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Review

Toward a more holistic perspective of soil erosion: Why aeolian research needs to explicitly consider fluvial processes and interactions

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ABSTRACT

Soil erosion is driven by not only aeolian but also fluvial transport processes, yet these two types of processes are usually studied independently, thereby precluding effective assessment of overall erosion, potential interactions between the two drivers, and their relative sensitivities to projected changes in climate and land use. Here we provide a perspective that aeolian and fluvial transport processes need to be considered in concert relative to total erosion and to potential interactions, that relative dominance and sensitivity to disturbance vary with mean annual precipitation, and that there are important scale-dependencies associated with aeolian–fluvial interactions. We build on previous literature to present relevant conceptual syntheses highlighting these issues. We then highlight relative investments that have been made in soil erosion and sediment control by comparing the amount of resources allocated to aeolian and fluvial research using readily available metrics. Literature searches suggest that aeolian transport may be somewhat understudied relative to fluvial transport and, most importantly, that only a relatively small number of studies explicitly consider both aeolian and fluvial transport processes. Numerous environmental issues associated with intensification of land use and climate change impacts depend on not only overall erosion rates but also on differences and interactions between aeolian and fluvial processes. Therefore, a more holistic viewpoint of erosional processes that explicitly considers both aeolian and fluvial processes and their interactions is needed to optimize management and deployment of resources to address imminent changes in land use and climate.

Contents

1. Introduction

Aeolian processes in general, and soil transport and erosion in particular, present widespread and substantial challenges in environmental science and management (Pye, 1987; Toy et al., 2002; Peters et al., 2006; CCSP, 2008). The consequences of aeolian transport processes have important global implications (Cooke et al., 1993; Goudie, 2008) and are perhaps most evident in major dust storms across regionally degraded landscapes, as experienced throughout much of North America during the 1930s Dust Bowl era (Worster, 1979; Peters et al., 2007, 2008) and in China in association with degraded northern drylands (Chepil, 1949; Shao and Shao, 2001). Although dust deposition in some regions can have important beneficial effects, such as the transport of nitrogen, phosphorous, and other essential nutrients to aquatic and terrestrial systems (Swap et al., 1992; Chadwick et al., 1999; Neff et al., 2008), the detachment and removal of wind-blown sediment from source

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areas can significantly lower soil fertility and water holding capacity (Lal et al., 2003; Li et al., 2007, 2008), alter biogeochemical processes (Schlesinger et al., 1990; Jickells et al., 2005), and increase land surface inputs of dust to the atmosphere (Gillette and Passi, 1988; Tegen and Fung, 1994; Reynolds et al., 2001).

The catastrophic impacts of the North American Dust Bowl of the 1930s, as well as the Sirocco dust events of 1901–1903, led to a widespread surge in interest in aeolian processes and a significant increase in the number of publications in aeolian research (Stout et al., 2009), many of which focused on basic aeolian transport processes or soil conservation through improved land management. This interest subsequently benefitted from novel, quantitative advances developed by Bagnold (1941), which have served as a basic foundation for much of our current understanding of aeolian transport processes. The aeolian research community has been growing steadily since Bagnold's (1941) classic work on aeolian entrainment and founding studies of the geomorphology of dune fields (Stout et al., 2009). Aeolian transport is now clearly recognized as critical to land surface dynamics for the environmental and geosciences research community and by many within the resource management community (Peters et al., 2006; CCSP, 2008).

Although aeolian transport is generally recognized as important, current understanding and focus on aeolian processes is often in isolation from the other primary driver of land surface dynamics: fluvial transport (Heathcote, 1983; Baker et al., 1995; Breshears et al., 2003; Visser et al., 2004). More specifically, researchers and practitioners in soil conservation generally segregate into one of two disciplines, those focusing on wind erosion or those focusing on water erosion. Many geomorphological studies focus on inferring relative importance of aeolian vs. fluvial processes in soil profiles, but these studies do not directly quantify concurrent, co-located rates of both wind and water erosion. Although both wind and water erosion have contributed close to one billion tons of soil loss per year within the United States (NRCS, 2000a,b), and they operate on many similar fundamentals, there are critical differences between the two types of processes that drive this separation (Toy et al., 2002; Breshears et al., 2003; Visser et al., 2004). These include major differences in the density of the transport fluid (water vs. air), directionality of sediment and dust transport, temporal scales of the erosion events, and spatial scales of the impact (from localized to global). Though research on aeolian transport has generally proceeded in isolation from fluvial transport, there are numerous reasons to re-evaluate the interrelationships between aeolian and fluvial processes (Heathcote, 1983; Baker et al., 1995; Breshears et al., 2003; Bullard and McTainsh, 2003; Visser et al., 2004) because such interrelationships may have important environmental and ecological consequences (Aguiar and Sala, 1999; Peters et al., 2006; Ravi et al., 2007b). The degree and manner in which aeolian and fluvial transport processes are interrelated could also have important implications for relative investments in research and soil conservation for controlling erosion of both types. This issue is particularly pressing given the growing environmental challenges related to maintaining agricultural productivity, preventing ecosystem degradation, and adapting to the projected impacts of global climate change (Lal et al., 2003; Nearing, 2005; CCSP, 2008).

The potential for soil erosion and land degradation due to synergistic effects of aeolian and fluvial transport may well far exceed that of either type of process alone (Bullard and Livingstone, 2002). Aeolian and fluvial transport processes can degrade ecosystems and accelerate desertification (Schlesinger et al., 1990; Belnap, 1995; Peters et al., 2006; Okin et al., 2009), and both processes can contribute substantially to total erosion (Breshears et al., 2003; Bullard and McTainsh, 2003; Visser et al., 2004). Combined, the effects of aeolian- and fluvial-driven soil loss have resulted in moderate to severe soil degradation throughout much of the world's arable land (Oldeman et al., 1990; Pimentel, 1993). Globally, perhaps as much as one-third of all arable land has experienced accelerated rates of erosion that undermine long-term productivity (Brown, 1981; USDA, 2006). It is clear that a majority of lands, whatever the use pattern, are subject to both aeolian and fluvial transport processes and that these processes operate together to redistribute soil and other critical resources, such as nutrients, organic debris, seeds, and water (Schlesinger et al., 1990; Aguiar and Sala, 1999; Bullard and McTainsh, 2003). Interactions between aeolian and fluvial processes can have a large influence on the transport and deposition of fine sediment and sand-sized material in dryland environments. For example, aeolian entrainment from lake beds, river beds, and flood plains can transport fluvial sediment long distances and subsequently deposit it as aeolian material, at which point either fluvial or aeolian processes can further redistribute the sediment, thus increasing the potential for interactions between aeolian and fluvial processes (Bullard and Livingstone, 2002). Additional examples of aeolian–fluvial interactions include glaciogenic outwash in major drainage systems supplying silt for aeolian entrainment to form loess (Sun, 2002; Muhs et al., 2008), raindrop destruction of soil aggregates to yield particle sizes suitable for deflation (Cornelis et al., 2004; Chappell et al., 2005; Erpul et al., 2009), micro-topography formation beneath plant canopies (Schlesinger et al., 1990; Ravi et al., 2007a), and reworking of hillslope loess to form pedisediment (Ruhe et al., 1967).

Despite the importance of wind and water erosion over vast areas, field studies comparing the absolute and relative magnitudes of both types of erosion are largely lacking (Breshears et al., 2003; Visser et al., 2004). Although conceptual models and limited field measurements suggest that both wind and water erosion can be of similar magnitude in many environments (Kirkby, 1980; Baker et al., 1995; Valentin, 1996; Breshears et al., 2003), substantial uncertainty remains about the relative magnitudes of the two types of erosion and how they interrelate with each other because few studies explicitly evaluate both processes. In addition, an integrated perspective of how these processes contribute to total erosion and how they vary with scale and the degree to which they interact is lacking. Given that recent field measurements and erosion models indicate that both processes contribute substantially to total erosion (NRCS, 2000a,b; Breshears et al., 2003) and that the ways in which they interact are being considered more directly (Bullard and Livingstone, 2002; Bullard and McTainsh, 2003; Visser et al., 2004), a key challenge that lies before the aeolian and fluvial research communities is to develop a more integrated perspective of aeolian–fluvial dynamics. The uncertainty about the relative magnitudes of aeolian and fluvial transport processes needs to be addressed to develop more effective land management and could be useful in guiding future deployment of resources. Here we address these key issues about aeolian transport processes in the context of fluvial transport. Specifically, we (1) discuss the scale-dependent and interactive ways in which aeolian and fluvial transport operate across humid through arid environments; (2) evaluate relative investments in research as measured through the number of publications globally and the amount of government funded erosion control based on data from the United States, and (3) propose a prospectus for future studies of aeolian transport in a scale-dependent context that explicitly considers aeolian–fluvial interactions.

2. Environmental and scale-dependencies of aeolian transport relative to fluvial transport

Precipitation has a multifaceted role in soil transport that is particularly relevant in that the magnitude of aeolian transport rela-