Aeolian Research 1 (2009) 9–17

Contents lists available at ScienceDirect

Aeolian Research

journal homepage: www.elsevier.com/locate/aeolia

Review

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

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ARTICLE INFO

Article history:
Received 22 December 2008
Revised 9 April 2009
Accepted 26 April 2009

Keywords:
Aeolian
Fluvial
Wind erosion
Water erosion
Dust
Sediment

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.

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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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doi:10.1016/j.aeolia.2009.04.002

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 relative to fluvial transport likely varies strongly with precipitation regimes among arid, semiarid/subhumid, and humid environments. Precipitation amount affects vegetation cover, soil characteristics, and topography, all of which are critical factors driving the amount of soil transport through both aeolian and fluvial processes (Pye, 1987; Visser et al., 2004; Li et al., 2005). In general, there is usually greater potential for soil erosion and transport in arid and semiarid environments relative to humid environments, especially in areas with large available sediment supplies (Fig. 1a). One of the most obvious spatial differences between aeolian and fluvial sediment transport is the direction and dimensions of transport characteristics specific to each process (Fig. 1a; Bullard and Livingstone, 2002; Breshears et al., 2003; Reiners and Driese, 2004; Visser et al., 2004). Aeolian transport is two-dimensional, with transport occurring in both vertical and horizontal directions, and omni-directional, with material potentially being transported in any wind direction. In contrast, fluvial transport is primarily one-dimensional, with flow occurring horizontal to slope, and unidirectional, with the direction of transport being downslope. Fluvial transport is largely irreversible because material transported in one direction will not be transported back toward the source location in subsequent fluvial events. The spatial scales of aeolian and fluvial transport are also different. Aeolian transport not only can occur in any changing wind direction, but wind can transport dust on a much larger spatial scale, including globally (Prospero et al., 2002; Goudie and Middleton, 2006). In contrast, fluvial transport is not only limited to downslope direction but is also constrained by topographic barriers associated with watershed drainage areas (Reiners and Driese, 2004). Although important temporal differences exist between aeolian and fluvial transport, both processes can occur over similar time scales in response to unique weather and climatic events. For example, aeolian and fluvial sediment transport often occur as sporadic, event-based phenomenon associated with either periods of strong winds (Stout, 2001; Whicker et al., 2002) or intense rain events (Dingman, 1994). However, aeolian sediment transport in many dryland systems may be expected to occur more frequently than fluvial transport, perhaps on almost a daily basis, because even short bursts of wind on generally calm days can result in the detachment and transport of sediment (Stout and Zobeck, 1997).

Both aeolian and fluvial transport are sensitive to disturbances in vegetation cover and soil surfaces, and these can change the relative magnitudes of the two types of transport in a precipitation-regime-dependent context (Fig. 1b). Disturbances such as fire and livestock grazing can alter both aeolian and fluvial transport and may alter their relative importance (Toy et al., 2002; Whicker et al., 2002; Visser et al., 2004; Breshears et al., 2009). In arid environments, which are typically characterized by sparse vegetation cover (Greig-Smith, 1979; Aguiar and Sala, 1999), the effect of disturbance on total ground cover is often less pronounced compared to changes in total ground cover that would be expected following disturbance in humid environments or other environments that may have nearly complete vegetation cover prior to disturbance (Breshears et al., 2009). For example, the loss of protective vegetation cover due to disturbance in a humid environment can have a dramatic impact on fluvial transport (Brooks et al., 2003) because vegetation cover can change rapidly from nearly complete cover to bare following disturbance (White, 1979; Sousa, 1984). A dramatic reduction in vegetation cover can allow overland flow to become more concentrated and can increase total runoff and sediment transport potential because fewer sink areas are available for water storage (Johansen et al., 2001; Dunkerley, 2002; Wilcox et al., 2003). Aeolian transport in humid settings will also likely increase to some degree following disturbance, but will probably be limited due to the higher soil moisture content and atmospheric humidity associated with humid environments (Ravi et al., 2004; Ravi and D'Odorico, 2005). Vegetation in humid environments should generally recover more rapidly than in dryland environ-

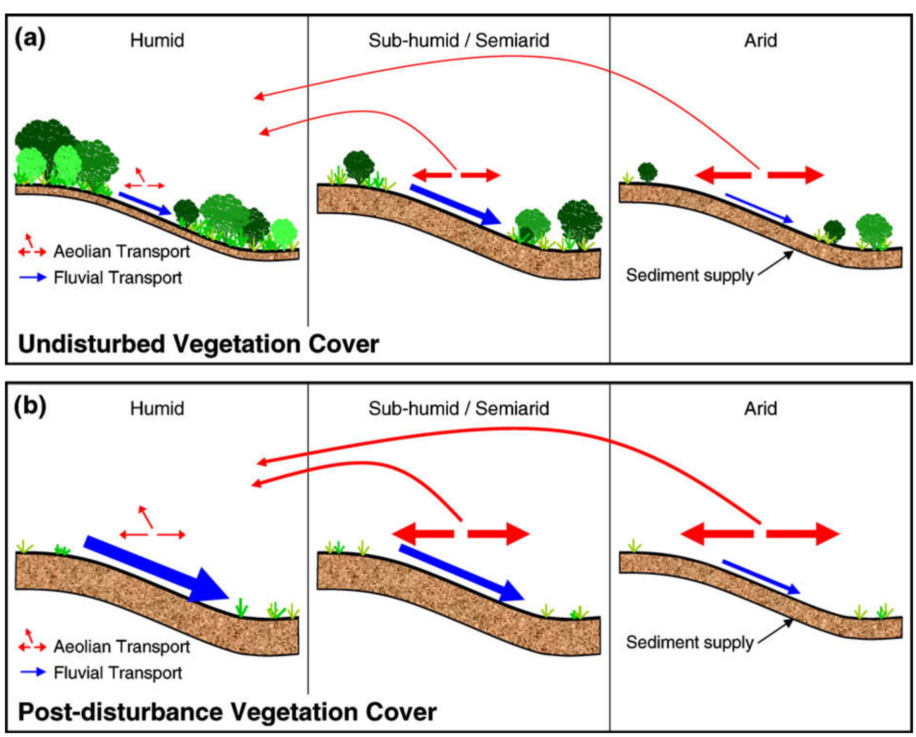

Fig. 1. Erosion behavior under (a) undisturbed vegetation cover and (b) post-disturbance vegetation cover along a hypothetical moisture gradient spanning humid to arid environments. Length of arrow approximates transport distance; width of arrow approximates transport capacity or total sediment flux by aeolian (red) and fluvial (blue) processes; vertical arrows indicate vertical dust flux and length represents the degree of connectivity. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

ments because xeric soil conditions often cause plant water stress and can impede vegetation recovery (Burke et al., 1998; Berlow et al., 2003; Chaves et al., 2009), thereby increasing the total amount of soil erosion over time. Consequently, arid and semiarid climates can be viewed as being more vulnerable to long-term increases in erosion following disturbance (unless, for example, channel erosion in a humid environment becomes a persistent, reinforcing problem following disturbance).

When aeolian transport is considered in a more holistic context with fluvial transport, the potential importance of total sediment transport from both processes and their interactions becomes more readily apparent (Fig. 2a). Total sediment transport could be a simple additive result of aeolian and fluvial transport, a starting assumption we make here. If so, then the differential dependencies of aeolian and fluvial transport on precipitation regimes would imply that total sediment transport in relatively undisturbed systems should be greatest in semiarid environments rather than humid or arid ones. Fluvial processes are typically thought to dominate sediment transport potential in humid or mesic environments, whereas aeolian processes are typically thought to dominate sediment transport in arid or xeric environments (e.g., Schumm, 1965; Marshall, 1973; Kirkby, 1978; Bullard and Livingstone, 2002). However, in semiarid and drylands systems, which

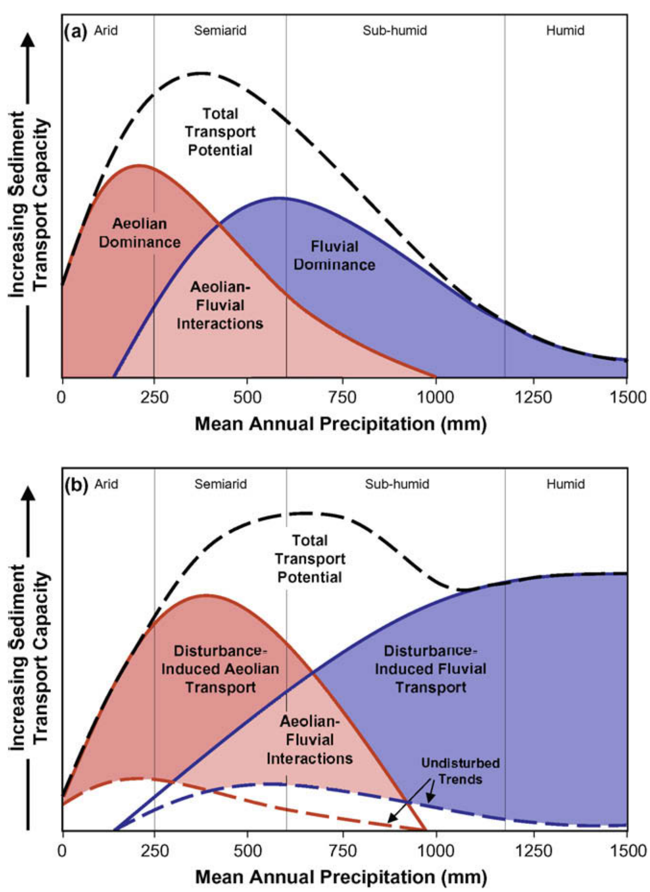

Fig. 2. Hypothesized trends of potential sediment transport capacity as a function of mean annual precipitation to highlight the potential total sediment transport for (a) undisturbed and (b) disturbed sites (modified from Schumm, 1965; Marshall, 1973; Kirkby, 1978). At the most arid sites, aeolian sediment transport is supply limited (except for sand dunes and highly disturbed systems), and at the most mesic sites, fluvial sediment transport is limited due to high vegetation cover. Note that the scales differ, with curves from (a) provided for reference in (b). Potential for increased sediment transport following disturbance is greater for fluvial transport than for aeolian transport because there is a greater potential for a large reduction in vegetation cover in humid environments relative to arid environments.

constitute approximately 40% of the earth's land surface, neither aeolian nor fluvial processes may dominate, based on the limited relevant studies that have considered both types of transport directly (Breshears et al., 2003; Visser et al., 2004). Note that the maximum for potential aeolian sediment transport does not necessarily occur at the lowest levels of annual precipitation (Fig. 2a) because the lack of moisture in hyperarid systems can result in the lack of available sediment for transport (Schumm, 1965; Bullard and Livingstone, 2002; Gillette and Chen, 2001); exceptions would include highly weathered or disturbed systems such as dune fields and agricultural land. Similarly, the maximum potential for fluvial transport does not necessarily occur at the highest levels of annual precipitation because vegetation cover typically increases as moisture availability increases, thereby reducing the amount of exposed soil susceptible to fluvial transport. Given these precipitation-regime dependencies for aeolian and fluvial transport, the maximum potential for interaction between these two processes is likely to occur under semiarid climatic conditions where neither process solely dominates (Kirkby, 1978; Heathcote, 1983; Baker et al., 1995; Bullard and Livingstone, 2002; Breshears et al., 2003). Semiarid systems have the greatest potential for aeolian–fluvial interactions because these systems are often characterized by sparse vegetation cover, making them highly erodible under both aeolian and fluvial forces. The greatest potential for total sediment transport (i.e., combined aeolian and fluvial sediment transport) would therefore likely be found in semiarid systems (Fig. 2a), where both processes are thought to contribute substantially to total sediment transport (Breshears et al., 2003; Visser et al., 2004).

Total sediment transport potential across precipitation regimes should differ between disturbed and undisturbed conditions (Fig. 2b). We hypothesize that short-term fluvial transport would increase more dramatically following disturbance relative to aeolian transport because fluvial transport dominates humid systems, which undergo the most dramatic change in vegetation cover following disturbance (Heathcote, 1983; Baker et al., 1995; Johansen et al., 2001; Brooks et al., 2003). When compared to humid systems, disturbances in arid and semiarid systems likely result in a smaller decrease in the relative amount of vegetation cover because inherently a large portion of the soil surface is already void of protective vegetation cover (Aguiar and Sala, 1999). The maximum potential for aeolian–fluvial interaction, as well as the maximum total sediment transport potential, is therefore expected to shift toward a more mesic environment following disturbance and the loss of vegetation cover (Fig. 2a and b).

Additional insights emerge about the spatial and temporal scale-dependencies associated with both aeolian and fluvial processes, as well as about their precipitation dependencies, when a more holistic perspective is considered (Fig. 3a). As noted previously, aeolian transport differs fundamentally from fluvial transport in that it can occur in both the horizontal direction, as horizontal sediment flux that contributes to localized redistribution, and vertically, with the suspended dust being subject to long-distant redistribution (Breshears et al., 2003; Zobeck et al., 2003). Event-based sediment transport at small spatial and temporal scales (e.g., 10^2 m and 10^{-2} h, respectively) is dominated by fluvial processes because larger sediment and rock fragments can constitute the majority of mass being moved short distances over very short times (e.g., during flash floods), whereas the force of wind is not great enough to immobilize these larger fragments (Brooks et al., 2003). At large spatial and temporal scales, however, aeolian transport is expected to be dominant because fluvial transport is confined to channels and rivers within watershed boundaries, whereas aeolian transport is not confined to watersheds and can therefore transport dust at distances that span the globe (Fig. 3a). Notably, the greatest potential for aeolian–fluvial interactions occurs at intermediate spatial and temporal scales (Fig. 3a)

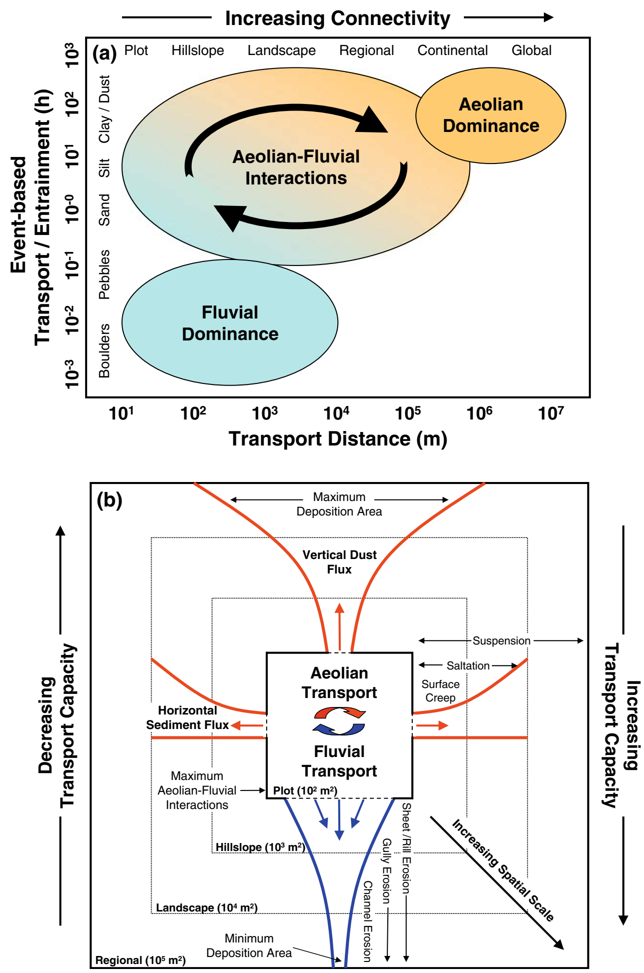

Fig. 3. (a) Transport distances and event-based transport/entrainment times, highlighting differences between fluvial vs. aeolian dominance and scales at which aeolian–fluvial interactions are potentially most important. (b) Scale-dependent interactions between aeolian and fluvial transport, highlighting maximum interactions at plot scale. Width between red or blue lines indicates the maximum depositional area. Note that the potential for fluvial sediment transport capacity increases with increasing scale, but the maximum deposition area simultaneously decreases. Horizontal aeolian sediment flux can move to hillslope and landscape scales, whereas vertical dust flux can extend to regional scales and has the maximum deposition area. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

because both wind and water have the potential to transport small- and medium-sized particles (e.g., sand, silt, and clay) over intermediate distances (e.g., 10^1–10^6 m). Fluvial processes, in contrast to aeolian processes, concentrate sediment transport capacity per unit source area with increasing spatial scale because water flows only downslope, thereby cumulatively compounding the potential to transport sediment while at the same time reducing the relative spatial area affected by the transported sediment (Fig. 3b; Reiners and Driese, 2004).

Because of these fundamental differences, aeolian and fluvial transport processes are likely to interact to a lesser degree with increasing spatial scale. For example, at the plot or hillslope scale, both processes can have roughly the same potential transport capacity (Breshears et al., 2003) and both might be expected to have similar areas impacted by the deposition of transported sediment (Fig. 3b). However, as spatial scale increases to the landscape and regional scale, the potential for aeolian–fluvial interactions likely decreases because aeolian transport capacity becomes weaker as the depositional area increases, whereas fluvial transport capacity becomes stronger as the depositional area decreases (e.g., gully and channel erosion; Fig. 3b).

3. Research output and resource investment in aeolian transport relative to fluvial transport

Given that aeolian transport is hypothesized to dominate sediment transport in many arid environments (Kirkby, 1980; Valentin, 1996), and is expected to be co-dominant and potentially interactive with fluvial transport in more mesic environments (Bullard and Livingstone, 2002; Visser et al., 2004), and that these environmental settings account for a large proportion of the terrestrial biosphere, to what extent does previous research and investments in soil erosion and sediment control reflect the relative importance of aeolian transport in these settings? Although there are limitations associated with simple assessments of trends in peer-reviewed literature, such assessments can nonetheless provide useful insights on research activity within the scientific community. We evaluated the literature by conducting literature searches (using ISI Web of Science) to quantify the number of publications associated with keywords related to aeolian and fluvial processes. We considered some of our results relative to a precipitation gradient distinguishing among arid, semiarid/subhumid, and humid environments. Our limited evaluation of available scientific papers on aeolian and fluvial transport suggests that there are more studies on fluvial than aeolian transport, even in drier environments where aeolian processes may indeed dominate (Fig. 4a). More importantly, most studies only consider the aeolian or fluvial transport component – very few explicitly considering both. Similarly, there appears to be more studies of land surface dynamics and sediment transport processes that focus on fluvial rather than aeolian transport processes, particularly those that evaluate erosional processes and their impacts (Fig. 4b).

The results of our literature search suggest there have been more studies of fluvial than aeolian transport and are notable given the previously raised point that the limited relevant studies suggest that aeolian and fluvial transport can be of similar magnitude in many environments (Kirkby, 1980; Baker et al., 1995; Valentin, 1996; Breshears et al., 2003). To extend our overview to other metrics, we used the United States as an example to compare the relative magnitudes of wind and water erosion on agricultural land, the economic cost of both types of erosion, and the amount of resources devoted to soil conservation and aeolian and fluvial research. Although it is likely these trends vary greatly for other countries and need to be considered in a broader context to assess global trends, we focused here on wind and water erosion within the United States where relevant data on both processes were readily available. Wind erosion for United States agricultural lands, estimated to account for $\sim 8 \times 10^5$ tons of soil loss per year, is nearly as large as water erosion, estimated to be $\sim 1 \times 10^6$ tons of soil loss per year (NRCS, 2000a,b). The total area of United States agricultural land (cropland and Conservation Reserve Program land only; data not readily available for rangeland) that is eroding at a rate greater than 5 tons per acre per year, which is over twice the national average, is approximately the same for wind erosion (40 million acres) and water erosion (41 million acres; NRCS, 2000a,b). Additionally although the western United States is primarily dominated by wind erosion and the eastern United States is primarily dominated by water erosion, there are substantial areas in the central, mid-west, and northwest portions of the United States where neither of the two processes dominates and both contribute substantially to total erosion rates, based on model assessments (Fig. 5a).

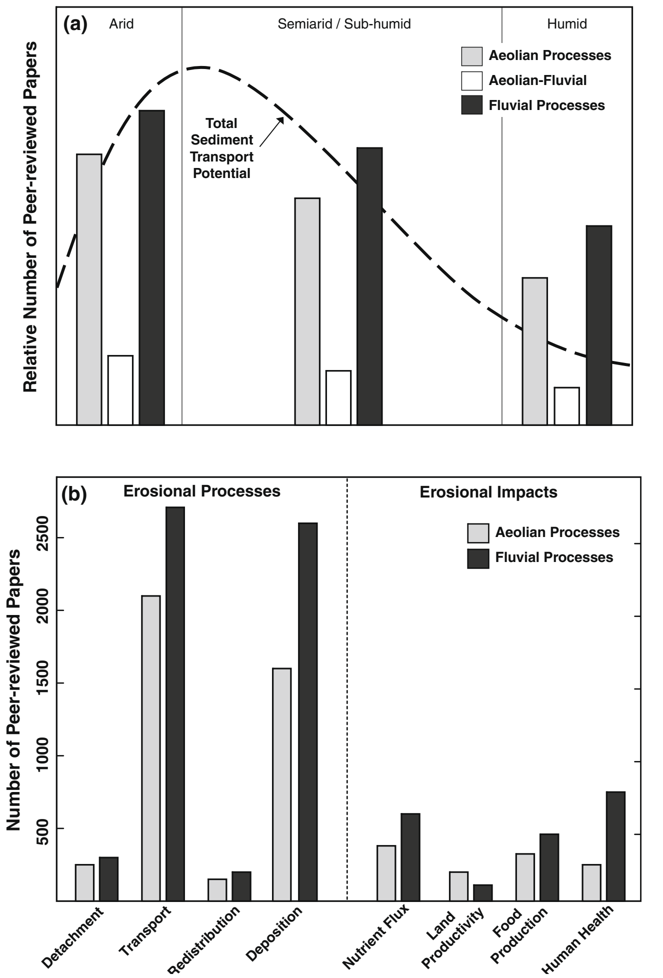

Fig. 4. Literature search results based on ISI Web of Knowledge: (a) total number of aeolian and fluvial papers as a function of aridity; and (b) total number of aeolian and fluvial papers by erosional process and erosional impact. Searches were based on the following criteria Timespan = (1978–2007). Databases = SCI-EXPANDED. Refined by: Document Type = (ARTICLE OR PROCEEDINGS PAPER OR REVIEW). Keywords for *Aeolian Processes:* Topic = (aeolian OR eolian OR loess OR "wind erosion" OR "wind-driven transport" OR "surface creep" OR saltation OR "dust flux" OR "dust transport" OR "dust load"). Keywords for *Fluvial Processes:* Topic = (fluvial OR alluvium OR alluvial OR "water erosion" OR "sheet erosion" OR "rill erosion" OR "gully erosion" OR "channel erosion" OR "suspended sediment load" OR bedload). Keywords for *Both Processes:* at least one term from both the aeolian search and fluvial search.

In short, these examples highlight that both aeolian and fluvial transport are important to consider in many cases when assessing the overall environmental and economic impact of sediment transport and soil erosion (Pimentel, 2000; Lal et al., 2003; Visser et al., 2004). The total on-site and off-site costs of wind and water erosion on United States agricultural land have previously been estimated to be 9.6 and 7.4 billion United States dollars per year, respectively (Pimentel et al., 1995). Notably, however, the amount of resources allocated to help combat erosion and its environmental and ecological impact is not distributed proportionally relative to annual rates and costs associated with wind and water erosion in the United States. For example, the USDA Environmental Quality Incentive Program (EQIP) spends up to 60 times the amount per acre of agricultural land on soil erosion and sediment control practices in the water-erosion dominated eastern United States than in the wind-erosion dominated western United States (Fig. 5b; NRCS, 2008), even though annual rates of wind and water erosion are nearly identical in the United States for agricultural cropland and land in the Conservation Reserve Program (NRCS, 2000a,b). Resources in the United States are also not distributed proportionally among money spent on aeolian and fluvial research. The USDA Agricultural Research Service (ARS) is the primary research agency in the United States responsible for assessing and mitigating erosional impacts on agricultural lands. The amount of resources and number of research locations devoted to aeolian and fluvial research within this agency suggests a disproportionate amount of resources is directed toward research related to fluvial processes. For example, the number of USDA-ARS experimental watersheds outnumbers the number of wind-erosion units by a factor of 18 (Fig. 5c). This apparent fluvial bias is somewhat ironic because much of the current United States soil conservation policy was initiated as a direct response to the devastating environmental and economic impacts of wind erosion and dust storms from agricultural lands in the Great Plains during the 1930s Dust Bowl (Worster, 1979).

These collective points summarizing research and resource investments imply that there may be a bias toward fluvial processes over aeolian processes such that investments in research (globally) and erosion control (at least within the United States) have not been in proportion to the relative importance of aeolian transport processes. If additional assessment supports the findings of this initial overview, then insights from adopting a more holistic perspective of aeolian and fluvial processes could aide scientists, land managers, government agencies, and especially policy-makers in optimizing effective distribution of resources.

4. Addressing emerging challenges with a more holistic perspective of soil erosion

Emerging challenges related to land use intensification and climate change reinforce the need for a more holistic perspective of soil erosion and associated aeolian and fluvial processes. Because co-located, simultaneous measurements of wind and water erosion are lacking, it is difficult to assess how changes in land use and particularly climate change will alter relative rates of wind and water erosion. In regions such as the southwestern United States where climate is projected to shift to more arid, "Dust-Bowl-like" conditions (Seager et al., 2007) and land use is also projected to intensify (CCSP, 2008), risks to soil surface stability could be substantial. Importantly, assessing such risks requires evaluating how both wind and water erosion – not simply one or the other – will likely respond. Little information exists in support of the widespread implicit assumption that wind erosion is not influenced by water erosion. If aeolian processes contribute a substantial amount to total erosion, as contended here and elsewhere (Kirkby, 1980; Baker et al., 1995; Valentin, 1996; Breshears et al., 2003), then we suggest that aeolian researchers should explicitly consider how aeolian transport processes influence and depend on fluvial transport processes in a scale-dependent and environmental gradient context. We propose some themes that could be the center of a research agenda addressing the relative importance of aeolian and fluvial transport processes, their interactions, and implications for land management and economics (Table 1).

In presenting a holistic perspective that emphasizes considering aeolian transport relative to fluvial transport, we have highlighted two major points. First, that aeolian and fluvial transport processes need to be considered in concert to appropriately assess and manage total erosion and the associated scale-dependencies of aeolian–fluvial interactions. Second, that investments made in aeolian research on dust emission and management, based on data from the United States – but perhaps relevant elsewhere – have been smaller than those for fluvial research. These points are based on limited relevant information but are consistent with available

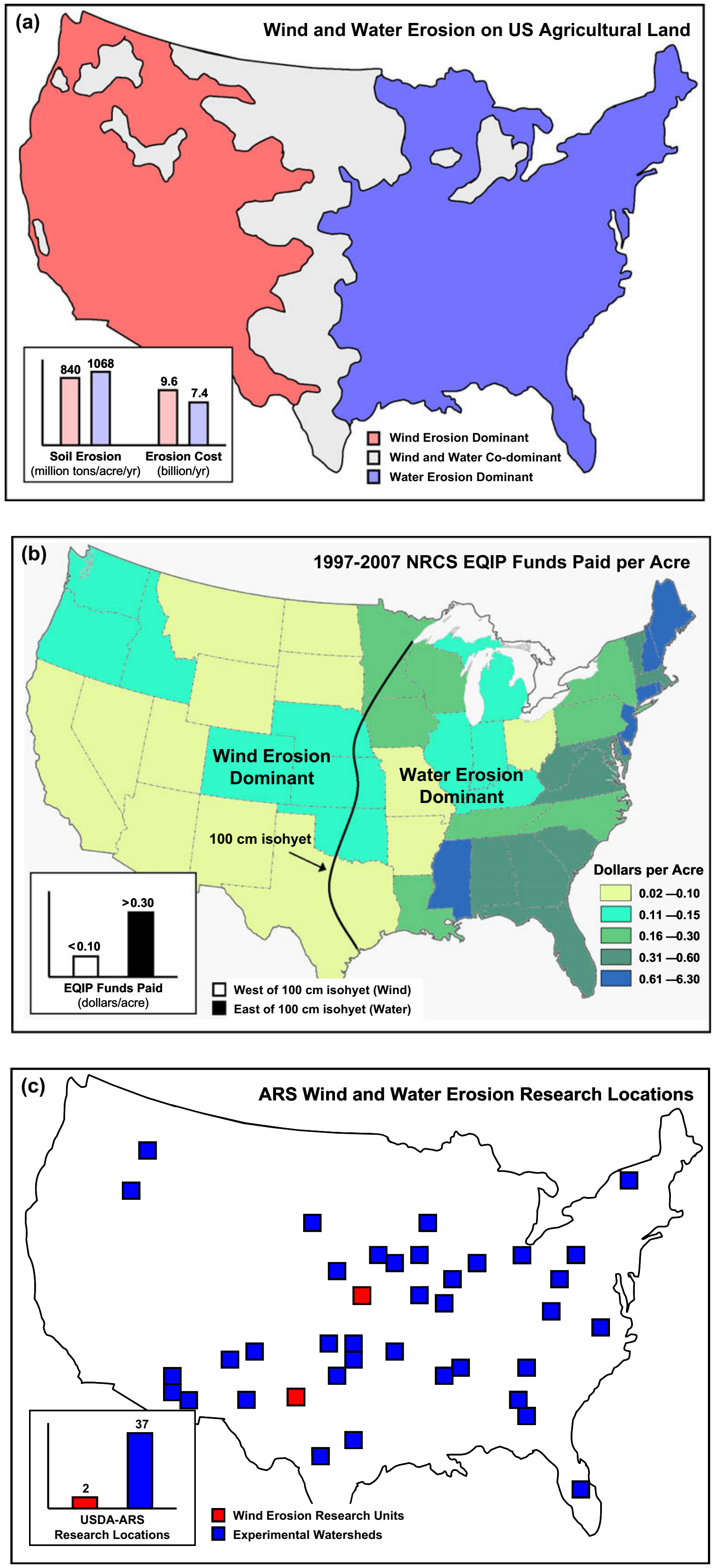

Fig. 5. (a) Agricultural areas (cropland and Conservation Reserve Program lands only) dominated by wind and water erosion are similar in magnitude and area (from NRCS, 2000a,b) and are similar with respect to total off-site costs of erosion (Pimentel et al., 1995). (b) The amount of EQIP funds spent on soil erosion and sediment control (from NRCS, 2008) is much greater in areas dominated by water erosion than in areas dominated by wind erosion. (c) Locations of the Agricultural Research Service sites focused on fluvial transport (experimental watersheds) and on aeolian transport (wind-erosion units).

Table 1
Key knowledge gaps about aeolian transport relative to fluvial transport.

Relative magnitudes across precipitation gradients	Total sediment transport from aeolian and fluvial processes is usually greatest in semiarid ecosystems relative to arid, subhumid, and humid ecosystems	Figs. 1a and 2a
	Aeolian transport is usually most sensitive to disturbance in semiarid ecosystems, whereas fluvial transport is usually most sensitive to disturbance in humid ecosystems because vegetation cover can be reduced from complete to nothing	Figs. 1b and 2b
Interactions	Aeolian and fluvial processes can be closely interrelated at intermediate scales (e.g., aeolian transport can prime fluvial transport; fluvial transport can concentrate or expose new sediment, increasing availability for aeolian transport; rainsplash can simultaneously affect both processes)	Fig. 3a
	Aeolian and fluvial processes are likely to exhibit maximum potential for interactions at small spatial and temporal scales; at large scales the processes are likely to be more decoupled because fluvial transport is unidirectional and concentrates sediment with increasing spatial scale, whereas aeolian transport is omni-directional and disperses sediment with increasing spatial scale	Fig. 3b
Management and economics	Investments in soil erosion and sediment control within the United States disproportionally match risks associated with wind and water erosion	Fig. 5a and b
	The amount of resources and number of research locations within the USDA Agricultural Research Service suggests that a disproportionate amount of resources is directed toward research related to fluvial processes	Fig. 5c

research, previously posed hypotheses, and available cost and management metrics. The key hypotheses that we present emerge from previous syntheses and recent research and provide both challenges and opportunities for aeolian researchers to more directly engage fluvial researchers and to enhance overall management effectiveness related to erosion. We suggest that addressing such a research agenda will be important scientifically and could provide a means for realigning research and management investments with relative magnitudes of wind and water erosion. Importantly, the implicit assumption that is made in most studies and assessments that wind and water erosion do not influence each other is one that should be explicitly tested. In conclusion, we suggest that land management that depends on soil surface stability in the face of changing land use and climate is unlikely to be effective unless we develop a more holistic understanding of not only aeolian transport and erosional processes alone but also of their potential interactions with fluvial transport and erosional processes.

Acknowledgements

This paper was developed with support of the Arizona Agricultural Experiment Station (DDB), the U.S. Department of Agriculture Cooperative State Research, Education, and Extension Service (JPF, DDB; CSREES 2005-38420-15809), the National Science Foundation (DDB, JPF; NSF-DEB 0816162), and the Department of Energy (JJW; DE-AC52-06NA25396). We thank D.J. Law for assistance.

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