Remote Sensing of Environment 114 (2010) 1471–1479

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Regional aboveground live carbon losses due to drought-induced tree dieback in piñon–juniper ecosystems

Cho-ying Huang [a,b,*], Gregory P. Asner [a], Nichole N. Barger [c], Jason C. Neff [d], M. Lisa Floyd [e]

[a] Department of Global Ecology, Carnegie Institution for Science, Stanford, CA 94305, USA
[b] Department of Geography, National Taiwan University, Taipei 10617, Taiwan
[c] Department of Ecology and Evolutionary Biology, University of Colorado, Boulder, CO 80309, USA
[d] Geological Sciences and Environmental Studies Departments, University of Colorado, Boulder, CO 80309, USA
[e] Environmental Studies Program, Prescott College, Prescott, AZ 86301, USA

ARTICLE INFO

Article history:
Received 18 February 2009
Received in revised form 26 October 2009
Accepted 6 February 2010

Keywords:
Bark beetle
Carbon storage
Colorado Plateau
Juniperus osteosperma
Landsat
Pinus edulis
Spectral mixture analysis
Tree mortality
Wildfire

ABSTRACT

Recent large-scale dieback of piñon–juniper (P–J) woodlands and forests across the western US occurred as a result of multi-year drought and subsequent insect and disease outbreaks. P–J vegetation is spatially extensive, thus large-scale mortality events such as the one that has occurred over the past several years could significantly alter regional carbon (C) budgets. Our objective was to use a remote sensing technique coupled with field-based data to estimate changes in aboveground live C stocks across a 4100 km^2 region of Colorado caused by P–J tree mortality. We hypothesized that dieback would amplify the phenological dynamics of P–J vegetation, and these variations would be related to drought-induced losses of live P–J aboveground biomass (AGB) that are discernible using time-series remote sensing vegetation data. Here, we assess live P–J AGB loss using dry season fractional photosynthetic vegetation cover (PV) derived from multi-year Landsat images. Our results showed a strong linear positive relationship between the maximum decline in PV and field-measured losses of live P–J AGB during the period 2000–05 ($r^2 = 0.64$, $p = 0.002$). These results were then used to map AGB losses throughout the study region. Mean live aboveground C loss (±sd) was 10.0 (±3.4) Mg C ha^{-1}. Total aboveground live P–J C loss was 4.6 Tg C, which was approximately 39 times higher than the concurrent C loss attributed to wildfire and management treatments within or near to the national forests of the study region. Our results suggest that spatially extensive mortality events such as the one observed in P–J woodlands across the western US in the past decade may significantly alter the ecosystem C balance for decades to come. Remote sensing techniques to monitor changes in aboveground C stocks, such as the one developed in our study, may support regional and global C monitoring in the future.

1. Introduction

Carbon (C) dynamics during and following major disturbance events in forest and woodland ecosystems have been recognized as potentially important but poorly understood components of C budgets of North America (van Mantgem et al., 2009). Over the past several years drought-induced mortality, and subsequent insect and disease outbreaks, have been observed across a range of forest types in western North America (Pennisi, 2009). Tree mortality has climbed upwards by 90% in some forest stands and tree loss at this intensity and spatial scale has the potential to significantly alter regional C storage in western forest and woodland types for decades into the future (Breshears et al., 2005; Kurz et al., 2008; Shaw et al., 2005). Thus developing techniques to monitor landscape level changes in C storage associated with large-scale mortality events is critical, not only to our understanding of short- and long-term C dynamics in these ecosystems, but also to a better managing for biospheric C storage.

Piñon (*Pinus edulis*, *P. monophylla*) and juniper (*Juniperus osteosperma*, *J. monosperma*) (P–J) woodlands are widespread vegetation types occupying approximately 18% (220,000 km^2) of the natural vegetation in the southwestern US landscapes (Lowry et al., 2007). The recent multi-year drought across the Southwest began in 1998, but the intensity of the drought has been variable throughout the region (McPhee et al., 2004). Anecdotal reports of drought affecting P–J woodlands started in 2000, and massive tree dieback, which took place predominantly across piñon pine populations with junipers remaining relatively unimpacted, occurred in 2002 (Shaw et al., 2005). According to yearly large-scale (83,000 km^2) aircraft-based field surveys (Drought Impact on Regional Ecosystems Network; http://mprlsrvr1.bio.nau.edu/direnet/), approximately 11% of the P–J vegetation in the Colorado Plateau was infested by insects during 2000–05. However, spatial patterns of tree mortality are patchy (Kurz et al., 2008), and are influenced by factors such as stand density, age and topography (Greenwood & Weisberg, 2008). Other studies show that the green

* Corresponding author. Tel.: +886 2 3366 3733; fax: +886 2 2362 2911.
E-mail address: choying@ntu.edu.tw (C. Huang).

0034-4257/$ – see front matter © 2010 Elsevier Inc. All rights reserved.
doi:10.1016/j.rse.2010.02.003

vegetation cover might decline due to the acceleration of runoff and soil erosion after dieback induced surface fire (post-fire scenario, Fig. 1) (Allen, 2007), or space left by dead P–J may be occupied by herbaceous plants following a major rainfall event (herbaceous ramp-up scenario, Fig. 1) (Rich et al., 2008).

Although it is possible to derive woody aboveground biomass (AGB) across large forested regions using remote sensing techniques (Goetz et al., 2009; Zheng et al., 2004), it is generally more difficult to do so in arid and semi-arid environments due to the complexity of land surfaces (Goslee et al., 2003; Scanlon et al., 2002; Weisberg et al., 2007). One effective strategy is to derive woody photosynthetic vegetation cover (PV) from fine spatial resolution, multi-spectral satellite images collected in the dry season using spectral mixture analysis (Adams et al., 1993; Bradley & Fleishman, 2008). Estimates of PV can then be converted to AGB based upon field-estimated allometric relationships because the crown cover tends to scale with stand-level biomass stocks in these open woodland systems (Asner et al., 2003; Huang et al., 2007). PV in drylands is dominated by woody vegetation when the remote sensing data are acquired during the dry season, a time when the majority of herbaceous plants (grasses, sedges and forbs) are senescent. Therefore, a rapid reduction of remotely sensed tree cover through the drought years (time-series) could indicate the loss of live tree AGB (defined as converting live trees to dead woody materials such as coarse woody debris, red- and gray colored needles, etc.) regardless of the post dieback conditions (Fig. 1). Following this approach, a large-scale assessment of the impacts of tree dieback on C storage might then be performed. In this study, we addressed the following questions: (a) what are the impacts of tree dieback on the regional live C stocks in P–J ecosystems? and (b) what is the feasibility and potential for utilizing time-series multi-spectral satellite data to estimate changes in live C stocks in P–J systems?

2. Methods

2.1. Site description

This study was conducted in P–J ecosystems of southwestern Colorado encompassed by a set of Landsat Worldwide Reference System (WRS-P35R34) (The Landsat Program; http://landsat.gsfc.nasa.gov/about/wrs.html). The spatial extent of the study region is approximately 4100 km^2 determined from the southwest Regional

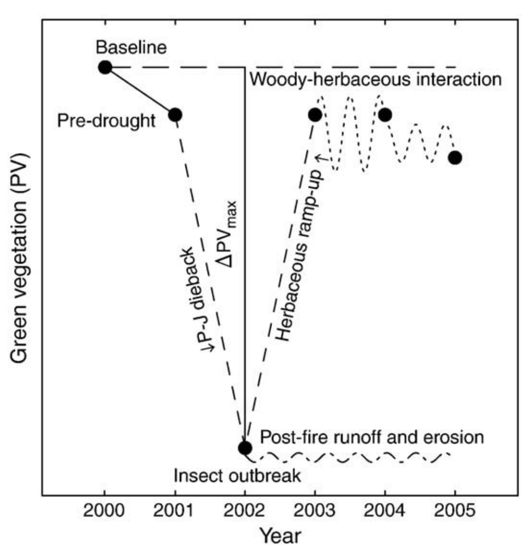

Fig. 1. An illustration of green vegetation (e.g., photosynthetic vegetation cover [PV]) variations and dynamics through the observation period (2000–05) in an area experiencing high tree mortality in the piñon–juniper vegetation.

Gap Analysis Program (ReGAP) vegetation coverage (Lowry et al., 2007) (Fig. 2), and covers two national forests (Uncompagre and San Juan) and nine counties (Archuleta, Dolores, Gunnison, Hinsdale, La Plata, Montezuma, Montrose, Ouray and San Miguel). The elevation range of the P–J vegetation in the study area is about 1400–2800 m. The climate of the region is generally temperate and semi-arid. Mean (± standard deviation, sd) annual precipitation and temperature of the study region are 389 (±60) mm and 8.5 (±1.1) °C, respectively, according to long-term interpolated climate records (1895–2006) from the PRISM (Parameter-elevation Regressions on Independent Slopes Model) (Daly et al., 1994). Dominant overstory trees across the study area are Colorado piñon (*P. edulis*) and Utah juniper (*J. osteosperma*), understory shrubs including serviceberry (*Amelanchier utahensis*), antelope bitterbrush (*Purshia tridentata*), Gambel oak (*Quercus gambelii*) and sagebrush (*Artemisia* spp.), and cold season perennial bunchgrasses.

US Forest Service Forest Inventory Analysis (FIA) annual inventory indicated that the P–J vegetation of the study region suffered the most severe tree dieback during the recent drought period in the southwestern US. In some areas, up to 100% of piñon pines were killed (Shaw et al., 2005). The drought across our study region, defined as rainfall failing to reach the long-term average over consecutive months and years resulting in declines in water supply, began in 2000 and lasted for four consecutive years (2000 = −25 mm mean annual precipitation, 2001 = −59 mm; 2002 = −126 mm, 2003 = −49 mm) (Fig. 3b). Throughout this period the mean annual air temperature was about 1.1 °C above the long-term average with the occurrence of several consecutive dry/hot months (Fig. 3b). FIA data revealed that the initiation of high P–J mortality (mainly *P. edulis*) across this region began in 2001, with the mortality peaking in 2002–03 (Shaw et al., 2005). Although P–J mortality was estimated to peak around this time across southwestern Colorado, field observations of high P–J mortality did occur in subsequent years (Floyd et al., 2009).

2.2. Field data collection

Root collar diameter (RCD, cm) of all live and recently dead P–J plants (reddish or grayish colored needles) were measured from 12 representative plots across a wide spectrum of P–J abundance and tree mortality along an elevation gradient (2000–2300 m) within or nearby Mesa Verde National Park (Fig. 2, lower left inset). These plots were sampled from late spring to early summer (April–July) of 2005, and were geolocated using a high accuracy Trimble Geoexplorer Global Position System (GPS) with post-processing differential correction (Trimble Navigation Limited, Sunnyvale, CA, USA). The size of each plot was 1350 m^2 (45 × 30 m), which was sufficient to cover the local P–J cover variation of a site (Floyd et al., 2004) and matched with the pixel size of moderate spatial resolution satellite images such as Landsat Thematic Mapper (TM). RCD is a measure of the sum of each stem diameter at the ground level (Grier et al., 1992), which is specifically for delineating the structures of multi-stemmed plants such as piñon and juniper trees. Allometric equations were used to estimate AGB (kg) of *P. edulis* and *J. osteosperma* from RCD (cm) (Darling, 1967) where:

$$AGB_{\text{PIED}} = 0.024RCD_{\text{PIED}}^{2.67} \quad (1)$$

$$AGB_{\text{JUOS}} = 0.013RCD_{\text{JUOS}}^{2.81} \quad (2)$$

The subscripts PIED and JUOS in Eqs. (1) and (2) are *P. edulis* and *J. osteosperma*, respectively. To our knowledge, these allometric equations are the only available models for the specific P–J plants of the study region. Although no information on model fitness (r^2) was reported in Darling (1967), there was an excellent fit based upon visual inspection (approximate estimates of r^2 > 0.98 for both species).