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Editor's Choice Research Article

Spatially Explicit Rangeland Erosion Monitoring Using High-Resolution Digital Aerial Imagery☆,☆☆

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ABSTRACT

Nearly all of the ecosystem services supported by rangelands, including production of livestock forage, carbon sequestration, and provisioning of clean water, are negatively impacted by soil erosion. Accordingly, monitoring the severity, spatial extent, and rate of soil erosion is essential for long-term sustainable management. Traditional field-based methods of monitoring erosion (sediment traps, erosion pins, and bridges) can be labor intensive and therefore are generally limited in spatial intensity and/or extent. There is a growing effort to monitor natural resources at broad scales, which is driving the need for new soil erosion monitoring tools. One remote-sensing technique that can be used to monitor soil movement is a time series of digital elevation models (DEMs) created using aerial photogrammetry methods. By geographically coregistering the DEMs and subtracting one surface from the other, an estimate of soil elevation change can be created. Such analysis enables spatially explicit quantification and visualization of net soil movement including erosion, deposition, and redistribution. We constructed DEMs (12-cm ground sampling distance) on the basis of aerial photography immediately before and 1 year after a vegetation removal treatment on a 31-ha Piñon-Juniper woodland in southeastern Utah to evaluate the use of aerial photography in detecting soil surface change. On average, we were able to detect surface elevation change of $\pm 8-9$cm and greater, which was sufficient for the large amount of soil movement exhibited on the study area. Detecting more subtle soil erosion could be achieved using the same technique with higher-resolution imagery from lower-flying aircraft such as unmanned aerial vehicles. DEM differencing and process-focused field methods provided complementary information and a more complete assessment of soil loss and movement than any single technique alone. Photogrammetric DEM differencing could be used as a technique to quantitatively monitor surface change over time relative to management activities.

Introduction

Soil and site stability are key attributes of assessing the health of arid and semiarid lands (National Research Council, 1994; Pyke et al., 2002) because these lands are susceptible to high rates of wind and water erosion. Erosion results in loss of soil nutrients and organic matter, leaving it less productive (Pimentel and Kounang, 1998; Heng et al., 2010) and vulnerable to transition to undesirable alternate and/or degraded states (Chartier and Rostagno, 2006; Okin, 2008; Kéfi et al., 2010). Nearly all of the ecosystem services supported by rangelands, including production of livestock forage, carbon sequestration, and provisioning of clean water, are negatively impacted by soil erosion (Hassan et al., 2005). Soil loss due to hydrologic processes can reduce water quality in streams and rivers, while wind-blown soil can reduce air quality, damage property, and negatively impact downwind mountain snowpack (National Research Council, 1994; Pimentel et al., 1995; Painter et al., 2010; USDA, 2010). In addition, soil erosion driven by land use and climate plays a large role in desertification (Schlesinger et al., 1990; Peters et al., 2004, 2007). Accordingly, monitoring the severity, spatial extent, and rate of soil erosion is essential for long-term sustainable management of rangelands.

A variety of field techniques have been developed to measure and monitor the rates of erosion and sediment transport. Sediment traps, perhaps the most common method, include passive dust samplers for measuring wind-driven flux (Wilson and Cooke, 1980; Fryrear, 1986) and hillslope or catchment-scale overland flow retainers for measuring water-driven fluxes (silt fences and stock ponds; Loughran, 1989; Robichaud, 2005; Nichols, 2006). From accumulation of sediment in the traps over time, sediment transport rates (e.g., g·m^{-2}·d^{-1}) caused

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by either wind (dust samplers) or water (silt fences, stock ponds) can be estimated. A limitation of these methods is the difficulty of identifying the area from which the sediment originated and where it is going. Determining the source area for dust samplers is not easily done, and typically horizontal flux (not erosion) rates are estimated (Zhang et al., 2011). The potential source area can usually be determined for water-transported sediment, allowing for estimates of fluvial erosion rates (e.g., $t \cdot ha^{-1} \cdot y^{-1}$). However, soil erosion is not evenly distributed across a watershed and pinpointing fluvial erosion sources within catchments is still elusive.

Another suite of field methods allows for estimating the spatial distribution of erosion and deposition by measuring net soil surface change over time. Unlike sediment traps, these techniques can account for the spatial variation of sediment movement to help identify sources and sinks of eroded material. These surface change methods do not measure flux, nor are they typically process specific as they measure the aggregated effect of wind, water, and other disturbances. Commonly used techniques include erosion pins (Fanning, 1994; Sirvent et al., 1997) and erosion bridges (Shakesby, 1993; Wilcox et al., 1996) that measure the subsidence of soil compared with a fixed datum. Soil movement can also be tracked by detecting environmental tracers such as Cesium-137 isotopes (Ritchie and McHenry, 1990; Zapata, 2003).

Net soil movement can also be measured with a time series of ground-based digital elevation models (DEMs). By geographically coregistering the DEMs and subtracting one surface from another, an image of soil elevation change can be created (referred to as DEM differencing throughout the paper). Such analysis enables spatially explicit quantification and visualization of net soil movement. Ground-based DEMs can be made from a few different sources including surveying (Martínez-Casasnovas et al., 2002; Wheaton et al., 2010), terrestrial laser scanning (Perroy et al., 2010; Bremer and Sass, 2012; Schneider et al., 2012), and close-range photogrammetry (Welch et al., 1984; Gessesse et al., 2010; Nouwakpo and Huang, 2012).

The resolution and spatial extent of in situ methods for measuring soil erosion is a function of the labor and time allocated for installation, maintenance, and data collection. Intensive field protocols can quickly become expensive in large monitoring programs (Pellant et al., 1999; Booth and Cox, 2008; Marzolff and Poesen, 2009). As a result, field methods usually cover only plot and hillslope scales (an exception being Nichols, 2006). In addition, sample locations may be inaccessible or difficult to access in vehicles or on foot (Pellant et al., 1999). These factors combined with heterogeneity of soil conditions across landscapes make it difficult to scale up soil erosion measurements to make inferences to catchment and watershed scales.

There is a growing effort to monitor natural resources at broad scales that is driving the need for new soil erosion monitoring tools. Regional and continental scale rangeland monitoring programs such as National Resource Inventory (NRI; Nusser and Goebel, 1997; Herrick et al., 2010) and Bureau of Land Management's Assessment, Inventory, and Monitoring program (Toevs et al., 2011) rely on field measurements from thousands of sample locations to track vegetation and soil characteristics. To reduce costs associated with data collection, efficiencies must be sought. Remote sensing techniques employing high-resolution aerial imagery can increase the extent and efficiency of measuring vegetation attributes in rangelands (Booth et al., 2005, 2006; Duniway et al., 2011; Karl et al., 2012) and could potentially be used for monitoring soil erosion rates.

DEM differencing can also be produced from airborne sensors such as airborne laser scanning (i.e., LiDAR), synthetic aperture radar, and photogrammetry from cameras to cover a larger extent of land compared with field methods. Airborne DEM differencing has been demonstrated to measure topographic change for a variety of applications and environments including gullies (Thomas et al., 1986; Vandaele et al., 1996; DeRose et al., 1998; Betts and DeRose, 1999; Martínez-Casasnovas, 2003; Marzolff and Poesen, 2009; Marzolff et al., 2011; d' Oleire-Oltmanns et al., 2012), riverbeds (Smith et al., 2000; Brasington et al., 2003; Lane et al., 2003; Thoma et al., 2005), sand dunes (Brown and Arbogast, 1999), landslides (Bremer and Sass, 2012; Lucieer et al., 2013), and artificial catchments (Schneider et al., 2011, 2012).

However, little research has been conducted with specific consideration to monitoring large upland rangeland landscapes, an application with unique technical challenges (e.g., inaccessibility, variability in woody and herbaceous vegetation cover). To reduce the costs associated with field visits, a workflow that minimizes the need for field-collected ground control is necessary. Also, the spatial resolution of the imagery needs to be fine scale enough to 1) automatically identify and exclude individual trees and shrubs from the DEMs and 2) detect the subtle topographic changes that can occur on rangelands due to erosional processes (cm scale; Fanning, 1994; Sirvent et al., 1997).

We conducted DEM differencing from high-resolution aerial imagery to test the ability to quantify soil erosion on a 31-ha Piñon-Juniper woodland in southeastern Utah. In 2009, a suite of fuel-reduction vegetation treatments were carried out with the goal of reducing fuel loads while restoring native understory vegetation. The specific objectives of this research were to 1) measure soil movement over the course of a year using photogrammetric DEM differencing, 2) assess the precision of the imagery products and subsequent soil erosion estimates and compare the results to concurrent field measurements of sediment flux, and 3) compare rates of erosion and sediment flux between treatment areas to evaluate DEM differencing as a method for estimating soil erosion following land management activities. We were not, however, trying to determine if the specific treatments were the cause of varying erosion rates. We discuss the advantages, as well as the technical and ecosystem limitations, of remote sensing methods compared with field methods for quantifying soil erosion. We also discuss why we chose to use aerial photogrammetry methods as opposed to available LiDAR or synthetic aperture radar.

Methods

Study Area

The study area for this project was on Shay Mesa (lat 37.9858°N, long 109.5575°W), a 31-ha Upland Shallow loam piñon-juniper site (Site ID: R035XY315UT, USDA Soil Conservation Service, 1991) in southeastern Utah (Fig. 1). Shay Mesa is located approximately 25 km northwest of Monticello, Utah, at an elevation of 2237 m with an average slope of 8 degrees. The mean annual maximum and minimum temperatures are 18.2°C and 3.0°C, respectively (PRISM Climate Group, 2013). The mean annual precipitation is 317 mm and follows a bimodal distribution with monsoonal rains in the summer and snow in the winter. Average annual wind speeds for the study period were $2.8\ m \cdot s^{-1}$ with the prevailing winds from southwest to northeast (USGS CLIM-MET 2014). Shay Mesa is public land managed by the US Department of the Interior's Bureau of Land Management.

Vegetation Treatments

Shay Mesa is dominated by two-needle piñon (*Pinus edulis* Engelm.) and Utah juniper (*Juniperus osteosperma* [Torr.] Little). Other common native plants found within the study site included mountain big sagebrush (*Artemisia tridentata* Nutt. ssp. vaseyana [Rydb.] Beetle), broom snakeweed (*Gutierrezia sarothrae* [Pursh] Britton & Rusby), Indian ricegrass (*Achnatherum hymenoides* [Roem. & Schult.] Barkworth), and blue grama (Bouteloua gracilis [Willd. ex Kunth] Lag. ex Griffiths). In the summer of 2009, a vegetation treatment was conducted to reduce wildfire fuels. Three vegetation removal methods were tested to determine the best method to promote native understory species growth while preventing exotic grass establishment and minimizing soil erosion (see Fig. 1). The methods included mechanical mastication (*M*), lopping of vegetation with the slash collected in piles and then burned (*P*), and lopping of vegetation followed by a broadcast burn