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# Hydrologic responses to restored wildfire regimes revealed by soil moisture-vegetation relationships

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ABSTRACT

Many forested mountain watersheds worldwide evolved with frequent fire, which Twentieth Century fire suppression activities eliminated, resulting in unnaturally dense forests with high water demand. Restoration of pre-suppression forest composition and structure through a variety of management activities could improve forest resilience and water yields. This study explores the potential for "managed wildfire", whereby naturally ignited fires are allowed to burn, to alter the water balance. Interest in this type of managed wildfire is increasing, yet its long-term effects on water balance are uncertain. We use soil moisture as a spatially-distributed hydrologic indicator to assess the influence of vegetation, fire history and landscape position on water availability in the Illilouette Creek Basin in Yosemite National Park.

Over 6000 manual surface soil moisture measurements were made over a period of three years, and supplemented with continuous soil moisture measurements over the top 1m of soil in three sites. Random forest and linear mixed effects models showed a dominant effect of vegetation type and history of vegetation change on measured soil moisture. Contemporary and historical vegetation maps were used to upscale the soil moisture observations to the basin and infer soil moisture under fire-suppressed conditions. Little change in basin-averaged soil moisture was inferred due to managed wildfire, but the results indicated that large localized increases in soil moisture had occurred, which could have important impacts on local ecology or downstream flows.

## 1. Introduction

The importance of forested montane watersheds for water supply in many regions worldwide has long raised the question of whether forest management could be used to enhance water yields (Baker, 1986; Hawthorne et al., 2013; Hibbert, 1965; Kattelmann et al., 1983; Lesch and Scott, 1997; Troendle, 1983). More recently, the potential for such management actions to improve forest health and productivity in fire-suppressed forests has raised the prospect of a "win-win" scenario for ecology and water supply. Fire suppression has led to unnaturally dense forests in many parts of the world, including California's Sierra Nevada (Collins et al., 2011; McIntyre et al., 2015). Forest management that reduces tree density could increase growth rates of the remaining trees (Bréda et al., 1995; Ruprecht and Stoneman, 1993), reduce competition between trees for scarce resources (Grant et al., 2013), and reduce the potential for catastrophic wildfire (Aust and Blinn, 2004; Kauffman, 2004; Pollet and Omi, 2002), thus improving forest resilience. In turn, reduced water demand in thinned forests can result in higher water availability downstream, and increasing non-forested wetland area can increase a watershed's capacity for water storage (Dubé et al., 1995; Fletcher et al., 2014). Soil moisture is a hydrologic variable that integrates all of these processes, as subsurface stores provide a source of water for both vegetation needs and streamflow generation, and changing soil moisture reflects changes in local water balance.

The hydrologic impacts of forest management practices are highly uncertain; scientific studies are limited and have mixed results. For example, observed flow increases following forest thinning range from as little as 1% to 70% (Kattelmann et al., 1983; Lesch and Scott, 1997). Differences in outcome appear to depend on many factors including the specifics of the forest treatment, local topography, vegetation type, and weather (Baker, 1986; Hawthorne et al., 2013). Problematically, increases in water yield typically persist for only $\approx 5$ years following forest treatments (Brown et al., 2005), suggesting that frequent re-treatment would be needed to sustain water supply benefits. Such high frequencies may impose important feasibility constraints on the implementation of labor-intensive management efforts. Conventional forest management practices such as thinning, clearing, or prescribed fire, may also be difficult to upscale to the point where they can have

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meaningful impacts on water resources. Thus, identifying alternative and scalable forest management strategies would be attractive.

Managed wildfire may offer such an approach. Under this management strategy, naturally ignited fires are allowed to burn, provided a fire management plan is identified and clear conditions for fire operations are in place (e.g. to prevent air quality impacts or protect sensitive areas). The fire-return interval in many fire-prone mountain watersheds is relatively short (e.g. ≈ 7–15 years in the mid-pine belt in the Sierra Nevada, Collins and Stephens, 2007), meaning that this approach can alter the understory and ground litter (Collins et al., 2016; Stephens et al., 2009), reduce forest density and leaf area (Kane et al., 2014), and replace land cover (Boisramé et al., 2017a) on timescales commensurate with those of hydrologic recovery from such disturbance.

Managed wildfire policies have been implemented long-term in only a few watersheds. In these locations, they are associated with large-scale reductions in forest cover and density over multi-decadal timescales (Boisramé et al., 2017b; Kane et al., 2014). These changes may have reduced the extent of severe fires (Collins and Stephens, 2007), lowered drought-induced forest mortality relative to neighboring basins (Boisramé et al., 2017a), and increased the biodiversity of pollinating insects (Ponisio et al., 2016). These positive outcomes support the potential for managed wildfire to mimic some of the landscape-scale benefits of thinning or patch-felling at large scales and at relatively frequent intervals, without requiring mechanized harvest and the associated costs, labor, and soil disturbance. To date, however, the hydrologic impacts of managed wildfire are poorly understood. The basins with long-term managed wildfire regimes lack long term stream gauges and baseline (i.e. pre-treatment) hydrologic measurements. The study watershed considered here, the Illilouette Creek Basin (ICB), is gauged after its confluence with the larger Upper Merced River. While there may be a small signal of enhanced streamflow production at this gauge following the institution of the managed wildfire regime in the ICB in 1972 (Boisramé et al., 2017a), analysis of flow trends offers little insight into the effects of the fire regime on basin hydrology (both due to uncertainty caused by high interannual variability in flows, and the basin-aggregated nature of streamflow). Soil moisture provides a useful metric for observing sub-watershed scale hydrology, representing the local balance between precipitation, deep drainage, evapotranspiration, and discharge.

Soil moisture dynamics in a burned watershed are altered by a complex suite of hydrologically relevant processes initiated by wildfire (Brown et al., 2005). For instance, burning can have counteractive effects on the amount and timing of snowmelt inputs to groundwater stores: blackened trees provide a source of long-wave radiation, and canopy losses reduce shading, speeding melting and sublimation rates (Neary et al., 2005; Tague and Dugger, 2010), but canopy losses also reduce interception and can reduce long-wave radiation, enhancing snowpack accumulation and delaying snowmelt compared to dense forest (Ellis et al., 2013; Lundquist et al., 2013). Similarly, although loss of mature trees can reduce transpiration (Bréda et al., 1995; He et al., 2013; Ma et al., 2010; Rambo and North, 2009; Zhang et al., 2001), loss of shading can increase soil evaporation (Biederman et al., 2014) while regrowth of understory vegetation or young life-stages can increase water demand, reducing soil moisture levels (Lane et al., 2010; Neary et al., 2005; Tague and Dugger, 2010; Vertessy et al., 1995; 2001). Most literature regarding fire-effects on watershed hydrologic balance focuses on large individual fires (Helvey, 1980; Langford, 1976, e.g.), or individual clearing/thinning treatments (Brown et al., 2005), rather than the long-term effects of cumulative vegetation change. Thus, the net hydrologic impact of managed wildfire over many decades and at basin scales remains uncertain.

The Illilouette Creek Basin is one of two basins in California (four in the western United States) where a managed wildfire regime has been in place for multiple decades. It holds wilderness status, meaning that soil and surface hydrology are relatively undisturbed by humans. Although no direct observations of change in the basin hydrology during the institution of the managed wildfire regime are available (there are no data for soil moisture, streamflow, or weather within the ICB dating from its fire suppressed state), fire effects on vegetation cover in the ICB have been reconstructed from air photo records (Boisramé et al., 2017b). These reconstructions show that between 1970 (when the basin was still fire-suppressed) and 2012 the watershed lost 24% of its conifer cover, while dense meadow area increased by 155%, shrub area by 35%, and sparse meadow area by 199% (Boisramé et al., 2017b).

The type of vegetation growing at a location is frequently correlated with local hydrological conditions (e.g. Araya et al., 2011; Milledge et al., 2013; Mountford and Chapman, 1993). For example, lodgepole pine (*Pinus contorta*, PICO), a common species in ICB, establishes in intermediately wet areas of meadows (Helms and Ratliff, 1987), while whitethorn ceanothus (*Ceanothus cordulatus*) grows in exposed, dry sites (Fites-Kaufman et al., 2007). Within the ICB, Kane et al. (2015) found relationships between water balance and forest structure, suggesting that vegetation observations can be related to water availability, and the history of vegetation change in the basin could therefore provide a proxy history of hydrologic changes. In this study we use soil moisture to represent these hydrologic changes, since it integrates shallow hydrologic fluxes and therefore is a useful spatially-explicit indicator of water budget partitioning. Reconstructing hydrologic change (as represented by changing soil moisture) using vegetation is undoubtedly an approximate method, but it overcomes major limitations of other approaches such as remote sensing of soil-moisture related indices (Musick and Pelletier, 1988), which are precluded in areas with dense vegetation cover (Crist and Cicone, 1984), and thus cannot be used to examine the effects of transitions from forested to unforested sites.

This study aims to identify the effect of the changing fire regime on water availability in the ICB by measuring surface soil moisture, establishing its dependence on vegetation, fire history and topography, and using these relationships to extrapolate soil moisture observations to the basin scale under contemporary and historic vegetation distributions. Differences in these basin-scale soil moisture surfaces would then provide an estimate of the change in soil moisture following the change in fire management. In order to justify this modeling approach, we first answer the following questions:

- Is surface soil moisture a useful indicator of ecologically-relevant water storage (as might be influenced by, or might influence, local vegetation)?
- Is vegetation a useful indicator of surface soil moisture values?
- Under a given vegetation type, can topography and fire history explain spatial variations in soil moisture?

Ideally, we would estimate total soil water storage using continuous moisture measurements over the depth of the soil profile at many locations. This would give the most complete measure of the balance between precipitation, evapotranspiration, and runoff. However, wilderness regulations (U.S. Congress, 1964) limited such observations (which require disturbance of the soil profile and installation of temporary instrumentation) to three sites in the ICB. Therefore we relied primarily on spatially extensive but shallow (top 12 cm) soil moisture measurements ( > 6000 in 90 sites) made twice annually over three consecutive growing seasons (2014 through 2016). Although surface soil moisture cannot be directly extrapolated to subsurface water storage, it is often closely related to water table depth (Sörensen et al., 2006) and plant available water (Gonzalez-Zamora et al., 2016). All observations were made during drought years of varying characteristics and severity (from extreme drought in 2014–2015 to near-normal winter precipitation in 2015–2016) and therefore do not necessarily apply to wet years. The observations were made at least nine years after the most recent large fire in the ICB and do not capture short-term post-