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Catchment response to bark beetle outbreak and dust-on-snow in the Colorado Rocky Mountains

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SUMMARY

Since 2002, the headwaters of the Colorado River and nearby basins have experienced extensive changes in land cover at sub-annual timescales. Widespread tree mortality from bark beetle infestation has taken place across a range of forest types, elevation, and latitude. Extent and severity of forest structure alteration have been observed through a combination of aerial survey, satellite remote-sensing, and in situ measurements. Additional perturbations have resulted from deposition of dust from regional dry-land sources on mountain snowpacks that strongly alter the snow surface albedo, driving earlier and faster snowmelt runoff. One challenge facing past studies of these forms of disturbance is the relatively small magnitude of the disturbance signals within the larger climatic signal. The combined impacts of forest disturbance and dust-on-snow are explored within a hydrologic modeling framework. We drive the Distributed Hydrology Soil and Vegetation Model (DHSVM) with observed meteorological data, time-varying maps of leaf area index and forest properties to emulate bark beetle impacts, and parameterizations of snow albedo based on observations of dust forcing. Results from beetle-killed canopy alteration suggest slightly greater snow accumulation as a result of less interception and reduced canopy sublimation and evapotranspiration, contributing to overall increases in annual water yield between 8% and 13%. However, understory regeneration roughly halves the changes in water yield. A purely observation-based estimate of runoff coefficient change with cumulative forest mortality shows comparable sensitivities to simulated results; however, positive water yield changes are not statistically significant ($p \leqslant 0.05$). The primary hydrologic impact of dust-on-snow forcing is an increased rate of snowmelt associated with more extreme dust deposition, producing earlier peak streamflow rates on the order of 1–3 weeks. Simulations of combined bark beetle and dust-on-snow produced little compounding effects, due to the relatively exclusive nature of their impacts. Potential changes in water yield and peak streamflow timing have important implications for regional water management decisions.

1. Introduction

The Colorado River Basin is an essential freshwater resource for the southern Rocky Mountains and U.S. Southwest, providing water supply to seven states and over 40 million people, and irrigation to roughly 5.5 million acres of farmland (Deems et al., 2013). The majority of water originates in the headwaters region and hence hydrologic changes to this region will impact downstream water availability. In the past decade, bark beetle species such as the mountain pine beetle (*Dendroctonus ponderosae*), spruce (*Dendroctonus rufipennis*) and *Ips* beetles have grown from endemic to epidemic levels, killing large areas of montane and subalpine forests. Across western North America, Bark Beetle (BB) related tree mortalities have affected an estimated 600,000 km^2 of forested watershed since 1996 (Bentz et al., 2009). Following a

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severely dry year in 2002 (Pielke et al., 2005), bark beetles have impacted more than 16,000 km^2 in Colorado (Pugh and Small, 2012), or roughly 2/5 of the forested watersheds. Broad interest has been lavished on the relationship of BB within forest ecosystems owing to their visible impacts on a range of sectors, including recreation, timber, fire risk, as well as water supply. Despite increasing BB research in recent years, comparatively few studies have examined the distributed impact of BB on hydrology over large areas. Meanwhile, recent episodic dust-on-snow events have been shown to alter snowmelt dynamics over a large portion of the basin headwaters for which hydrology is snowmelt-dominated (Deems et al., 2013; Painter et al., 2007, 2010, 2012a; Skiles et al., 2012). This combination of landscape-level disturbances raises the question of the relative magnitude of their effects and possible interactions. The work presented here explores a range of BB impacts together with dust-on-snow disturbances in several catchments within the Colorado River Basin headwaters and Colorado Front Range. Findings of local-impact studies using satellite and aerial-survey data are spatially integrated within a hydrologic modeling framework.

1.1. Bark beetles (BB)

Irrespective of geographical variations, the impact of BB infestations on a forest consists of five general stages. Here we describe the stages of the mountain pine beetle, which impacted three of the four study catchments, whereas the fourth catchment had minimal overall insect-related mortality. The first stage involves the initial attack of the beetles, in which females bore through the bark to the phloem and cambium region where the egg gallery is constructed (Alfaro et al., 2004). A beetle-borne fungus, the primary agent of mortality, produces a blue stain in the sapwood drastically disrupting water and sap flow in as short as ten days post-infestation (Hubbard et al., 2013). The second stage of impact, termed red-phase, begins with the onset of tree death (i.e. loss of transpiration) and lasts approximately one to three years as needles change in color from green to yellow to red, usually beginning in the tree crown (Wulder et al., 2006). Through the course of the red-phase, needles drop from the trees and reduce effective albedos of the cold-season snowpacks (Pugh and Gordon, 2012). Hydrologically important changes due to red-phase trees include: reduction in snow albedo due to needle litter, cessation of root water uptake and transpiration, reduction in canopy coverage and effective leaf area for moisture interception and radiative diffusion.

The end of red-phase is marked by complete needle loss, which marks the start of gray-phase, where trees appear as "skeletons" with only trunks and branches (Pugh and Gordon, 2012). The hydrologic alterations associated with the gray-phase include: recovery of sub-canopy snow albedo relative to red-phase due to cessation of needle litter (Boon, 2007; Pugh and Small, 2012), substantial loss of overstory canopy area leading to reduced canopy interception, decreased canopy snow sublimation, increased sub-canopy wind speeds, and greater radiation transmission through a diminished canopy (Pugh and Gordon, 2012). The gray-phase can last between roughly 4 and 20 years (Lewis and Hartley, 2006) before significant decay occurs. Enhanced regeneration of the understory has been observed progressively through the gray-phase, driven by water availability and sunlight exposure for the existing and new saplings (Collins et al., 2011).

Under unmanaged conditions, the gray phase may conclude following several different scenarios, such as increased risk for blowdown due to high winds and increased likelihood of fire due to higher fuel availability, although the latter has been disputed. Simard et al. (2011) showed that for lodgepole pine just north of the Colorado River Basin boundary (i.e. in Yellowstone National Park, USA), that BB outbreaks may *reduce* the probability of active crown fire in the short term by disconnecting adjacent tree crowns. The fourth and fifth stages are therefore concerned with degradation of dead biomass and complete regeneration of new forest, respectively. Given the broad range of uncertainties in these processes and their time horizons, the focus of this study is restricted to the impacts of the red and gray phases of BB infestation.

While there has been an abundance of stand-level work in beetle-kill forests, very few studies have attempted to spatially integrate BB impacts over larger scales (i.e. an entire catchment). Availability of satellite and remote sensing products over multi-year periods has enabled broader scale evaluations. For example, O'Halloran et al. (in press) used the Moderate Resolution Imaging Spectroradiometer (MODIS) imagery together with in situ observations to estimate changes in radiative forcings caused by BB tree mortality. Hicke and Jenkins (2008) used USDA Forest Service satellite classification to assess forest stand susceptibility to BB mortality. Other studies have used aerial (Ciesla, 2006; Meddens et al., 2011) or satellite imagery (White et al., 2005; Hicke and Logan, 2009; Dennison et al., 2010; Buma et al., 2013) to classify temporal patterns of BB into either total severity or into red and gray phases.

Another means to evaluate spatial impacts of BB on hydrology has been through modeling studies. Hydrologic modeling offers an attractive approach to assessing impacts, since it overcomes incongruences of paired-watershed studies (e.g. Bethlahmy, 1974; Stednick and Jensen, 2007), in effect making each watershed its own control, and also enables the integration of multiple streams of data, including meteorological, land cover, and geomorphic data. Recently, studies such as Alila et al. (2009) and Bewley et al. (2010) in British Columbia, Rudolph (2012) in Wyoming, Mikkelson et al. (2013), and Perrot et al. (2014) in Colorado, have simulated areal extents and severity of BB impacts.

1.2. Dust-on-snow

Rocky Mountain regional hydrology is dominated by the accumulation and melt of seasonal snowpacks. The energy exchange between the snowpack and the atmosphere, which governs the rate of snowmelt, is predominantly dictated by solar irradiance (Cline, 1997). Recent investigations have quantified snowmelt timing and runoff impacts due to perturbation of the mountain snowpack surface energy balance by deposition of mineral dust from regional dryland sources (Deems et al., 2013; Painter et al., 2007, 2010, 2012a, 2012b; Skiles et al., 2012). Dust loading strongly reduces the snow surface albedo, thus increasing absorption of incident solar radiation and influencing snowmelt runoff magnitude and timing. The aforementioned studies estimated hydrologic impacts of dust loading via point models and a relatively coarse-resolution distributed model (i.e. 12 km grid cells) informed by in situ measurements. All of the studies detail earlier peak streamflow associated with increasing dust loading. The full basin-scale modeling studies suggest decreasing annual water yield with increasing dust due to increased evaporative losses. Deems et al. (2013) suggest that dust-on-snow impacts may be further exacerbated by projected climate change. Unlike BB impacts, which are restricted to specific forest stands, dust-on-snow impacts are more spatially widespread.

It is hypothesized that BB-infestations may enhance the hydrologic impacts of dust-on-snow, since BB-related canopy reductions could increase the radiative exposure of sub-canopy snowpack and subsequently amplify the effect of dust-on-snow-driven snow albedo changes. Therefore, the objective of this work is to examine catchment-scale hydrologic response due to BB-induced alterations to forest structure, specifically during the red and gray phases, and to dust-on-snow influence on snow albedo. We