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Persistent effects of fire-induced vegetation change on energy partitioning and evapotranspiration in ponderosa pine forests

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ABSTRACT

We compared energy fluxes between a site converted from ponderosa pine (*Pinus ponderosa*) forest to sparse grassland by a severe wildfire 10 years ago and a nearby, unburned forest. We used eddy covariance and associated instruments to measure total radiation, net radiation, albedo, and fluxes of energy into latent heat, sensible heat, and the soil. Total radiation, vapor pressure deficit, and air temperature were similar for each site. Compared to the unburned site, net radiation efficiency (net radiation/total radiation) was 30% lower and albedo 30% higher at the burned site. The magnitude of sensible and latent heats varied seasonally at both sites. Sensible heat was the major component of the energy balance in cold or dry seasons, whereas latent heat was the major component in the warm and wet season. Soil heat flux was the smallest in magnitude of the measured energy fluxes. Compared with the unburned forest, the burn-created grassland generally had lower sensible and latent heats, but greater soil heat flux for both soil cooling in winter and warming in summer. The grassland had similar maximum air temperature as the forest, and warmer surface soil temperature during the summer. Thus, the lower albedo and greater sensible heat of the forest did not produce a warmer site compared with the grassland, apparently because of the cooling effect of greater latent heat in the forest. Our results suggest only small changes in site air temperature, but larger changes in site surface soil temperature by shifts from forest to grassland caused by severe fire in northern Arizona ponderosa pine forests.

1. Introduction

Local climate may be strongly influenced by interactions between large-scale atmospheric circulation and fine-scale spatial variation in land cover (e.g., Diffenbaugh et al., 2005; Went et al., 2007; Bonan, 2008). Changes in land-cover, such as caused by severe wildfire, can act as climate-forcing events by altering vegetation, surface color, albedo, emissivity, and the partitioning of radiant energy between latent and sensible heat fluxes (Thompson et al., 2004; Feddema et al., 2005; Jin and Roy, 2005; Beringer et al., 2007). While partitioning of energy between latent and sensible heat fluxes is thought to be

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an important influence on land-atmosphere coupling of energy exchange (Gu et al., 2006), our understanding of how disturbance modifies components of energy balance is limited by lack of data for most vegetation types (Bonan, 2008).

In the southwestern U.S., wildfire is a common and potentially severe disturbance in forests dominated by ponderosa pine. Over a century of fire suppression and heavy livestock grazing have altered the structure of ponderosa pine forests and disrupted the natural low-intensity surface fire regime throughout the region (Cooper, 1960; Covington et al., 1994; Swetnam and Baisan, 1996; Fulé et al., 1997). Ecosystem structure has shifted from open, savanna-like forests to dense stands of small trees with little understory (Covington et al., 1994; Swetnam and Baisan, 1996; Fulé et al., 1997). Stand-replacing wildfire is now considered inevitable over large areas of southwestern ponderosa pine forests given current high fuel loadings (Covington et al., 1994; Fulé et al., 2004; Moore et al., 2004) and recent climate warming (Brown et al., 2004; Westerling et al., 2006). Large forest fires are increasing in frequency in ponderosa pine forests of the southwestern U.S. (Swetnam and Betancourt, 1998; Westerling et al., 2006) and impact a significant amount of forest area. For example, recent estimates of the area of ponderosa pine forests burned in Arizona and New Mexico over all land ownerships based on the differenced normalized burn ratio indicate that 0.33 million ha of 2.3 million ha of this forest type (O'Brien, 2002, 2003) burned between 1999 and 2007 with 0.034 million ha in the high severity class and 0.07 million ha in the moderate severity class (C. McHugh, USDA Rocky Mountain Research Station, unpublished data).

Vegetation shifts between forests and grasslands or crops can accelerate or slow climate warming. While forests slow climate warming due to carbon sequestration, they may accelerate climate warming compared with other vegetation types due to their lower albedo that produces greater site net radiation and sensible heat (Gibbard et al., 2005; Bonan, 2008). Yet, this potential effect of forests on site energy balance is moderated by the cooling effect of latent heat. The impact of shifts between forests and grasslands on interactions among albedo and energy balance components, and hence forcings and feedbacks on climate are poorly understood for temperate forests in part because of a lack of empirical data for such forests (Bonan, 2008). In this study, we examined effects on the energy balance of the vegetation change from ponderosa pine forest to grassland caused by stand-replacing wildfire in northern Arizona. Over a one-year period, we compared the energy fluxes at a site burned in a stand-replacing wildfire ten years before our study to a similar nearby site that was not burned. We evaluate the hypothesis produced by model simulations of global-scale replacements of forests by grasslands (Gibbard et al., 2005) – grasslands are cooler than forests in the same region – for the change from forest to grassland that commonly occurs when dense ponderosa pine forests burn in the southwestern U.S.

2. Methods

2.1. *Study sites*

Our study compares two sites within the region of northern Arizona that is dominated by ponderosa pine: an unmanaged, undisturbed forest and a forest that burned in a stand-replacing wildfire during the summer of 1996. The sites are located near Flagstaff, AZ, USA, are 35 km apart, and have similar climatic and edaphic conditions (Table 1). The climate of the area is characterized by cold winters, and irregular and moderate precipitation (610 mm, 1977–2007 average, Western Regional Climatic Center, http://www.wrcc.dri.edu/index.html) concentrated as snow during the winter and as rain during the July and August monsoon season. The spring and fall seasons between these precipitation periods are generally dry (Sheppard et al., 2002). The long-term average length of the frost-free season is 94 days.

The unburned site is located in the Northern Arizona University Centennial Forest (35°5′20.5″N, 111°45′43.33″W, elevation 2180 m), and represents a typical stand of ponderosa pine in northern Arizona that has not been disturbed by tree harvest, thinning, or fire for decades, but has been indirectly managed through the policy of fire suppression. Seasonal maximum leaf area index (LAI; projected area) during the study averaged 2.3 $m^2\,m^{-2}$, tree basal area averaged 30 $m^2\,ha^{-1}$, and average tree age was 87 years (Table 1; Dore et al., 2008). The forest is dominated by ponderosa pine in the overstory, with a bunchgrass-dominated understory that includes *Festuca arizonica*, *Elymus elymoides*, *Boutelua gracilis*, and *Blepharoneuron tricholepis*. The seasonal maximum LAI of the understory vegetation was 0.06 $m^2\,m^{-2}$ (Dore et al., 2008).

Table 1 – Mean stand and soil characteristics of the unburned and burned sites (±one standard error). For the burned site, estimates of the pre-fire characteristics were made from adjacent, unburned areas (Dore et al., 2008).

Characteristics	Unit	Unburned	Burned
Total leaf area index	$m^2\,m^{-2}$	2.30 (±0.38)	0.6/before fire 2.4 (±0.45)
Understory leaf area index	$m^2\,m^{-2}$	0.06 (±0.02)	0.60 (±0.17)
Tree density	no. ha^{-1}	853 (±189)	0/before fire 343 (±49)
Basal area	$m^2\,ha^{-1}$	30 (±4.7)	0/before fire 31 (±6)
Canopy height	m	18 m	<0.5 m
Soil type	USDA Soil Taxonomic subgroup	Complex of Mollic Eutroboralfs and Typic Argiborolls	Mollic Eutroboralf
Depth of A horizon	cm	0–5	0–7
Bulk density A horizon	$Mg\,m^{-3}$	1.15	1.01
Depth of B horizon	cm	5–15	7–15
Bulk density B horizon	$Mg\,m^{-3}$	1.15	1.21