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Effects of climate change and wildfire on soil loss in the Southern Rockies Ecoregion

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ABSTRACT

Forests in the Southern Rockies Ecoregion surround the headwaters of several major rivers in the western and central US. Future climatic changes will increase the incidence of wildfire in those forests, and will likely lead to changes in downstream water quality, including sediment loads. We estimated soil loss under the historic climate and two IPCC climate change emissions scenarios (A2 and B1); each scenario was modeled using statistically downscaled climate data from global circulation models (GCMs; ECHAM5 and HadCM3) for each of thirteen land cover types. We used the Revised Universal Soil Loss Equation (RUSLE) and developed a way to calculate rainfall erosivity, a key factor in RUSLE, to account for climate change. We also incorporated the effects of climate change on wildfire to create stochastic spatial distributions of wildfires and to inform changes in land cover. Based on 100 simulations of future wildfire applied to RUSLE for each GCM-scenario combination, we found that soil loss will likely increase above historic levels but that considerable uncertainty remains about the amount of increase. Across the GCM-scenario combinations, mean soil loss increased above historic levels by from 3% (HadCM3-A2) to 65% (ECHAM5-B1) for climate change only and the effects of wildfire increased soil loss an additional 3 to 5%.

1. Introduction

The effects of increased erosion and sedimentation on aquatic ecosystems including fish habitat, channel morphology, and municipal water supplies are critical issues in many watersheds (e.g. EPA, 2000; MacDonald and Stednick, 2003; Shaw and Richardson, 2001; Troendle and Olsen, 1994). Sediment is probably the most important water quality concern (EPA, 2000), as increased sediment raises the cost to treat and supply domestic water, reduces reservoir storage, and increases reservoir maintenance needs (Graham, 2003; Palmieri et al., 2001). Further, several other pollutants preferentially bind to fine sediment particles, which may be transported downstream, degrading the quality of raw water supplies (EPA, 2000). In the western United States, 65% of the water supply originates on forested watersheds (Brown et al., 2008) and the Southern Rockies Ecoregion (SRE) provides the headwaters to many of the rivers that supply this water.

Climate change, which will affect precipitation, temperature, and land cover, is likely to strongly influence the processes causing surface erosion. Surface erosion is the removal and transportation of soil by raindrop impact and overland flow (Foster and Meyer, 1977; Wischmeier and Smith, 1978). These processes are driven by rainfall intensity and amount, and are modified by topography, soil and land cover types. In the western US, projected increases in temperature and changes in precipitation (Ray et al., 2008) will likely affect both erosion and wildfire in the SRE. When temperatures increase, more precipitation falls as rain (instead of snow) and extreme rainfall events become more likely (IPCC, 2007). The increase in the amount and intensity of rain is the dominant process most likely to increase erosion (Nearing, 2001).

The length of fire seasons and extent of annual burned area are strongly related to seasonal changes in precipitation and temperature (Balshi et al., 2009; Bartlein et al., 2003; Littell et al., 2009; Westerling et al., 2006). Burned area is significantly and positively correlated with spring and summer temperatures (Littell et al., 2009). Summer and autumn precipitation control fuel moisture (Drever et al., 2009; Littell et al., 2009; Westerling et al., 2006). In the southwestern US, climate models consistently project increased temperatures for the 21st century but disagree about the amount of future precipitation. Increases in temperatures are likely, aside from any change in precipitation, to expand the total area burned by wildfires worldwide (IPCC, 2007), in north America (Drever et al., 2009; Spracklen et al., 2009; Westerling et al., 2006), and in the SRE (Litschert et al., 2012).

Wildfires in the SRE burn with varying severity and can result in decreased vegetation cover, the conflagration of organic material such as leaf litter, development of hydrophobic soils, and soil sealing (DeBano, 1981; Larsen et al., 2009). The removal of organic material

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that previously absorbed precipitation leads to increased surface erosion, in some cases by several orders of magnitude as compared to undisturbed areas, as rain splash causes detachment or entrainment of sediment (Moody and Martin, 2001; Neary et al., 2005). Similarly, hydrophobic soils reduce infiltration because moisture may not penetrate the hydrophobic layer (DeBano, 1981). Precipitation on bare mineral soils, exposed by wildfires, converges as overland flow that causes further erosion in the form of rills and gullies that may connect to streams, increasing downstream sedimentation. In summary, climate change will likely affect precipitation, land cover, and fire regimes; hence it is important to consider these effects on potential changes in erosion.

In recent years, climate modeling for the western US has been refined to include key factors such as the El Nino-Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) (Cañon et al., 2007, 2011). In a test of 16 global circulation models (GCM), HadCM3 and ECHAM5 were considered the best for simulating climate in the southwestern US (Dominguez et al., 2010). Improvements in downscaling global circulation model (GCM) output have resulted in data that can be used as input into watershed scale hydrologic and sediment models (e.g. Cañon et al., 2011; Hay et al., 2000; Wood et al., 2004). Hence, hydrologic and sedimentary changes for future climate conditions can be estimated using the downscaled climate data.

Given that strong temperature and precipitation gradients in this mountainous region dictate patterns of land cover type, our goal for this study was to calculate future soil loss for different land cover types across the SRE using projected changes in climate and wildfire extent. The underlying objective was to provide land managers with a quantitative assessment of changes in soil loss and of the uncertainty associated with soil loss changes in the future. To achieve this goal we: (1) used a burned area model to estimate the extent of future wildfires and to stochastically generate and map future wildfire events (Litschert et al., 2012); (2) combined the resulting wildfire maps with broad land cover types; (3) estimated spatial patterns of rainfall erosivity for historic and projected climates; and finally (4) used the modified land cover and rainfall erosivity layers to estimate soil loss using the Revised Universal Soil Loss Equation (RUSLE) for each of thirteen land cover types. In RUSLE, soil loss is a product of values for rainfall erosivity, soil erodibility, slope length and gradient, land cover, and agricultural practices (Renard et al., 1997). We computed soil loss for a past time period (1970–2006), and for two future time periods (2010–2040 and 2040–2070) for each of four sets of downscaled climate data corresponding to two Intergovernmental Panel on Climate Change (IPCC) global emissions scenarios (A2, B1) each modeled using two GCMs (ECHAM5 and HadCM3).

2. Site description

The SRE (Bailey et al., 1994) consists of almost 144,000 km^2 of generally mountainous terrain in central Colorado, southern Wyoming and northern New Mexico, ranging in elevation from 1000 to 4400 m. The SRE is of critical importance for water supply as it contains the headwaters of the Colorado, Platte, Arkansas, Rio Grande, and Canadian Rivers (Fig. 1). Mean annual precipitation (1971–2000) ranges from 170 mm at the lower elevations to 1600 mm at the highest elevations. Mean annual temperatures for 1970–2000 range from −4° to 13 °C at highest to lower elevations respectively. Vegetation in the SRE includes prairie, shrub lands, and pinyon–juniper woodlands at the lower elevations; ponderosa pine, lodgepole pine and sub-alpine fir at the mid and higher elevations; and alpine tundra at the highest elevations.

3. Methods

We estimated average annual soil loss using RUSLE (Renard et al., 1997) in ESRI™ ArcGIS 9.2 using Python 2.4. Because we wanted to provide information to land managers about potential changes in soil loss and sedimentation due to climate change, we needed to select an approach that was appropriate for modeling changes over large areas. RUSLE is a relatively simple and computationally efficient model well suited for modeling changes at the broad, landscape level. Using RUSLE, we were able to examine nine historic and future data combinations across the SRE, each of which was implemented 100 times. The use of a more detailed, physically based model was impractical over such a large and heterogeneous area as the SRE (e.g. Caminiti, 2004; Merritt et al., 2003). Despite its origins in agriculture, RUSLE has been used to calculate soil loss in a variety of other land cover and topographic types, including forested watersheds (e.g. Breiby, 2006; Gonzalez-Bonorino and Osterkamp, 2004; Toy and Foster, 1998). We next describe how we parameterized the six factors of RUSLE, calculated soil loss for climate change and wildfire combinations, and analyzed the RUSLE output.

Fig. 1. The Southern Rockies Ecoregion (SRE) showing the sources of several major rivers and surrounding states.

3.1. Parameterizing RUSLE

In RUSLE, the rate of annual soil loss (A; Mg ha^{-1} yr^{-1}) is the product of six factors:

$$A = R \times K \times L \times S \times C \times P \quad (1)$$

where R is annual rainfall erosivity (MJ mm ha^{-1} h^{-1} yr^{-1}), K is soil erodibility (Mg ha h ha^{-1} MJ^{-1} mm^{-1}), L is slope length, S is slope gradient, C is land cover, and P is agricultural practices (Renard et al., 1997). L, S, C, and P are dimensionless. We calculated A for a two-dimensional surface of the SRE represented by a raster with cells identified with coordinates (i,j). We implemented RUSLE at a spatial