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Assessing the Effects of Fire Disturbances and Timber Management on Carbon Storage in the Greater Yellowstone Ecosystem

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Abstract

Accurate characterization of Carbon (C) consequences of forest disturbances and management is critical for informed climate mitigation and adaptation strategies. While research into generalized properties of the forest C cycle informs policy and provides abstract guidance to managers, most management occurs at local scales and relies upon monitoring systems that can consistently provide C cycle assessments that explicitly apply to a defined time and place. We used an inventory-based forest monitoring and simulation tool to quantify C storage effects of actual fires, timber harvests, and forest regeneration conditions in the Greater Yellowstone Ecosystem (GYE). Results show that (1) the 1988 fires had a larger impact on GYE's C storage than harvesting during 1985–2011; (2) continuation of relatively high harvest rates of the region's National Forest land, which declined after 1990, would have shifted the disturbance agent primary importance on those lands from fire to harvest; and (3) accounting for local heterogeneity of post-disturbance regeneration patterns translates into large regional effects on total C storage. Large fires in 1988 released about 8.3 ± 0.3 Mg/ha of C across Yellowstone National Park (YNP, including both disturbed and undisturbed area), compared with total C storage reductions due to harvest of about 2.3 ± 0.3 Mg/ha and 2.6 ± 0.2 Mg/ha in adjacent Caribou-Targhee and Gallatin National Forests, respectively, from 1985–2011. If the high harvest rates observed in 1985–1989 had been maintained through 2011 in GYE National Forests, the C storage effect of harvesting would have quintupled to 10.5 ± 1.0 Mg/ha, exceeding the immediate losses associated with YNP's historic fire but not the longer-term net loss of carbon (16.9 ± 0.8 Mg/ha). Following stand-replacing disturbance such as the 1988 fires, the actual regeneration rate was slower than the default regional average rate assumed by empirically calibrated forest growth models. If regeneration following the 1988 fire had reached regionally average rates, either through different natural circumstances or through more active management, YNP would have had approximately 4.1 Mg/ha more forest carbon by year 2020. This study highlights the relative effects of fire disturbances and management activities on regional C storage, and demonstrates a forest carbon monitoring system that can be both applied consistently across the US and tailored to questions of specific local management interest.

Keywords Carbon monitoring · Forest management · 1988 Yellowstone fires · Heterogeneous forest regeneration · Post-Disturbance carbon accumulation

Introduction

Forest ecosystems play an important role in the terrestrial carbon (C) cycle, sequestering more than one quarter of annual anthropogenic CO_2 emissions globally (Pan et al.

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2011). Natural disturbances (e.g., fires) and land management activities (e.g., timber harvests) directly alter C stored in forest ecosystems, and subsequent forest recovery is critical for long-term regional C balance (Williams et al. 2012). Understanding the effects of forest disturbance processes and management activities on regional C dynamics is the basis for developing appropriate adaptation and mitigation strategies (FAO 2015; Williams et al. 2016). In fact, there are multiple mechanisms through which sustainable forest carbon management is at least acknowledged if not rewarded. For instance, offset markets compensate landowners for management resulting in net increases in carbon storage (Marland et al. 2017). The US Forest Service, which manages about a fifth of the nation's forestland, does not participate in carbon offset schemes, but is nevertheless directed through the 2012 Forest Planning Rule (USDA 2012) to assess the amount and drivers of carbon storage on each individual national forest. Each of these frameworks requires a consistent and credible monitoring system to make defensible assertions over the very particular spatial and temporal domains that are often of interest to individual entities.

Unfortunately, the tools we use to understand global carbon exchange between forests and the atmosphere are typically not calibrated to support inference at relatively fine scales. In developing heuristic models of ecological processes to understand complex systems across large areas, these tools are not meant to apply precisely to any individual place. They can generate local carbon cycling estimates, but imprecise representation of fine-scale ecological and management patterns limits applicability in contexts where issues of public forest management or market-based compensation may be at stake.

One approach developed to support management of the US National Forests using locally calibrated carbon accounting is the Forest Carbon Management Framework (ForCaMF). ForCaMF is not a tool designed for discovery of global ecosystem dynamics, but is instead a mechanism for verifying the effects of management and natural disturbance on carbon storage for specific landscapes (Dugan et al. 2017). It combines a regionally calibrated growth model (Raymond et al. 2015) with high-resolution maps of biomass, vegetation type, and disturbance (Zhao et al. 2015a) to estimate the difference in carbon storage among different disturbance/management scenarios over time (Healey et al. 2016). An innovative probabilistic technique called "PDF Weaving" constrains ForCaMF simulations to nationally available inventory data from the Forest Service's Forest Inventory and Analysis (FIA) network, both at the 30-m pixel level and at the population level (Healey et al. 2014).

While ForCaMF has only been used for standardized baseline assessments of the relative impact of harvest, fire, insect activity, and wind across each of more than 130 national forests (as required by the 2012 Planning Rule), it has the potential for more customized analysis to address novel questions to provide practical, landscape-specific decision support. This paper presents a case study of how ForCaMF can be expanded across non-Forest Service owners and beyond previous standardized reports. It is structured as a series of questions different managers in the Greater Yellowstone Ecosystem (GYE) might ask, with results presented in the context of ForCaMF's Monte Carlo-based uncertainty estimates.

The GYE contains Yellowstone National Park (YNP) as well as National Forests (NFs) and other management units (Fig. 1). The co-occurrence of multiple management directives within the same ecosystem provides a good opportunity to compare C consequences of different management approaches. Forests in National Parks are generally allowed to burn and regenerate naturally to preserve natural ecosystem processes. Neighboring NFs are operated under multiple-use policies and managed for timber, wildlife and other benefits, so a certain amount of harvest is allowed, fires are generally suppressed (wildfires still occur but the burn area and severity are likely reduced), and post-disturbance forest planting is more common (Burroughs and Clark 1995). As a hot spot for studying forest disturbances, regeneration and C balances, many studies have been conducted in the GYE to examine the C dynamics associated with disturbances and management activities (Kashian et al. 2006; Kashian et al. 2013; Smithwick et al. 2009; Smithwick et al. 2011). However, unlike other temperate ecosystem in the US (Turner et al. 2015; Bradford et al. 2013), the comparative effects of forest disturbance types on GYE's C dynamics have not been examined, and the effect of regeneration patterns following large disturbance events on subsequent regional C storage are also unknown.

This study aims to quantify and compare the C storage effects of fire disturbances and timber harvests in an ecosystem with multiple (possibility conflicting) management objectives, and explores the use of remote sensing data in monitoring post-disturbance regeneration status and constraining regional C modeling, using GYE as an example study area. We answer the following questions: (1) what were the effects of recent (1985 to 2011) fire disturbances and timber harvests on regional C storage in GYE land management units? (2) In light of the fact that GYE National Forests significantly reduced harvest rates in the 1990s, how would continuation of the high harvest rates from the 1980s through 2011 have affected C storage in GYE National Forests? (3) Compared with regionally averaged regeneration rates derived from inventory data, what differences would remote sensing observed patterns of regeneration (heterogeneous across the burned area) make for C storage following the 1988 fires? This study has important implications for regional C dynamics at GYE

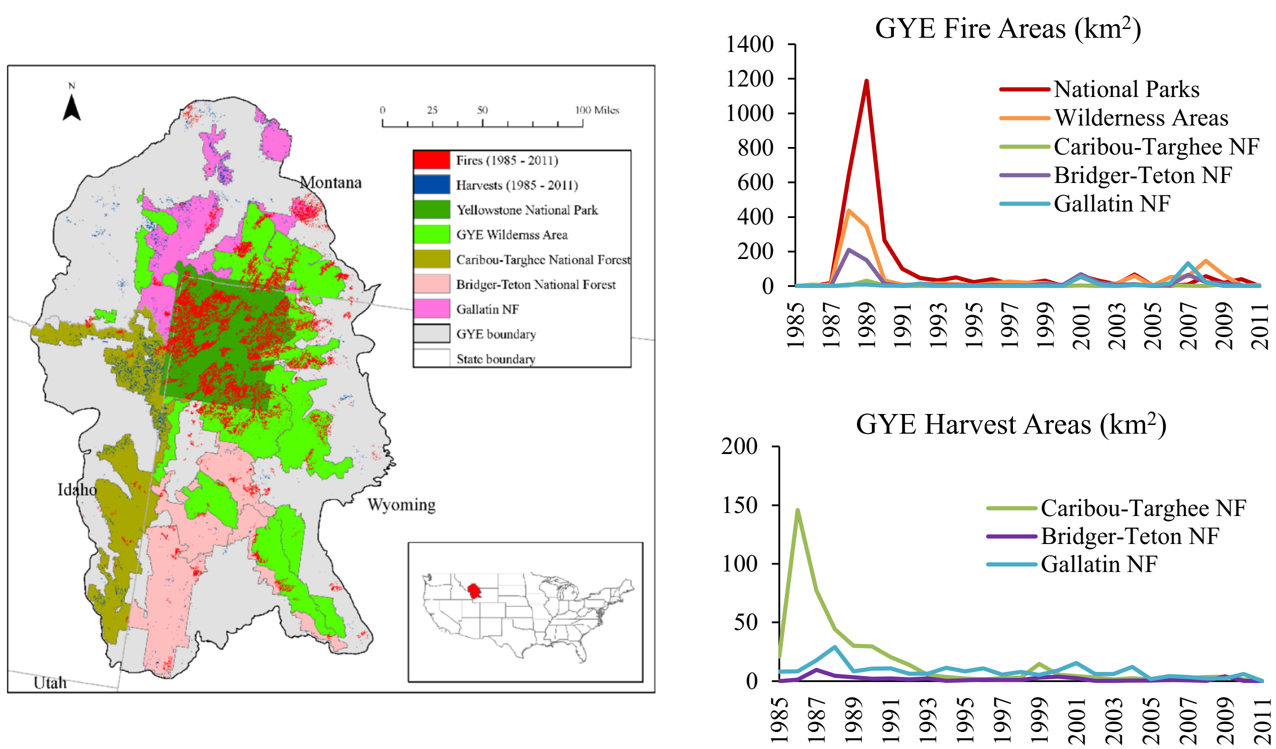

Fig. 1 Boundary of major land management units within the GYE, and spatial and temporal distribution of forest fires and harvests in GYE ownerships from 1985 to 2011. Fire and harvest disturbance areas were calculated from Zhao et al. (2015a, b)

management units, and provides insights on the effects of forest regeneration on regional C storage following large disturbance events.

Methods

The Forest Carbon Management Framework (ForCaMF)

We used the ForCaMF to investigate the effects of recent fire disturbance and forest management activities on C storage in GYE biomass C pools (including both aboveground and belowground biomass), and explore the potential effects of post-disturbance regeneration heterogeneity on long-term C storage in GYE forests. ForCaMF is a C monitoring system that examines the relative effect of disturbance, growth, and management on C storage in forested landscapes over time. Given categorical Landsat-based maps of starting vegetation conditions and subsequent disturbances, ForCaMF applies forest inventory based, regionally averaged C accumulation curves to track C dynamics at the pixel level (Healey et al. 2014; Healey et al. 2016) (Fig. 2). As pixel-level C stores are summed to the landscape level, ForCaMF uses a Monte Carlo approach to vary the input values used to associate each pixel with particular C change curves.

Inputs for ForCaMF in this study included: 30-m disturbance type and magnitude maps from 1985 to 2011; 30-m forest type group map; an initial aboveground C map for year 1985 at 30-m resolution; and the forest inventory-based C accumulation functions (Fig. 2). Disturbance type maps were produced and validated, with overall accuracy of 85%, in a previous study (Zhao et al. 2015a). Disturbance magnitude maps and initial stand C maps were produced using Landsat satellite data, calibrated and validated with FIA inventory information, following the approaches of Healey et al. (2006) and Powell et al (2010). The forest type group map for the study area was extracted from the US Forest Service national forest type group map (Ruefenacht et al. 2004) and re-sampled to 30-m resolution. Pixels in these 30-m, Landsat-based vegetation and disturbance maps were grouped into 10-hectare "simulation units" to reduce the Monte Carlo computation burden. Each simulation unit was made up of pixels that were not necessarily spatially contiguous but shared the same mapped starting conditions and disturbance histories. The appropriate C growth function was called for each simulation unit based on its disturbance history and starting condition, with the ForCaMF program varying the C growth over time in each Monte Carlo simulation based on the standard error of the associated C growth curve (described by Raymond et al. 2015). As input values and C growth curves were varied for each simulation, the variation of resulting differences in

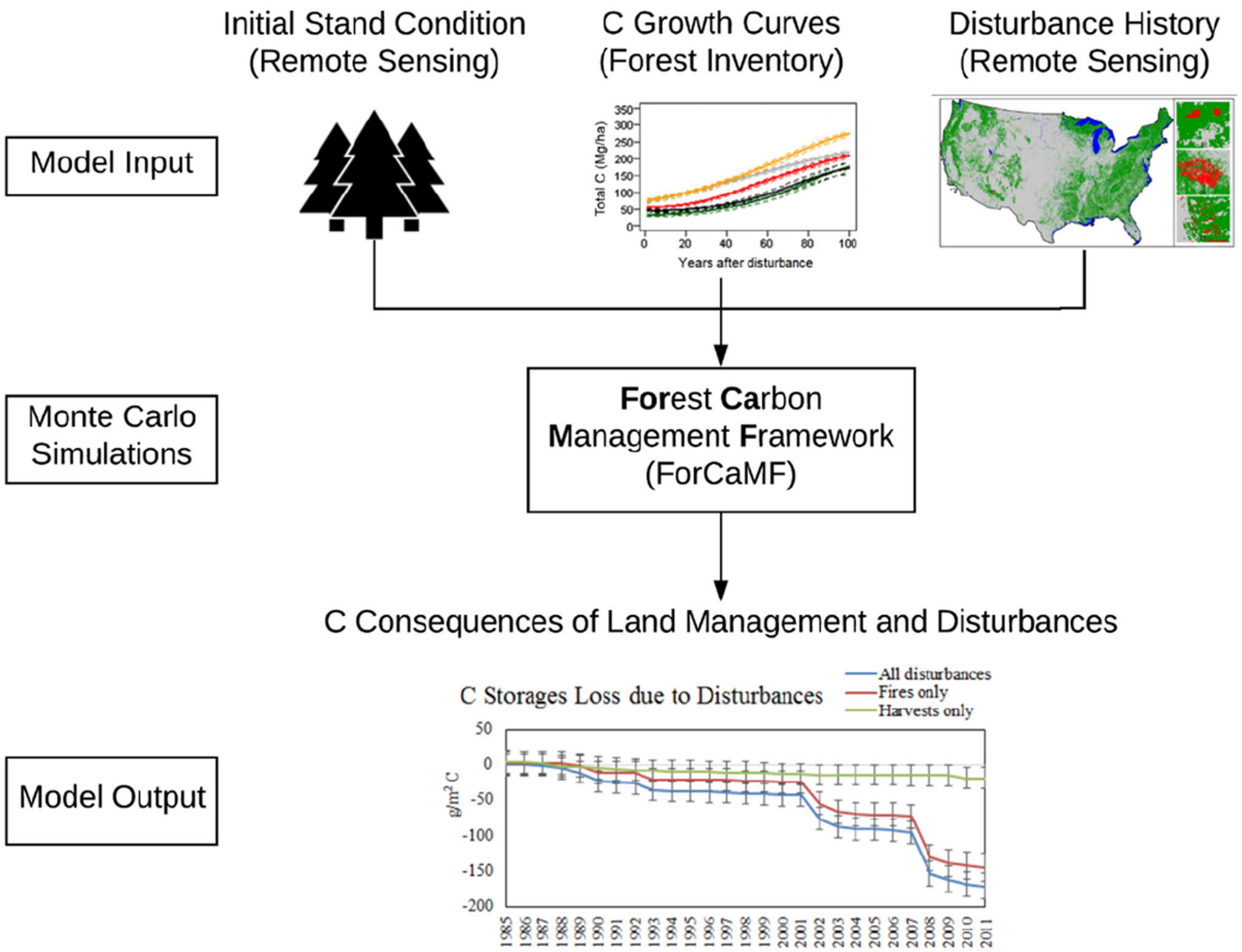

Fig. 2 Flowchart for assessing effects of management and disturbances on ecosystem C dynamics using the Forest Carbon Management Framework (ForCaMF)

landscape C storage among alternative disturbance/recovery scenarios was taken as an empirical estimate of combined model and map input uncertainties.

Population level uncertainty analysis was developed through comparison with field observations of forest carbon stocks, forest type group, and forest canopy cover made by the US Forest Service FIA Program (O'Connell et al. 2017). Specifically, a process called "PDF Weaving" was used to create probability density functions that simulated pixel-level error at a similar frequency to pixel-plot comparisons, and calibrated the total C for the mapped population to fall within the confidence intervals of FIA's published estimate for the entire population (Healey et al. 2014; Healey et al. 2016). Results from 500 Monte Carlo simulations were summarized to identify mean results as well as 2.5 and 97.5-percentile values given variation generated by simulated uncertainties related to input maps and C accumulation functions.

The key capability of ForCaMF for this analysis is the straightforward manipulation of a landscape's disturbance history and, separately, its forest regeneration conditions on C storage over time. The sub-sections below describe three such alterations: changing all pixels to undisturbed growth (where mortality is only simulated due to resource limitation); maintaining high harvest rates instead of representing the decline in harvest that was observed; and changing post-fire regeneration patterns from remote sensing observed to regional optimum regeneration rates. Differences in landscape-level C stocks under these alternative scenarios were targeted to provide insights into the relationship between disturbance and near-term C storage in GYE.

Assessment of C Storage Losses From Recent Fires and Harvests (1985–2011) in GYE Management Units

GYE forests have undergone many fire disturbances and land management activities in the past three decades (Zhao et al. 2015a), and the C consequences of these events were never fully assessed or compared. In this study, we used

ForCaMF to quantify and compare the C storage effects of all fires and timber harvests in recent decades in Yellowstone National Park and the surrounding Wilderness Areas and National Forests of the GYE (Fig. 1). Using input data discussed above, we initialized ForCaMF simulations for each management unit (National Park, Wilderness Area and National Forest) from 1985 to 2011.

The effect of each type of disturbance was estimated as the difference in the landscape's biomass C stocks at different points in time between a scenario where only that type of disturbance occurred during the observation period and a scenario where only normal background, density-dependent, tree mortality occurred (Healey et al. 2016). An estimate of the disturbance's C storage effect, summed over all pixels for each of the management units depicted in Fig. 1 and expressed in Mg/ha, was produced for every year from 1985 to 2011. Uncertainties associated with input maps and inventory-based C growth curves were estimated from the 500 Monte Carlo simulations, and the PDF technique was used to constrain model output and force the results match regional estimates from FIA data (Healey et al. 2014). This element of the study was similar to previous baseline ForCaMF analysis performed on each of the national forests (Healey et al. 2016).

Comparing C Storage Effects of Current Reduced Harvest Rates vs. High Harvest Rates Scenario in the GYE National Forests

As mentioned above, GYE National Forests significantly reduced forest harvest levels in the 1990s; this was particularly true for the Caribou-Targhee NF. Quantification of this reduced harvest on regional C storage is important for managers to understand the potential effects of specific management decisions. Therefore, we took two steps to identify the C storage effects of this harvest reduction, in relation to the baseline disturbance effects identified by the activities described in Section 2.2. First, we calculated the total harvest rate as a fraction of total forest area from 1985 to 1989 in the Caribou-Targhee NF from the Landsat-based disturbance maps; this period was the high point of harvest activity during the study period. Second, we prescribed this high point mean annual harvest rate to occur annually from 1985 to 2011 in the NF by revising disturbance scenarios within ForCaMF to replace lower harvest rates in the 1990s and 2000s with high harvest rates. Only simulation units with the same forest types as those harvested in the 1980s were changed to reflect hypothetical extended harvest. As in other comparisons throughout this paper and elsewhere (Healey et al. 2016), 500 Monte Carlo simulations were used to quantify the uncertainties associated with the input maps and the C growth curves derived from the inventory data.

Examining the Effects of Forest Regeneration Heterogeneity on Subsequent Regional C Dynamics Following the 1988 Fires in Yellowstone National Park

Previous studies show that forest regeneration following the 1988 fires was highly heterogeneous (Franks et al. 2013; Turner et al. 1999; Turner et al. 2016), but this spatial-temporal heterogeneity was rarely considered in large scale C modeling studies. In light of the extraordinary size and severity of the 1988 Yellowstone fires, disruption and delay of natural regeneration vectors was widespread and could potentially have a huge impact on regional C dynamics. To assess the effect of forest regeneration heterogeneity on subsequent regional C dynamics, we separately calculated C storage using rates of regeneration that were calculated locally using remote sensing data following the 1988 Yellowstone fires.

Regionally averaged forest regeneration rates calculated from FIA seedling data, which are commonly used in ecosystem C modeling practices, were used as a baseline scenario for comparison. To estimate actual regeneration that occurred following this fire event, we used a time series of high spatial resolution images to determine long-term post-fire forest regeneration patterns. 100 points were randomly selected from the area burned in 1988, and these points were then overlaid with high spatial resolution images from 2003 to 2015 in the Google Earth Pro interface as well as images from the National Agriculture Imagine Program (NAIP) (Boryan et al. 2011). An estimate of regeneration status was recorded at each point, specifically determining whether initial tree regeneration was likely to have occurred within 5 years after the fire, 5–15 years after the fire, or not at all. This judgement was visually determined based upon the degree of canopy closure and soil exposure, tree size and tree density in the earliest available image. As described in the supplementary materials, a set of post-fire C accumulation curves approximating the observed distribution of regeneration rates was developed, in addition to the regional average curves. As in previous sections, ForCaMF was used to compare the carbon storage trajectory and assess the uncertainties associated with the remote sensing observed heterogeneous regeneration status versus those associated with the regional average regeneration rates estimated from FIA inventory plots.

Results

Effects of Recent Management and Disturbance Activities on Regional C Storage

ForCaMF outputs showed the relative contributions of fire and harvests on forest C dynamics in GYE (Fig. 3). Recall

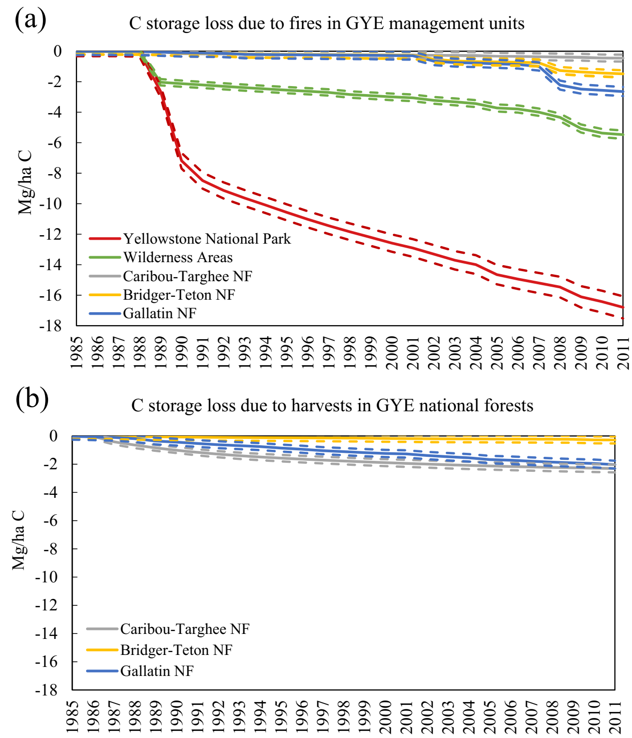

Fig. 3 Changes in GYE biomass C storage due to **a** fires **b** harvests in major management units in GYE. Negative values indicate the difference in C storage in relation to a no-disturbance scenario. Dashed lines show estimated standard errors from the Monte Carlo simulations. Wilderness Areas were designated by the 1964 Wilderness Act and specifically referred to Wilderness Areas within National Forest lands. National Forests here only contained timber-managed area excluding Wilderness Areas

that ForCaMF quantifies the difference over time between a no-disturbance background mortality scenario for the management unit and a scenario where all previous (since 1985) disturbances of a particular type (harvest, fire, etc.) have occurred. In other words, post-disturbance C stocks are compared to C stocks as they would have evolved in the absence of these disturbance events.

At the management unit level, C storage loss in Yellowstone National Park and GYE Wilderness Areas showed similar temporal trends: 1988 fires were the major C emission source in the past few decades, with some additional C storage loss from fires throughout the study period, and increasing fire-related emissions in the late 2000s. In YNP, the fires in 1988 caused the ecosystem C storage of the whole park (including both the burned and unburned area) to drop immediately by about 8.3 ± 0.3 Mg/ha, a reduction of C storage equivalent to nearly four times the reduction due to all harvests occurring in Caribou-Targhee NF (2.3 ± 0.3 Mg/ha) and Gallatin NF (2.6 ± 0.2 Mg/ha) from 1985 to 2011. Most burned area in 1988 was in YNP, although the 1988 fires crossed into Wilderness Areas within NFs. Forest C storage loss caused by the 1988 fires

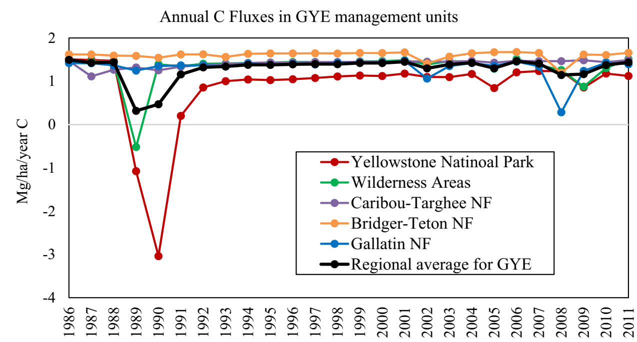

Fig. 4 Annual forest biomass C fluxes (C storage difference with previous year) in GYE. This net difference in C storage show combined effects of C loss from disturbances and C gain from forest growth in each year, in all biomass C pools

in GYE Wilderness Areas (2.2 ± 0.2 Mg/ha) were about 25% of those in YNP.

Temporal C storage trends in National Forests told different stories. The Caribou-Targhee NF was heavily harvested in the 1980s, and timber harvests accounted for more than four times the C storage loss caused by fires (2.3 ± 0.3 vs. 0.5 ± 0.2 Mg/ha) from 1985 to 2011. Forests in the Bridger-Teton NF experienced relatively fewer changes during this interval, except for some fires and harvests after year 2000 causing cumulative C storage losses of about 1.5 ± 0.2 and 0.3 ± 0.1 Mg/ha, respectively. Total C storage losses from recent fires and harvests in the Gallatin NF were 2.0 ± 0.2 and 2.6 ± 0.2 Mg/ha, respectively.

Annual biomass C fluxes from each of the management units ranged from −3.0 to 1.7 Mg/ha, adding up to a total regional biomass C flux of 0.31–1.49 Mg/ha per year (Fig. 4). The 1988 fires and post-2000 fires constituted major regional C source events during the study interval. This was especially true for the 1988 fires, where the Yellowstone National Park and the Wilderness Areas became large C sources, with biomass C fluxes of −3.0 and −0.5 Mg/ha, respectively, and the regional average biomass C fluxes dropped from around 1.4–0.3 Mg/ha. Despite frequent natural disturbance and human management activities, the net flux of biomass C in GYE management units remained positive for most of the years in the past decades (except for the year 1988, and as we mentioned before, the delayed C response was due to lag between the disturbance occurrence and remote sensing detection). Positive fluxes indicated that C gain from forest growth in GYE exceeded the C loss from disturbance and management activities during the study interval.

C Implications of Long-term Intensive Harvesting in GYE National Forests

Using C storage effects of fire disturbances in the YNP and Wilderness Areas as references, we compared the C storage

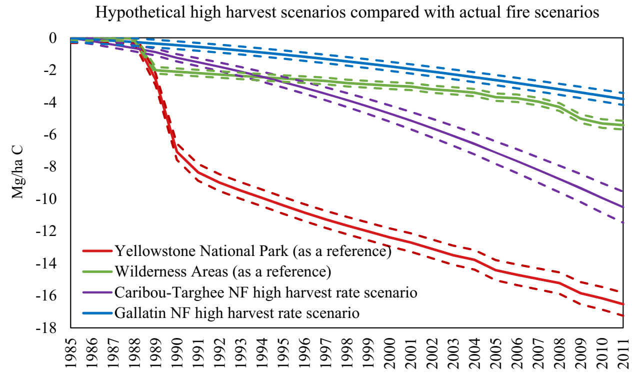

Fig. 5 GYE C storage losses under the high harvest scenario in the Caribou-Targhee and Gallatin National Forests (NFs), using actual C storage impacts from Yellowstone National Park and Wilderness Areas as a comparison. The high harvest scenario in the Caribou-Targhee and Gallatin NFs simulated the extension of their respective harvest rates of the late 1980s, when the harvest rates were higher than in subsequent decades, to 2011. Each NF's harvest rate was calculated by averaging timber harvest rates from 1985 to 1989 in the NF (mean annual harvested areas from 1985 to 1989, divided by the total forested areas of the NF). Negative values indicate C storage losses in relation to a no-disturbance scenario. Dashed lines show estimated standard errors from the Monte Carlo simulations

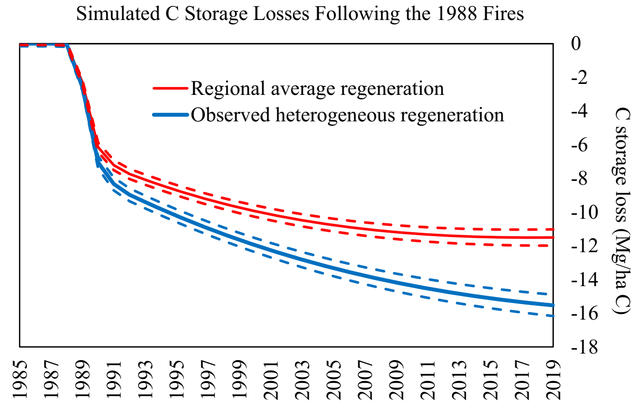

Fig. 6 Changes in biomass C storage in the Yellowstone National Park following the 1988 fires, comparing aerially observed heterogeneous regeneration patterns with regional average regeneration rates. This figure accounts for C storage changes for all of YNP, including both burned and unburned areas. Dashed lines show the estimated standard errors from the Monte Carlo simulations

losses from maintaining 1980s high harvest rates in Caribou-Targhee and Gallatin NFs (Fig. 5). Estimated total C storage losses from the high harvest scenario in the Caribou-Targhee and Gallatin NFs were 10.5 ± 1.0 and 4.2 ± 0.6 Mg/ha by year 2011, compared with C losses of 16.5 ± 0.7 and 5.5 ± 0.3 Mg/ha over the same period due to fires in the YNP and Wilderness Areas. Simulated C storage loss in the National Forests exceeded the actual C storage loss from fires in the Wilderness Areas after ten years of high harvest rates, but was still less than two thirds of the C storage loss from fires in YNP.

Effects of Heterogeneous Forest Regeneration on Regional C Modeling—Using the 1988 Yellowstone Fires as an Example

Forest recovery from past disturbances provides a significant offset to C losses due to those disturbances and to anthropogenic C emissions (Turner et al. 2015). Using the 1988 Yellowstone Fires as an example, we simulated long-term C sequestration during forest recovery under two scenarios—the remotely observed heterogeneous regeneration patterns which actually occurred, and regional average regeneration rates estimated from the FIA inventory data. Simulation results showed that biomass C storage loss in the areas burned in the 1988 fires reached 48.2 ± 2.1 Mg/ha by year 2020 under regionally averaged regeneration rates, compared with a C loss of 65.4 ± 2.7 Mg/ha for the actual regeneration scenario (Fig. 6). For the entire YNP (including the unburned area), C storage loss with regional average regeneration rates was about 11.5 ± 0.5 Mg/ha by year 2020, compared with a C storage loss of 15.6 ± 0.6 Mg/ha that account for observed regeneration rates, implying a C storage difference of 4.1 ± 1.1 Mg/ha for the whole park. Activities such as widespread tree-planting are statutorily prohibited in national parks and wildlife areas. However, if the fire had occurred on private or NF land, and active restoration had achieved regionally average regeneration rates, the post-1988 difference in C storage could potentially offset 50% of the instantaneous C storage loss (8.3 ± 0.3 Mg/ha), or about two times the C loss due to harvests in the Caribou-Targhee NF during 1985–2011 (2.3 ± 0.3 Mg/ha).

Discussion

ForCaMF as a C Monitoring System to Examine the Response of Regional C Storage to Disturbance and Management

In this study, the 1988 fires were shown to have larger effects on regional C storage than timber harvest removals in recent decades. As it is in many forested ecosystems in the Western U.S., fire is a natural and critical disturbance mechanism in the GYE with an average fire return interval of 100–300 years. However, the intentional human exclusion of fires, beginning in the 1900s, has moderately to heavily altered natural fire regimes in many forests (Keane et al. 2002; Zhao et al. 2015b). Fire exclusion can allow fuel accumulation and increase the risk of large and severe fires. With recent wildfires increasing in frequency, extent and severity in the Western U.S., spending on post-fire rehabilitation has increased in recent decades to protect public safety and other values at risk (North et al. 2015). As interest rises in the ability of public lands to mitigate climate change through C storage, the long-term C storage consequences of fire disturbances and post-fire forest regeneration are becoming a more important part of the forest management decision-making process (Robichaud et al. 2009).

Our results indicated that ForCaMF can be applied to monitor the C storage responses to disturbance and management in GYE management units with inputs from inventory and remote sensing data. Since FIA inventory and Landsat images are available for the whole U.S., this approach can be applied to other regions in the nation to assess C consequences of disturbances and land management activities. This national level applicability supports large-scale forest management policy making, and could influence resource planning that considers the effects of management on forest C sequestration. Forest managers or private landowners can also use the resulting assessments of C storage impacts to prioritize actions such as forest restoration or fire risk reduction. Quantification of the magnitude of C storage differences between different natural disturbances and management activities, as illustrated in this study, can establish a good foundation for scientific research in many fields, including but not limited to C dynamics, climate change, fire ecology, and forest management (Turner et al. 2015; Williams et al. 2016).

Because ForCaMF's carbon dynamics are derived from an empirically calibrated forest growth model (as described by Raymond et al. 2015), there is flexibility to investigate highly specific variations in management, disturbance, or stand characteristics, or regeneration rates. This examination of the effects of regeneration rate exemplifies other management-relevant questions that could be investigated with ForCaMF related to considerations such as site preparation, disturbance severity, or salvage operations.

Forest regeneration following disturbance events is often highly heterogeneous at the site level (Meng et al. 2015), especially following large fire events such as the 1988 Yellowstone Fires (Turner et al. 2016; Zhao et al. 2016). But fine-scale spatial heterogeneity of post-fire forest regeneration is seldom included in ecosystem C modeling (Meng et al. 2018), which could result in large uncertainties in long-term C modeling at the regional level. The ForCaMF simulation results show a large discrepancy in post-fire C dynamics using regional average regeneration rates (as estimated from FIA seedling observations) versus heterogeneous regeneration, as observed from remote sensing, following the 1988 Yellowstone Fires. If regeneration following the fire had proceeded at FIA's regionally averaged rates, either through different natural circumstances or through active management, YNP would have had approximately 4.1 Mg/ha more forest carbon by year 2020.

The effects of timber harvests on regional C dynamics in GYE are relatively small compared to the fire disturbances during the study interval, even with hypothetical intensified harvest scenarios. Pre-1990 harvests rates and associated C storage losses were high in GYE National Forests, but no higher than C storage loss from fire disturbances or C storage gains from net forest growth. Since 1990, harvest reduction on National Forests resulted in decreased C storage loss from these activities, and large areas that were harvested in previous decades entered a stage of strong C accumulation. A portion of the harvested carbon is stored in wood products—although it is lost from the ecosystem C storage, this C is not released into the atmosphere and will usually remain in these products for decades (Stockmann et al. 2012; Anderson et al. 2013).

Quantifying Uncertainty in the C Monitoring System

Numerous modeling efforts have sought to quantify the impact of forest fire and harvest on plot-, regional-, national- and global-scale C dynamics (Caspersen et al. 2000; Girod et al. 2007; Hurtt et al. 2002; Bond et al. 2005; Liu et al. 2011; Zheng et al. 2011; Williams et al. 2012; Bradford et al. 2012; Turner et al. 2015; Bachelet et al. 2015; Gu et al. 2016). Many modeling tools use either hypothetical landscapes or generalized conditions on real landscapes to infer carbon dynamics in forested ecosystems (McGuire et al. 2001; Running and Hunt 1993; Chen et al. 2000). Remote sensing can and does provide critical monitoring information for ecological models, commonly including surfaces related to biological productivity and representing vegetation structure and change (Meng et al. 2017). Several studies have proven the effectiveness of remote sensing data in improving accuracies of ecosystem carbon modeling (Hurtt et al. 2004; Thomas et al. 2008; DeFries 2008). While a few efforts have been made to account for map error in the uncertainty of model outputs using a Monte Carlo approach, e.g., French et al 2004, the PDF Weaving technique used by ForCaMF is unique in its generic approach for using inventory data to constrain simulation of map error.

Two types of uncertainties associated with input data were specifically considered in this ForCaMF modeling approach: uncertainties from the inventory-based C growth curves and the map errors inherent in remote sensing-based inputs. The PDF Weaving technique and 500 Monte Carlo simulations take account of the standard errors from the C growth curves, formally acknowledge known input map errors, allow error control over both pixel level and the population level, and aligns simulations with FIA regional inventory estimates (Healey et al. 2014; Healey et al. 2016).

ForCaMF's capacity for simulating fine differences in local conditions or disturbance patterns helps to reduce error that might appear when generalized parameters are used for monitoring at the local scale. Our simulation results show that by year 2020, simply accounting for remotely observed post-fire regeneration patterns after the 1988 burns produces a C storage difference of 4.1 ± 1.1 Mg/ha across the entire YNP (including both burned and unburned areas). Without this regeneration information from remote sensing data, we could have underestimated the C storage losses following this large disturbance event by simply applying the regional average regeneration rates. The magnitude of this difference would have been twice the per-hectare amount of C removed through timber harvests in the Caribou-Targhee NF from 1985 to 2011 (2.3 ± 0.3 Mg/ha). Using even more broadly generalized vegetation and carbon dynamics, as one might if applying a continentally calibrated process model, would likely produce even larger deviations from the actual conditions at the local scale.

Management Implications

Trade-offs among ecosystem services—such as wood production, wilderness conservation, and C storage—make public forest management decisions complex (Turner et al. 2011). The impact of harvest on factors such as timber value, habitat, or recreation can depend on both how trees are removed at the site level and how harvest sites are distributed over space and time. Spatial and temporal heterogeneity in natural forest regeneration after extremely large fires, especially in high severity burns, sometimes lead to recommendations for plantings of native species to enhance forest resilience and mitigate C storage loss (Millar et al. 2007; Ouzts et al. 2015). Conversely, cautions against post-fire planting arise from evidence that dense planting can increase future fire intensity (Thompson et al. 2007), and may not be cost effective for controlling fire-induced erosion (Beyers 2004). Further studies are required to investigate the effects of these disturbance and management activities for satisfying the needs of multiple ecosystem services. Specifically, simulations such as those illustrated here could provide insights into the appropriate density of post-fire planting to balance future fire risk and long-term C storage objectives. Forest recovery and regeneration information at finer spatial resolution are also required for improved characterization of post-fire C dynamics (Meng et al. 2017; Meng and Zhao, 2017).

Results from this study show that, in terms of C storage, the potential benefit of improving forest regeneration status following a large fire can have the same near-term C benefit as avoiding decades of relatively low-level harvests. This finding is relevant for managers of both public and private lands weighing the ecosystem service of climate change mitigation against planting costs. The 4.1 ± 1.1 Mg/ha hypothetical C storage benefit of active post-fire forest restoration (across YNP's 757,478 ha forested area) represents C storage equivalent to removing approximately 11.4 ± 3.1 million tonnes of CO2 from the atmosphere (using a 3.67 conversion ratio for C to carbon dioxide). This is approximately equivalent to keeping 2.3 ± 0.7 million automobiles off the road for 1 year (https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator). Viewed against a business-as-usual scenario of no planting, the offset value of this CO2 reduction (i.e., the amount it would be worth if its continued storage were sold on an open market at a currently realistic price of $10/tonne) would be approximately $114 ± 31 million. Management decisions about post-fire forest management will vary by owner, but this study shows that improving forest regeneration following very large fires can have significant long-term C implications.

Forests in the GYE region represent a complex matrix of management interests and disturbance patterns. ForCaMF brought unprecedented levels of locally specific monitoring data to bear in using those forests to investigate how both fire disturbances and timber harvests can affect subsequent C storage. Extreme events, because of their size and intensity, frequently disrupt typical regeneration patterns, and we documented that regeneration heterogeneity significantly affected C storage following historic fires occurring in YNP in 1988. Management goals and constraints vary widely even within a single landscape such as the GYE, and C sequestration is but one of many management considerations. Our findings highlight, however, the dominant and lasting effect that extremely large fires can have on a region's C cycle, and how decisions about fire management and timber harvest have a decades-long impact on the landscape's C balance.

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Compliance with ethical standards

Conflict of Interest The authors declare that they have no conflict of interest.

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