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Modeling spatially explicit fire impact on gross primary production in interior Alaska using satellite images coupled with eddy covariance

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ABSTRACT

In interior Alaska, wildfires change gross primary production (GPP) after the initial disturbance. The impact of fires on GPP is spatially heterogeneous, which is difficult to evaluate by limited point-based comparisons or is insufficient to assess by satellite vegetation index. The direct prefire and postfire comparison is widely used, but the recovery identification may become biased due to interannual climate variability. The objective of this study is to propose a method to quantify the spatially explicit GPP change caused by fires and succession. We collected three Landsat images acquired on 13 July 2004, 5 August 2004, and 6 September 2004 to examine the GPP recovery of burned area from 1987 to 2004. A prefire Landsat image acquired in 1986 was used to reconstruct satellite images assuming that the fires of 1987–2004 had not occurred. We used a light-use efficiency model to estimate the GPP. This model was driven by maximum light-use efficiency (E_{max}) and fraction of photosynthetically active radiation absorbed by vegetation (F_{PAR}). We applied this model to two scenarios (i.e., an actual postfire scenario and an assuming-no-fire scenario), where the changes in E_{max} and F_{PAR} were taken into account. The changes in E_{max} were represented by the change in land cover of evergreen needleleaf forest, deciduous broadleaf forest, and shrub/grass mixed, whose E_{max} was determined from three fire chronosequence flux towers as 1.1556, 1.3336, and 0.5098 gC/MJ PAR. The changes in F_{PAR} were inferred from NDVI change between the actual postfire NDVI and the reconstructed NDVI. After GPP quantification for July, August, and September 2004, we calculated the difference between the two scenarios in absolute and percent GPP changes. Our results showed rapid recovery of GPP post-fire with a 24% recovery immediately after burning and 43% one year later. For the fire scars with an age range of 2–17 years, the recovery rate ranged from 54% to 95%. In addition to the averaging, our approach further revealed the spatial heterogeneity of fire impact on GPP, allowing one to examine the spatially explicit GPP change caused by fires.

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1. Introduction

Gross primary production (GPP) is the amount of carbon fixed by vegetation through photosynthetic assimilation; it is critical in land surface–atmosphere interactions and a key component of ecosystem carbon fluxes and the carbon balance between the biosphere and the atmosphere (Mäkelä et al., 2008). The quantification of carbon fluxes between the terrestrial biosphere and the atmosphere is of scientific importance and relevant to climate policy making (Xiao et al., 2010). In a boreal region, the vegetation production plays an important role in the global cycles of carbon and the climate system (Melillo et al., 1993; Schulze et al., 1999). However, fire is the primary disturbance agent in most of the North American boreal forest; the frequency of large fires has increased dramatically over the past four decades and fire frequency and severity may increase further due to climate warming (Kasischke and Turetsky, 2006; Kasischke et al., 2011; Yi et al., 2010). After a disturbance, carbon dynamics are primarily driven by GPP (Amiro et al., 2010; Goulden et al., 2011).

The successional trajectories of boreal forests after fires are various (Beck et al., 2011; Johnstone et al., 2010; Shenoy et al., 2011). More frequent and larger fires in the late twentieth century resulted in deciduous trees and mosses increasing production at the expense of coniferous trees (Bond-Lamberty et al., 2007). Consequently, wildfires strongly influence boreal forest age structure, species composition, and thus vegetation photosynthesis process, affecting the carbon cycle and climate,

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which may persist for many decades (Bond-Lamberty et al., 2004; Randerson et al., 2006). This illustrates the need for a comprehensive examination of the magnitude and direction of changes in primary productivity as a result of altered ecosystem processes (Beck and Goetz, 2011).

Eddy covariance flux towers, which directly measure net ecosystem exchange (NEE) separable into GPP and ecosystem respiration (Re) (Baldocchi et al., 2001; Reichstein et al., 2005), and field measurements can be used to study the fire impact on carbon fixation. For example, Bond-Lamberty et al. (2004), Litvak et al. (2003), Goulden et al. (2006), Welp et al. (2006), and Goulden et al. (2011) all investigated carbon dynamics for chronosequence of postfire boreal forest stands based on field or flux measurements. These site-specific field measurement and flux observation studies have provided excellent information and aided a better understanding of the vegetation production associated with fire. Unfortunately, the high spatial and temporal variability of terrestrial ecosystems across complex landscapes results in a challenging task of regional extrapolation from point-based GPP measurements (Maselli et al., 2009). Significant efforts are still needed to upscale field observations or flux tower measurements from the stand scale to landscape, regional, continental, or global scales to advance toward explicitly incorporating the impacts of disturbance on ecosystem carbon exchange (Xiao et al., 2010, 2012), because the long-term carbon effects of fire disturbance are spatially heterogeneous at scales of 10 m to approximately 1000 m due to the complex interactions and the variation of burn severity, topography, drainage, prefire vegetation condition, and weather (Goetz et al., 2012; Huang et al., 2013).

Due to the weakness of spatial representation of point-based study, consistent and spatially continuous satellite remote sensing has played an increasing role in production estimation (Goetz et al., 1999; Potter et al., 1993). Several studies used satellite vegetation index to examine forest recovery in the boreal region. Kasischke and French (1997) analyzed Normalized Difference Vegetation Index (NDVI) of 14 test sites in the boreal forest of interior Alaska to examine the patterns of recovery. Epting and Verbyla (2005) used Landsat vegetation index to analyze the vegetation recovery. Goetz et al. (2006) compared NDVI anomalies of burned and unburned areas to analyze fire disturbance and forest recovery across Canada. Cuevas-González et al. (2009) used satellite vegetation index to analyze forest recovery after wildfire disturbance in boreal Siberia. Veraverbeke et al. (2012) assessed postfire vegetation recovery using red–near infrared vegetation indices. Unitless vegetation index is a good proxy of vegetation production, but it does not reflect the GPP quantity in a unit such as gC/m^2/month. However, it can be coupled with a vegetation production model such as light-use efficiency model for this purpose. Amiro et al. (2000) modeled NPP from the Advanced Very High Resolution Radiometer (AVHRR) leaf area index (LAI) and assessed forest carbon budgets following fire across Canada at the ecoregion level. Hicke et al. (2003) assessed the impact of 61 large fires on prefire and postfire NPP in the North American boreal forest using a 17-year record of satellite NDVI observations coupled with a carbon model. Since the interannual climate variability such as drought can influence successional vegetation production (Welp et al., 2007), an approach that examines fire-induced spatially explicit carbon fixation by minimizing the influence of other confounding factors (e.g., weather, soil, phenology) is still desired.

The objective of this study is to demonstrate a method of using eddy flux measurements, satellite images, and models to examine the spatially explicit impact of fire on vegetation production. Satellite images have been coupled with eddy covariance measurements to scale point-based fluxes to regional GPP (Ueyama et al., 2010; Wang et al., 2010a; Xiao et al., 2010). Based on the knowledge gained from these previous studies, we aim to further understand the relationship between disturbances and ecosystem dynamics. To achieve this goal, we used eddy covariance towers, which are located at two burned sites and one unburned site, to parameterize a vegetation photosynthesis model. This model estimated GPP from a satellite vegetation index and climate based on a light-use efficiency concept. This model was applied to two scenarios. In one scenario, actual postfire satellite images were used to drive the GPP model, and in the other scenario, reconstructed satellite images, where no fire was assumed to have occurred, were used to drive the GPP model. By comparing the pixel-by-pixel difference, the spatially explicit impact of fire on GPP was revealed.

2. Study area

Our study covered an area of 110 km by 130 km in the interior of Alaska and was conducted near Delta Junction, which is centered at 145.535 W and 64.293 N and covers a 110 km × 130 km area (Fig. 1). Based on the climate record at Big Delta (64.000 N, 145.440 W), Welp et al. (2006) reported that the average daily minimum temperature in January was −24 °C and the average daily maximum during July was 21 °C. The growing season length was approximately 115 days from mid-May to early September. The elevation ranges from 213 m to 1872 m, with a mean of 590 m and standard deviation of 262 m. National Land Cover Database 2001 (NLCD 2001, http://www.mrlc.gov/) data indicate that the vegetation cover is dominated by deciduous broadleaf forest (17%), evergreen needleleaf forest (46%), and shrub/scrub (20%). Based on the permafrost map (http://agdcwww.wr.usgs.gov/agdc/agdc.html), the area features a “mountainous area underlain by discontinuous permafrost” (77.73%), a “lowland and upland area underlain by numerous isolated masses of permafrost” (21.89%), and a “lowland and upland area underlain by moderately thick to thin permafrost” (0.38%).

Within this study area, we set up three sites for field survey: one that burned in 1987, one that burned in 1999, and one that burned in approximately 1920. These sites were located on relatively well drained silty loam soil and will be hereinafter referred to as the 1987 burn, 1999 burn, and control sites (Fig. 1). In the 1999 burn site, the Donnelly Flats crown fire consumed much of the aboveground biomass and soil organic matter. In 2002, there were 2691 ± 778 standing dead boles of black spruce per hectare with a mean height of 4 m, and 30% of the ground surface was covered by bunch grasses (*Festuca altaica*) and deciduous shrubs less than 1 m tall. In the 1987 burn site, the Granite Creek fire killed all of the aboveground vegetation, primarily black spruce. By 2002, some of the dead spruce boles remained standing, but most had fallen over. In 2002, the stand was dominated by an overstory of willow shrubs (*Salix* spp.) and deciduous aspen trees (*Populus tremuloides*) with a mean canopy height of 5 m and a density of 3956 ± 370 trees per hectare. The sparse understory vegetation included shrubs (*Salix* spp., *Ledum palustre*, *Rosa acicularis*, *Vaccinium uliginosum*, and *Vaccinium vitis-idaea*), black spruce (*Picea mariana*), and grasses (*Festuca* spp. and *Calamagrostis lapponica*) separated by patches of moss in open areas (*Polytrichum* spp.). In the control site, the canopy overstory consisted of homogeneous stands of black spruce (*P. mariana*) with a mean canopy height of 4 m and a mean age of 80 years. The mean canopy height was 4 m, and the sparse understory consisted of shrubs (*L. palustre*, *V. uliginosum* and *V. vitis-idaea*). The dominant ground cover was feathermoss (*Pleurozium schreberi* and *Rhytidium rugosum*) and lichen (*Cladonia* spp. and *Stereocaulon* spp.).

3. Dataset

3.1. Eddy covariance

CO$_2$ fluxes of three stands that were part of a fire chronosequence in interior Alaska (i.e., 1999 burn, 1987 burn, and control sites) were measured using the eddy covariance method (Fig. 1). From 2002 to 2004, eddy covariance measurements of NEE CO$_2$ fluxes were made at each stand and averaged at 30-min intervals along with vertical and horizontal wind velocity, sonic temperature, concentrations of CO$_2$ and water vapor, above-canopy incoming shortwave radiation and photosynthetic photon flux density (PPFD), precipitation, and vapor pressure deficit (VPD). Soil moisture and temperature at 10 cm

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