vegetation on the landscape, both aboveground and belowground plant carbon, and provided as grams of carbon uptake per meter square per year; in contrast, the net annual growth metric emphasizes above ground biomass in timberland and is calculated as cubic feet/acre/year), the NPP metric provides valuable insight on the inter-annual variability of forest productivity in these regions. The large decline in net annual growth in the Rocky Mountain region, primarily attributable to beetle induced mortality, is also evident in the NPP anomalies where 4 of the 6 years from 2008 to 2013 were the lowest on record, aside from 2002. However, within that time period, NPP displays an average year (2009), and a higher than average year (2010) which are not captured in the net annual growth record. Net annual growth in the other three regions remains relatively stable from 2006 to 2011, but some inter-annual variability in NPP is present and in particular, the net annual growth record does not capture the lowest NPP (2008) in the Pacific Coast region due to widespread drought conditions.

5 Land management and policy applications

Land managers are tasked with increasingly difficult challenges in the face of a changing climate (Milly et al. 2008; Heller and Zavaleta 2009; Mawdsley et al. 2009). They are responsible for maintaining sustainable ecosystems where the land provides economic (e.g., wood products, bioenergy supply), environmental (e.g., water resources, biodiversity), and societal (e.g., recreational, cultural heritage) benefits (Foley et al. 2005; Godschalk 2004; de Groot et al. 2010). These tasks must be balanced with mitigating or decreasing the severity of disturbances such as wildfire (North et al. 2015; Westerling et al. 2006) and land management strategies aimed at maintaining or increasing the long-term land surface carbon sink to mitigate anthropogenic carbon emissions (Houghton 2003; Derner and Schuman 2007). The GPP and NPP indicators, particularly when used in concert with other indicators, can serve as components in a decision matrix to aid managers, inform decisions that balance needs across sectors, and serve as monitoring tools to assess the results of those decisions. For example, recent state level policies (California S. 32 2006; Oregon S. 1547 2016) dictate an increase in renewable energy use to decrease fossil fuel consumption and carbon emissions. A portion of this renewable energy stock will be derived from forest biomass and managers must balance the supply of biomass, wildfire risks, and insect risks, while maintaining the carbon sink potential of those forest stands (Vogler et al. 2015). The NPP indicator provides annual status information on the strength and trajectory of the carbon sink potential of a forest stand and can aid in identifying priority areas for harvest or thinning operations (Kirby and Potvin 2007; Belote and Aplet 2014).

The continuous temporal and spatial coverage of the GPP and NPP indicators also provide highly relevant information beyond local or regional scales and can inform future policy decisions and assess the outcomes of past policy implementations. For example, in 2009 the U.S. Congress passed the Collaborative Forest Landscape Restoration (CFLR) Act, calling for collaborative science-based ecosystem restoration to encourage ecological, economic, and social sustainability, which has since funded 23 projects in 11 states with project areas ranging from 130,000 to 2.4 million acres. The CLFR Program developed a set of ecological indicators (fire resiliency, watershed condition, invasive species, and wildlife habitat) to provide programmatic-level reviews of all projects across CONUS (Forest Service 2015). Those indicators lack assessment of forest productivity response to treatments, likely due to the high cost of such measurements. The CONUS-wide NPP and GPP indicators can serve as critical components in assessing results of CLFR policies and practices and help answer critical questions such as: Do prescribed burns coupled with thinning operations result in increases of NPP as compared to pre-management conditions?; and How variable is the response of forest primary productivity, both within and across regional domains, to different treatment strategies? The indicators provide a monitoring mechanism of past policy initiatives, can inform future policy, and aid in determining the effectiveness of applying federal level policy across disparate regions.

6 Conclusion

The purpose of the National Climate Indicator System is to present climate-relevant information for use by a wide variety of stakeholders in the public and private sectors. The System aims to provide a foundation for assessing sector-wide vulnerability, and the effectiveness of response strategies across sectors, to ongoing change in the climate system. The current National Climate Indicator System includes vital indicators across atmospheric, oceanic, and terrestrial systems, yet it does not currently include a spatially and temporally comprehensive measure of vegetation productivity which is highly responsive to changes in climate. Also, vegetation productivity is a key carbon measurement of environmental health and ecosystem services, including food, fiber, and fuels supporting national economies, human sustainability, and quality of life. The GPP and NPP indicators described here are scientifically defensible, scalable, directly related to climate, nationally important, built on existing agency efforts, and linked to the conceptual framework of the National Climate Indicators System. Independently, they provide a rapid and straightforward assessment of vegetation primary productivity response to short and long-term changes in climate. They have applications across sectors and, as demonstrated here, can be used synergistically with existing indicators to provide a more comprehensive understanding of sector specific responses to changes in climate. The spatial scale and temporal resolution of the indicators, coupled with their continental coverage, allows their implementation in local scale decision matrices, informing national scale policy, and the assessment and monitoring of past and future policy implementations. Inclusion of the GPP and NPP indicators in the National Climate Indicator System would help achieve the goals of sustained assessments in support of future National Climate Assessments, improve understanding of changes and impacts of climate on plant productivity and the U.S. communities and economies that rely on that productivity, and ultimately aid in assessing the Nation's progress on climate change response and mitigation strategies.

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