Wind Impacts in Forests: Literature Review

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Wind has been described as a major natural disturbance in forest ecosystems (Mitchel, 2013). Primary wind impacts to forest include windthrow, wind-driven erosion, and evaporative losses of soil moisture. Among these impacts, a great deal of literature has focused on windthrow (a.k.a. blow down) in timber production and erosion, with less research focused on evaporative losses of soil moisture from wind.

Wind Erosion

According to a recent article by Duniway et al. (2019), wind erosion is one of the primary processes associated with the degradation of drylands in the US. Dust emissions caused by wind-erosion have a myriad of negative consequences, including economic impacts in the form of reduced agricultural productivity and property damage, human health impacts related to increased respiratory ailments from dust exposure and traffic accidents, and ecological impacts. Key ecological impacts of concern include more rapid melting of mountain snowpack leading to reduced water resources, impacts to vegetative productivity caused by the loss of fine soil particles associated with key nutrients for plant growth, and climate impacts as dust has been found to affect global climate via several mechanisms (Duniway et al, 2019; Miller et al., 2012). Climate feedbacks from dust emissions include, but are not limited to, the attenuation of sunlight, changes to cloud behavior which can lead to increased or decreased precipitation, changes in the land's ability to store CO2, further exacerbating effects of atmospheric CO2, and possibly the intensification and extension of drought conditions (Duniway et al, 2019). With these impacts in mind, it is important to consider the effects of land management practices in US drylands, especially given that a high proportion (approximately 1 in 3 acres) of these lands are managed as public lands (Duniway et al., 2019).

In the largest known record of field scale dust emissions for the southwest US, Flagg et al. (2014) evaluated dust emission rates across different plant communities while also taking into account land use history, physical site characteristics, and weather patterns across 85 sites in southeastern Utah. The study found that a combination of biotic, abiotic, and seasonal factors played a role in determining overall dust emission rates. Unsurprisingly, wind conditions were found to have a significant role in controlling the seasonal flux of sediment across all community types investigated, with mean peak wind speed exhibiting a strong positive correlation with sediment flux.

Additionally, plant community type, which the authors describe as a proxy for overall ground cover versus bare ground, was also a strong predictor of sediment flux. Plant communities in the Flagg et al. (2014) study were broadly categorized into four types: piñon-juniper (PJ) woodlands, sagebrush shrublands, blackbrush and ephedera shrublands, and perennial grasslands. Results showed that sites dominated by shrubs had higher sediment fluxes than grasslands and woodlands. This occurred even though PJ woodlands exhibit large bare spaces and low soil stability with high erosive potential. While tree density was not taken into account, this finding offers evidence that the structure of tall plants can buffer against wind erosion despite soil risk factors (Flagg et al., 2014). Abiotic factors including higher sand content, low soil aggregate stability, and large amounts of bare spaces between plants were all associated with higher sediment fluxes; however, these factors were found to contribute on finer spatial scales than vegetation and wind conditions (Flagg et al., 2014). The authors acknowledged that although it was not quantified within their study, extensive literature has proven that biological soil crusts aid in stabilizing surface soils and reducing wind erosion. Additionally, sediment flux was consistently higher in the spring than in summer or winter, which corresponded with peak wind speeds and event duration.

The complex interaction of climate, vegetation, soils, and soil erosion was further elucidated in a study by McAuliffe et al (2014) taking place in two small drainage basins in northwestern Arizona. At their sites, PJ woodlands dominate northern aspects which transition to shrub dominated vegetation on the more xeric southern aspects. Within these drainages, very pronounced differences existed between xeric and mesic aspects, with long term erosion rates being especially divergent. While xeric aspects were found to lose 14-23 cm per century in one basin and up to 50 cm per century in the other, mesic aspects had no net soil losses over the last several centuries. Xeric aspects were also found to have thinner soils and higher amount of exposed bedrock, which together characterize mesic aspects as “conserving” and xeric aspects and “non-conserving” in regard to their ability to retain water and soil (McAuliffe et al., (2014). Additionally, widespread exposure of roots on cliff rose indicate a continuous and relatively rapid slope denudation on xeric exposures, which was further supported by a higher frequency of dead trees on xeric aspects. The authors describe how these contrasts are further exacerbated by self-promoting feedbacks wherein loss of vegetation cover raises soil temperature, increases evaporative losses, and increases runoff and erosion leading to further soil loss which reduces the ability of plants to grow and survive on xeric aspects. Conversely, on mesic aspects, denser vegetation retains runoff, adds cohesion to soils and unconsolidated materials, and reduces overall loss of sediment (McAuliffe et a., 2014). The authors conclude that because soil temperature is the primary driver of evapotranspirative soil water loss and has a strong interconnectedness with weather, soil retention, vegetation and hydrology, even small temperature increases will likely hasten these ecotonal shifts favoring a further reduction in mesic and an expansion of xeric aspects in landscapes similar to those in the study.

Another area of research regarding wind erosion over the last decade is the role of fire in affecting the land's susceptibility to wind erosion. Considering the proposed impacts of increased drought and wind speeds from climate change in the Southwest, in addition to the history of fire suppression that has often created hazardous fuel conditions, the threat of intense wildfire is a growing concern in the region. As such, forest treatments including thinning and prescribed fire are increasingly being deployed to reduce wildfire risks.

Whether prescribed or natural, fire has been found to drive dramatic increases in wind-driven sediment losses (Karaban et al, 2021, Whicker et al, 2008, Delwiche, 2009). The intensity of soil loss has been found to directly relate to the amount of ground vegetation remaining at burned sites (Whicker, 2008; Delwiche, 2009; Williams et al., 2018). Karaban et al. (2021) investigated pile burning, broadcast burning, and mastication techniques in two SE Utah PJ woodlands over 2 years, finding that wind-driven sediment fluxes increased 11-fold and 58-fold respectively for pile and broadcast burning, while mastication did not have significant effects. When investigating impacts of prescribed fire and thinning in Ponderosa stands in the Jemez Mountains of northern New Mexico, Whicker et al. (2008) found that both methods had similar effects of elevating wind-erosion. However, thinning methods used in this study were highly mechanized and included the use of track-mounted branch fellers, skidders, and stroke delimbers, as well as logging trucks to remove the resulting wood products. While these studies occurred in different forest vegetation types, the opposing results regarding the effects of thinning demonstrate that methods affect the level of resulting wind erosion, as the Karaban study left wood chips on the ground to cover soils while the Whicker study removed woody biomass from thinned sites. In a study of the Milford Flat Fire area by Miller et al. (2012), modeling suggested that rather than wildfire itself, wind erosion was actually driven by changes to soil erodibility, plant cover, and upwind surface disturbance. Similarly, Karaban et al. (2021) found that the best predictor of soil loss included amount of bare soil, biocrust cover, herbaceous plant cover, and tree cover. However, no studies to date have directly investigated effects of different thinning technologies, nor in how spatial scale and pattern of burns affect wind-driven sediment losses. Increased wind erosion following wildfire has been found to follow strong temporal trends, with effects usually dissipating after groundcover vegetation can establish (Miller et al., 2012), which was found to reach background levels between 5-8 years following fires in the Colorado Front Range (Delwiche, 2009).

Several suggestions for mitigating wind erosion impacts following prescribed fire and thinning have been suggested in the literature. It is recognized that thinning methods that leave slash on the ground are preferable (Whicker, 2008; Grover, 2021), as is reducing overall disturbance associated with treatments (Karaban et al., 2021; Whicker et al., 2008) and timing treatments to reduce organic ground cover destruction (Delwiche, 2009). It is also recommended to consider soil properties, landscape settings, and the spatial extent and connectivity of surface disturbance (Miller et al., 2012). Karaban et al., (2021) suggest that in flat, semi-arid woodlands such as those in their study, managers should aim to maintain 5% tree cover and at least 10% herbaceous cover and less than 45% bare soil to protect from erosion, and more generally, that managers should consider site-specific dominant erosional processes and soil stability and plant cover thresholds when planning fuel treatments. Additionally, erosion fencing utilized in the Miller et al., (2012) study was found to mitigate wind-erosion when installed perpendicular to prevailing winds until soil stabilizing plants were able to establish.

Several studies in the arid southwest have found that seeding alone is not an effective mitigation measure to combat soil loss following burning (Karaban et al., 2021; Miller et al., 2012; Delwiche, 2009). It has been found also that following both fire and mastication, exotic or invasive plants may colonize the recently disturbed sites (Karaban, 2021; Miller, 2012). Therefore, it is still prudent to sow native seed after fuel treatments to reduce invasion susceptibility. However, additional practices that maximize soil coverage immediately following a burn (such as mulch or slash addition and/or maintaining vegetative coverage above a certain threshold) are needed to minimize wind erosion.

Blowdown

It is crucial to consider the risk of blowdown in forest management, as blowdown has been found to increase susceptibility of forests to secondary disturbances including beetle outbreaks (Schmid and Frye, 1977) and fire (Mitchel, 2013). Forest susceptibility to blowdown has been found to be dependent on the interaction of site topography, soils, biotic communities, climate, (Mitchell, 2013), and site disturbance history (Kulakowski and Veblen, 2002). In a review of tree blowdown by Mitchell (2013), the author poses several "diagnostic considerations" relating to the interaction of these factors and how they can be used to evaluate blowdown patterns. These are referenced below following the relevant sections.

Mitchell's (2013) review investigated the effects of topographic exposure to wind, finding that trees located in windward locations adapt to this environment with crown shaping, height growth suppression, and by forming local tree lines, while trees on the lee slope tend to be more vulnerable without these adaptations. A study by Kulakowski and Veblen, (2002) focused on a severe windstorm in northwest Colorado and had opposing results, finding that stands on easterly slopes were more susceptible to windthrow from primarily easterly winds in the region. In addition, Kulakowski and Veblen, (2002) also found greater susceptibility at higher elevations and along ridgelines, due to a higher exposure to wind. These opposing results may be due to the high severity of winds in the Colorado study, as adaptations which may increase resistance to damage may only be evident under low to moderate speed winds (Thompson 1983). Understanding the site-specific conditions and interactions of properties including slope, aspect, soils moisture, and canopy structure is critical to assessing blowdown susceptibility.

> **Mitchell's Diagnostic Consideration:** "In evaluating wind exposure in complex terrain, consider whether a given terrain unit is exposed or sheltered from routine winds and how this will affect the acclimation of trees and stands to wind. Then consider how exposure may change during extreme wind conditions. Finally, consider the effects of slope angle and ground concavity on drainage, since this will affect soil moisture during extreme weather events."

Mitchell (2013) goes on to describe how stand features affect blow down susceptibility, describing how trees grown at high densities have more slender trunks creating an upward shift in the center of gravity making the trees unstable. Additionally, while stands with dense and uniform canopies may experience less wind loading, the uniform crown size in combination with this shift in center of gravity may lead to a proliferation of damage from newly exposed stand edges during intense windstorms. Heterogeneity in tree forms, however, creates greater stability and enhances the likelihood of survival during such events (Mitchell 2013). It is also important to understand the impacts of forest gaps and gap size, as it has been found that even slight increases in the proportion of forest gaps can significantly increase wind damage due to increased wind speeds (Zeng et al., 2010). This also relates to the site's disturbance history, as newly created gaps from previous disturbance (windfall, wildfire, or mass die-off events) result in a more vulnerable forest surrounding the gap (Kulakowski and Veblen, 2002).

> **Mitchell's Diagnostic Consideration:** "In evaluating stand-level wind- firmness, or conducting storm post-mortems, consider whether individual trees are well acclimated to above-canopy winds, and whether if destabilized during a storm they would fall and destabilize neighboring trees, enabling propagation of damage through the stand during a storm."

Mitchell (2013) also investigated the effects of soils on blowdown susceptibility, finding that stands with shallow or poorly drained soils are often the site of blow downs, and that blow downs are more common among fertile than low-fertility sites. He described that while deep soils can support tall dense stands that are relatively stable, sites with shallow and fertile soils produce highly susceptible stands because height growth and canopy density are promoted but root anchorage is limited. The susceptibility is also closely tied to weather conditions, especially precipitation that occurs prior to or concurrent with windstorms which further promotes blow down. Additionally, the intensity and frequency of wind events are also important determinants of damage severity (Mitchell 2013).

> **Mitchell's Diagnostic Considerations**: "In evaluating soil effects on stand stability, consider – is the soil fertile enough to support a closed canopied stand in which trees grow tall and compete for growing space? Does the soil restrict anchorage, or become saturated during severe weather events?"
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> "In evaluating regional climate, consider the return period of high wind events, their coincidence with high rainfall or wet soils, dominant wind directions and the differential between severe weather conditions and routine wind conditions."

Mitchell (2013) concluded that the windthrow patterns can be best understood by considering the interaction between regional climate and terrain, evaluating stand stability in terms of adapted growth, and examining soils through their effects on stand productivity and root anchorage.

Evapotranspiration

In arid or semiarid settings, bare soil evaporation has been found to account for more than half of evapotranspiration (Huxman et al., 2005). While it is well known that wind is a significant driver of evaporative soil moisture losses (Davarzani, 2014), little literature focused on how management of forests can reduce these losses. Generally, it has been found that reducing bare ground, increasing presence of litter (Villegas et al., 2010), and increasing canopy cover from trees (Wallace et al., 1999) are all effective means to slow evaporation rates.

Conclusions

While each of the three wind impacts described here have their own suite of risk factors, many of the same overarching principles apply to evaluating and mitigating their risks. Namely, land managers should consider the interactions of site properties including biotic and soil conditions, landscape setting, and local climate to better understand and manage for wind impacts. Key practices to reduce these impacts include maintaining optimal soil coverage and finding the optimal maximum canopy gap size of forest openings given a site's terrain characteristics. This will be especially vital to address given the expected impacts of climate change in the southwest, including more frequent and extreme storms and increasing aridity (Duniway et al., 2019).

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