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Modeling the impacts of wildfire on runoff and pollutant transport from coastal watersheds to the nearshore environment

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ABSTRACT

Wildfire is a common disturbance that can significantly alter vegetation in watersheds and affect the rate of sediment and nutrient transport to adjacent nearshore oceanic environments. Changes in runoff resulting from heterogeneous wildfire effects are not well-understood due to both limitations in the field measurement of runoff and temporally-limited spatial data available to parameterize runoff models. We apply replicable, scalable methods for modeling wildfire impacts on sediment and nonpoint source pollutant export into the nearshore environment, and assess relationships between wildfire severity and runoff. Nonpoint source pollutants were modeled using a GIS-based empirical deterministic model parameterized with multi-year land cover data to quantify fire-induced increases in transport to the nearshore environment. Results indicate post-fire concentration increases in phosphorus by 161 percent, sediments by 350 percent and total suspended solids (TSS) by 53 percent above pre-fire years. Higher wildfire severity was associated with the greater increase in exports of pollutants and sediment to the nearshore environment, primarily resulting from the conversion of forest and shrubland to grassland. This suggests that increasing wildfire severity with climate change will increase potential negative impacts to adjacent marine ecosystems. The approach used is replicable and can be utilized to assess the effects of other types of land cover change at landscape scales. It also provides a planning and prioritization framework for management activities associated with wildfire, including suppression, thinning, and post-fire rehabilitation, allowing for quantification of potential negative impacts to the nearshore environment in coastal basins.

1. Introduction

Wildfire is an integral natural disturbance in many ecosystems. Anthropogenic climate change, however, is predicted to increase fire activity progressing through the 21st century (Abatzoglou and Kolden, 2011; Littell et al., 2009), creating disturbance patterns that may alter ecosystems in unprecedented ways. Wildfire is arguably the most common ecological disturbance in Mediterranean ecosystems of coastal California watersheds draining into the Pacific ocean (Keeley and Zedler, 2009), where large coastal wildfire events have been shown to negatively impact sea otter (*Enhydra lutris*) immune response (Bowen et al., 2014; Venn-Watson et al., 2013). As a key marine mammal predator, the sea otter is an indicator of nearshore ecosystem health and is listed in California as "Threatened" under the Endangered Species Act and protected under the Marine Mammal Protection Act (U.S. Fish and Wildlife Service, 2014). Despite this protection, the California sea otter population is recovering at a lower-than-expected rate, leading to queries seeking to identify factors impeding population growth rates (Johnson et al., 2009). Inputs to the sea otter's nearshore habitat from terrestrial watersheds, such as toxins, nutrients, and pollutants, have been shown to negatively affect sea otter health (Conrad et al., 2005; Johnson et al., 2009; Miller et al., 2010), but prior studies have focused primarily on pathogens (Johnson et al., 2009) or large, anthropogenic spill events like the Exxon Valdez oil spill of 1989 (Bodkin et al., 2002). This focus overlooks the contributions of ecological disturbance events like wildfire, in part because the pathways for transport of pollutants have not previously been explicitly identified or modeled.

Wildfire has the potential to alter terrestrial inputs to the adjacent nearshore environment by significantly altering the condition of soil and vegetation affecting infiltration and transport of

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nutrients and metals (Stein et al., 2012) and increasing erosion and sediment yields (Warrick et al., 2012; Moody et al., 2013). Wildfire increases the amount of phosphorus and nitrogen in streams (Spencer and Hauer, 1991; Coombs and Melack, 2013), even many years after the fire (Hauer and Spencer, 1998), as well as sediment and nutrient loads (Stein et al., 2012; Warrick et al., 2012), suggesting that large wildfires should also impact the nearshore environment as these nutrients and sediments then eventually drain into the ocean. The effects of wildfire on the increasing transport of sediment and nutrients have been shown to adversely affect freshwater aquatic ecosystems (Gresswell, 1999; Spencer et al., 2003), however, the effect of these increases in marine ecosystems has not been well documented.

The most common approach to measuring the specific effects of wildfire on runoff, sediment transport and nutrient loading has been through *in-situ* stream sampling (e.g., Stein et al., 2012). However, this approach severely limits the ability to understand the cumulative impacts of both the wildfire and the pre- and post-fire management actions (e.g., burned area rehabilitation efforts) on the nearshore ecosystem, for two primary reasons. First, wildfires often burn only portions of watersheds, and burn with variable severity across watersheds, but *in-situ* sampling does not account for this spatial heterogeneity (Shakesby and Doerr, 2006). Additionally, the results from studies collecting *in-situ* measurements are not transferable or easily comparable to other fires or watersheds across time and space due to differences in size, composition, and management impacts that are difficult to tease out from the single sample value. To our knowledge, no prior studies have attempted to model the spatially explicit impacts of a wildland fire event on runoff into the nearshore environment using a replicable, scalable, watershed approach.

Prediction of post-fire effects commonly has focused on runoff and erosion rates and relied on a variety of physically and empirically based models, spatially distributed models, and professional judgment (Larsen and MacDonald, 2007). Commonly used post-fire runoff models such as ERMIT (Robichaud et al., 2007), RUSLE (Renard and Foster, 1991), and Disturbed WEPP (Elliot and Hall, 2010) include land cover as an input, but do not maintain the spatially explicit information (*but see* Renschler, 2003), limiting the ability to link spatially variable wildfire effects and land management actions to model outputs. These models have also produced a wide range of runoff estimates, making comparisons difficult (Robichaud et al., 2000), and few have been validated in post-fire environments (Larsen and MacDonald, 2007). Among models that have been validated, results have demonstrated that the amount of vegetation cover post-fire has a strong impact on erosion rates (De Dios Benavides-Solorio and MacDonald, 2005).

A replicable approach to quantify and compare spatially explicit impacts of wildfire on nonpoint source pollutants must utilize standardized model inputs that reflect the spatial and temporal variability of wildfire effects and follow a clear framework for how fire affects model inputs. The primary input affected by wildfire at landscape scales is land cover, which is often classified from remotely sensed data and represents both vegetation and human development. Widely available data such as the National Land Cover Dataset (NLCD) (U.S. Geological Survey, 2014) are frequently used for modeling efforts that require land cover, but can be limiting because they are produced at infrequent intervals due to the challenges of acquiring adequate remotely sensed data and the intense effort required to produce continental-scale classifications. For example, the most recent NLCD data when this research was conducted was produced in 2006 and as a result does not account for subsequent years of land cover transition, including two large wildfires that burned on the Big Sur coast in 2008. Incorporating these land cover disturbances is essential to accurately modeling changes in transport of nonpoint sources of nutrients and sediments, and relies upon utilizing information about how the spatially heterogeneous severity of the fire impacts land cover.

As a result of wildfire, vegetation communities continue along established succession pathways or undergo type conversions from one community to another along alternative pathways depending on fire frequency and severity (Larson et al., 2013). The severity of a fire, often described as ‘burn severity’, or the magnitude of change in the post fire environment (Key and Benson, 2006), impacts vegetation succession and pattern (Larson and Churchill, 2012; Lutz et al., 2013), vegetation composition and structure (Lutz et al., 2012; Kane et al., 2013; Cansler and McKenzie, 2014) and therefore the potential for increased erosion and flooding (Robichaud et al., 2000). Understanding burn severity across landscapes and the resulting changes within these landscapes is especially important when considering effects occurring in coupled ecosystems like the nearshore environment and its adjacent terrestrial watersheds. Much research has been focused on characterizing burn severity through remotely sensed data (Van Wagtendonk et al., 2004; Key and Benson, 2006; Cansler and McKenzie, 2012; Kolden and Rogan, 2013; Kane et al., 2014) and looking at changes and trends in burn severity (Kolden et al., 2012; Miller and Safford, 2012). While several longitudinal studies have monitored wildfire influences on vegetation succession at the plot scale (Callaway and Davis, 1993; Santana et al., 2012; Halpern and Lutz, 2013), comparatively fewer studies have looked at relationships between burn severity and vegetation at landscape scales. These have mostly focused on characterizing pre-fire vegetation contributions to post-fire severity (Kolden and Abatzoglou, 2012; Birch et al., 2014) rather than linking severity to post-fire transitions, in part due to the relatively recent development of representative metrics that allow burn severity to be mapped.

Quantifying the relative impacts of wildfire on land cover change and subsequent runoff is critical to understanding how terrestrial disturbance and change can impact threatened species in the nearshore environment. While most studies surrounding the limited growth of the sea otter population in central California have focused on anthropogenic inputs (Conrad et al., 2005; Dowd et al., 2008; Johnson et al., 2009), the Big Sur population of sea otters is comparatively isolated and protected from anthropogenic inputs, but still limited in terms of population growth. We hypothesized that large wildfires have similar detrimental effects as anthropogenic inputs to the nearshore environment due to fire-altered land cover, and that the use of a spatially explicit runoff model would demonstrate the relationship between greater burn severity and higher runoff following wildfire. Here, we demonstrate an approach to assess the sensitivity of nonpoint source pollutants and runoff into the nearshore environment to wildfire-induced changes in land cover. Our objectives were: 1) to characterize the effect of burn severity on land cover within the study area, 2) to model nonpoint source pollutants utilizing a multi-year land cover time series that incorporates wildfire effects, and 3) to quantify the changes in modeled nonpoint source pollutants to the nearshore environment resulting from the fire effects.

2. Methods

2.1. Study area

The study area is located on the central California coast in an area formed by twelve adjacent watersheds covering 87,638 ha and draining a portion of the Santa Lucia Range in the northern portion of the Los Padres National Forest (Fig. 1). The Santa Lucia Range rises steeply from sea level to just below 1800 m within a few km from the coast, and experiences a Mediterranean climate, with fire