The Environmental Impacts of Contemporary, High-Severity Wildfires on Forest Ecology, Air Pollution, Soil Degradation, and Water Pollution

A Literature Review

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Introduction

The fastest growing land use type in the US is the Wildland-Urban Interface (WUI)-loosely defined as the area where houses meet or intermingle with undeveloped wildland vegetation (Radeloff et al. 2005). This growth presents a challenge to urban and emergency planners because of land use types, the WUI faces the greatest risk of wildfire due to the adjacency of human development and flammable vegetation (Radeloff et al. 2005, Radeloff et al. 2018). The risk wildfires pose to the built environment may provide the attention needed to advance wildfire mitigation and forest restoration thereby reducing the damage to natural systems and the built environment. This could be accomplished through existing environmental laws such as the Clean Air Act (Williams 2021). However, approaching wildfire and forest management through environmental laws for the purpose of lessening risk to the built environment first necessitates an understanding of the *environmental* impacts caused by wildfires. To this end, this review investigates and describes the literature surrounding the environmental impacts of wildfire related to four aspects of the environment: forest ecology, air pollution, soil degradation, and water quality.

Wildfires play a vital part in maintaining the health of forests and forest ecology. Healthy wildfires-those of low to medium severity-clear low-growing underbrush and remove debris which simultaneously provides more nutrients to the soil and reduces nutrient competition with healthy, established trees (Agee and Skinner 2005, Snow 2022). Low to medium severity fires also reduce the risk of high severity fires by removing built up fuel and by removing fire ladders-vegetation growing near or onto the trunk of a tree that allows fire to climb the tree and reach the canopy, leading to a more destructive crown fire (Agee and Skinner 2005, Snow 2022). Healthy wildfires change the density of the forest, leaving behind fewer, but larger and older trees and creating open space. This open space has cascading benefits on wildlife (Snow 2022).

However, due to ill-guided suppression tactics, increasing severity of droughts brought on by global climate change, and development near and within forestlands, wildfires regimes have changed (Abatzoglou and Williams 2016, Balch et al. 2017, Covington and Moore 1994, Hagmann et al. 2021, Jolly et al. 2015). Wildfires have increased in severity, range, and seasonal duration, particularly in the US West and Southwest (Balch et al. 2017, Dennison et al. 2014, Singleton et al. 2019). A century of wildfire suppression has led to an abundance of fuel in western forests, increasing fire severity and leaving behind an untenable forest ecosystem (Covington and Moore 1994, Hagmann et al. 2021, Singleton et al. 2019). Extended droughts and summer conditions have changed the temporal characteristics of fire regimes and have allowed for a longer fire season (Abatzoglou and Williams 2016, Jolly et al. 2015). And development in an around forests has increased wildfire ignition rates, as most wildfires are started by humans (Balch et al. 2017, Radeloff et al. 2018).

Fires that occur under these conditions, generally referred to as *contemporary* wildfires, burn large areas and at a high severity, resulting sparse or non-existent natural regeneration (Prichard et al. 2021). Beyond the immediate impacts to forests and forest ecology, there are several other mechanisms through which contemporary wildfires impact the environment, including air pollution, soil degradation, and water quality degradation.

Post-burn forest ecology

These changes in the fire regime have stressed forests and forest ecosystems. Where healthy, low to medium severity wildfires once brought about conditions beneficial for forest ecosystems, contemporary, high-severity wildfires further degrade forests and forest ecosystems (Agee and Skinner 2005, Hagmann et al. 2022). One of the effects of contemporary wildfire is that the large blazes reduce both the overall structural and compositional heterogeneity of forests (Cassell et al. 2019). Where forests were once composed large, dispersed, fire-resistant trees intermixed with dense groups of small diameter trees, they are now primarily high-density forests composed of mainly small diameter trees (Cassell et al. 2019). This shift in structural heterogeneity increases the continuity of vertical and horizontal fuels resulting in higher tree mortality when fires do occur (Agee and Skinner 2005). The reduction in species heterogeneity, facilitated by catastrophic wildfire that leaves few if any trees remaining, increases overall forest susceptibility to insects and disease (Cassell et al. 2019).

The change in structural composition, which was brought about by the century of fire suppression and intensive timber management, has left fire-excluded forests in a state far departed from the once fire resistant and drought resilient forests of the western US (Hagmann et al. 2022). Higher tree densities dominated by younger and smaller trees create high-risk conditions which reduce the options for management or restoration (Hagmann et al. 2022). This brings about the question of how to effectively manage modern forests and whether contemporary fires might eventually reduce fuel loads and help to restore forests as do prescribed burns and mechanical thinning. The problem with the contemporary fires is that current wildfire management policies call for aggressive suppression techniques and thus the fires that do escape suppression often occur during extreme fire conditions (Prichard et al. 2021). These unplanned fires in fire-excluded landscapes that occur during extreme fire conditions have a greater burn area and a higher burn severity than prescribed burns carried out to restore forests (Prichard et al. 2021). The greater severity of these fires often leaves few trees alive and the larger burn areas mean that seed sources for forest regeneration are further away, resulting in sparse or non-existent natural regeneration (Prichard et al. 2021).

Contemporary Wildfire Impacts on Air Quality

High-severity fires in fire-excluded forests reduce both structural and compositional heterogeneity of forest trees, resulting in forests that are more prone to fire, insects, and disease (Cassell et al. 2019). These changes in forest structure-created by a century of fire suppression and logging practices-create high-risk forests that are difficult to manage (Hagmann et al. 2022). However, management is crucial because fires that do occur under these conditions burn large areas and at a high severity (Prichard et al. 2021). These contemporary, high-severity wildfires that burn large areas can cause widespread and severe air pollution that poses risk to human health (Jaffe et al. 2020, Liu et al. 2015, McCaffrey et al. 2022).

Smoke from wildfires contains both particulate matter (PM) and gaseous compounds, and is more complex than industrial smoke (Jaffe et al. 2020). The gaseous compounds include nitrogen oxides (NOx), carbon monoxide (CO), methane (CH_4), and hundreds of volatile organic compounds (VOCs) and oxygenated VOCs (Jaffe et al. 2020). Furthermore, emissions from wildfires vary based on the type and amount of fuel, and by the meteorological conditions present during the time of the fire (Prichard et al. 2019).

Smoke from wildfires can be detected hundreds of miles away from the source, especially $PM_{2.5}$ and PM_{10}, which are tracked due to their risk to human health and their relevance to National Ambient Air Quality Standards (NAAQS) (Jaffe et al. 2020). The annual area burned by wildfires is increasing in the US and in recent years, smoke from these fires has caused severe concentrations of $PM_{2.5}$ and Ozone, with some cities in the western US measuring their highest recorded concentration of $PM_{2.5}$ during the wildfire seasons of 2017 and 2018 (Calkin et al. 2005, Jaffe et al. 2020). The most frequently studied air pollutant associated with wildfires is PM_{10}, which has been shown to be up to 10 times higher during wildfires than non-fire periods for the same locations (Liu et al. 2015).

Particulate matter is widely studied because it is the component of wildfire smoke that poses the greatest risk to human health (McCaffrey et al. 2022). $PM_{2.5}$ is of particular concern to immediate and long-term health because the size of $PM_{2.5}$ particles allows them to pass through the nose and throat and into the lungs, causing serious health effects (McCaffrey et al. 2022). While it is difficult to separate the health effects of wildfire from other airborne pollutants, wildfire is associated with increased risk of respiratory and cardiovascular diseases, and this effect is elevated for children and the elderly (Liu et al. 2015).

Wildfire Impacts on Soil Quality

Similar to the impacts on forest ecology, the wildfire impacts on soil characteristics vary greatly between contemporary, high intensity fires and low to moderate intensity fires (Agbeshie et al. 2022). Low to moderate intensity fires generally result in ash deposition on soil surfaces which benefits soil chemistry by increasing available nutrients (Agbeshie et al. 2022). High intensity fires result in negative impacts to soil chemistry. High intensity fires cause nutrient volatilization, particularly Nitrogen, and complete combustion of organic matter, which results in little ash deposition (Agbeshie et al. 2022). The temperatures associated with high intensity wildfires also effect soil structure by degrading soil aggregate stability, increasing soil bulk density, and increasing soil hydrophobicity, each of which contribute to decreased infiltration and increased erosion (Agbeshie et al. 2022). Soil is considered a non-renewable resource on human timescales because of its vulnerability and slow rate of formation, which compounds the impacts of soil degradation by high severity wildfires (Lal 2015).

Aside from the impacts to soil chemistry and structure, wildfire impacts soil microbial activity, one of the key components of soil (Ginzburg and Steinberger 2012). Microbes in soil produce extracellular enzymes that aid in the decomposition of organic matter, which releases essential nutrients for plant uptake (Holden and Treseder 2013). Contemporary, high intensity, wildfire causes extracellular enzyme activity (EEA) to decrease by 20%-40% by reducing soil microbial biomass and through the volatilization of nitrogen (Zhou et al. 2022).

The wildfire impacts to soil structure create a vulnerability to erosion, which can result in considerable hydrological and geomorphological change (Shakesby and Doerr 2006). The reduction in soil aggregate stability and increase in soil bulk density combine to decrease infiltration and increase rainsplash detachment (Agbeshie et al. 2022, Shakesby and Doerr 2006). Decreased infiltration leads to higher overland flow which, together with increased rainsplash detachment, contributes to post-fire soil erosion by precipitation (Shakesby and Doerr 2006). This erosion has been shown to result in elevated, and in some cases, large post-fire soil losses (Shakesby and Doerr 2006). The amount of soil loss on post-burn hillslopes is broadly correlated with the severity of the fire (Shakesby and Doerr 2006).

Contemporary Wildfire Impacts on Water Quality

Contemporary, high severity, wildfires have direct impacts on both soil chemistry and soil structure, and secondary impacts on water quality (Agbeshie et al. 2022, Paul et al. 2022). The temperatures associated with high intensity wildfires promote complete combustion of organic matter which deprives the soil of nutrient rich ash deposits as well as volatizing existing soil nutrients such as nitrogen (Agbeshie et al. 2022). However, it is the changes to soil structure that have secondary impacts on water quality. High intensity wildfires reduce soil aggregate stability and increase soil bulk density, both of which contribute to a higher runoff and the potential degradation of water quality (Agbeshie et al. 2022, Paul et al. 2022).

While the measurements are complicated by post-fire alterations to the local climate, as well as other post-fire changes in the landscape, it is generally accepted that higher runoff on post-burn hillsides produces higher stream flows in the catchment area (Hallema et al. 2017, Shakesby and Doerr 2006). Wildfires alter streamflow response to precipitation, and this effect has been shown to significantly impact high flows, low flows, and annual water yields in Southern California, with some streams shifting to temporarily to perennial flow after a wildfire (Hallema et al. 2017).

Increased erosion from post-burn landscapes coupled with this increased streamflow can mobilize a variety of pollutants that threaten the quality of drinking water sources (Dahm et al. 2015, Hohner et al 2019, Paul et al. 2022, Smith et al. 2011). These pollutants include sediment, dissolved organic compounds, and metals (Dahm et al. 2015, Hohner et al 2019, Paul et al. 2022, Smith et al. 2011). Post fire rainfall erodes ash and soil from landscapes and significantly increases turbidity, nutrient, and dissolved organic carbon (DOC) levels in streams and surface waters (Hohner et al. 2019). Though less studied, high levels of trace elements such as Fe, Mn, As, Cr. Al, Ba, and Pb have also been associated with post-burn runoff, especially in areas with a history of mining (Smith et al. 2011).

These elevated levels negatively affect water quality and pose challenges to water providers. There is also evidence that these water quality impacts may persist after high intensity fires, at least until vegetative recovery can provide soil stability (Hohner et al. 2019). In some cases, DOC and nitrogen levels have remained elevated for up to 15 years (Hohner et al. 2019). Along with this temporal reach, it has been shown that the water quality effects of post-burn landscapes can extend 50km downstream, though the spatial reach can vary widely depending on the post-burn landscape (Dahm et al. 2019). Forest watersheds serve as water supplies for many small and large communities, and these watersheds are vulnerable to the effects of post-burn runoff which threaten water quality (Hohner et al. 2019, Smith et al. 2011).

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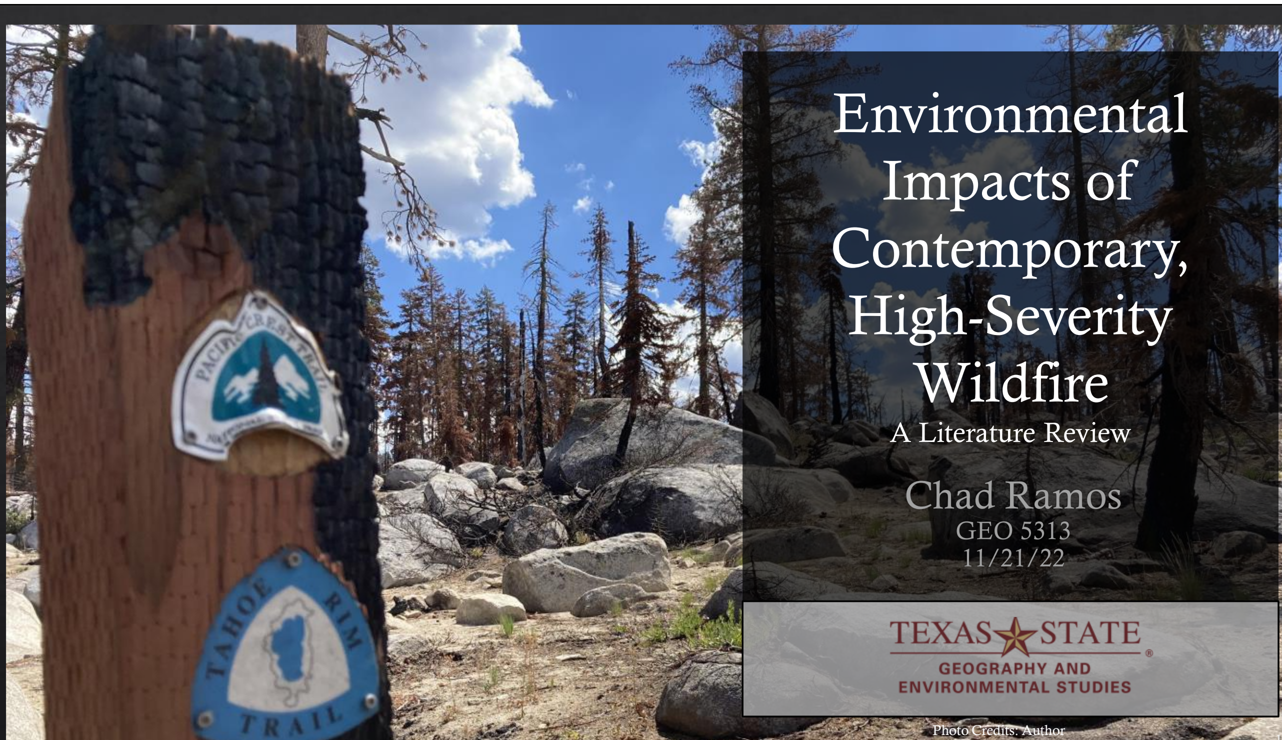

Environmental Impacts of Contemporary, High-Severity Wildfire

A Literature Review

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TEXAS STATE
GEOGRAPHY AND ENVIRONMENTAL STUDIES

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Introduction: *Contemporary* Wildfire and Changes to the Fire Regime

Due to ill-guided suppression tactics, increasing severity of droughts brought on by global climate change, and development near and within forestlands, wildfires regimes have changed (Abatzoglou and Williams 2016, Balch et al. 2017, Covington and Moore 1994, Hagmann et al. 2021, Jolly et al. 2015).

Wildfires have increased in severity, range, and seasonal duration, particularly in the US West and Southwest (Balch et al. 2017, Dennison et al. 2014, Singleton et al. 2019).

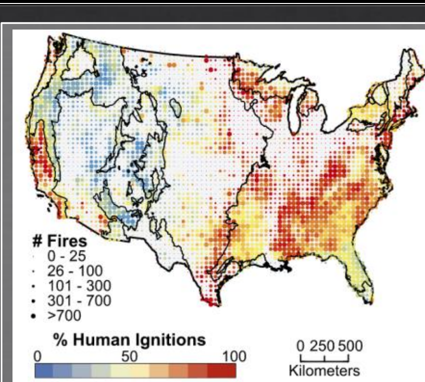


Fig. 1. The total number of wildfires (dot size) and the proportion started by humans (dot color: red indicating greater number of human started fires) within each 50 km × 50-km grid cell across the coterminous United States from 1992 to 2012. Black lines are ecoregion boundaries, as defined in the text.

From Balch et al. 2017

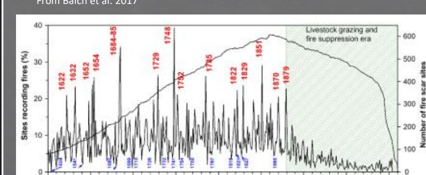
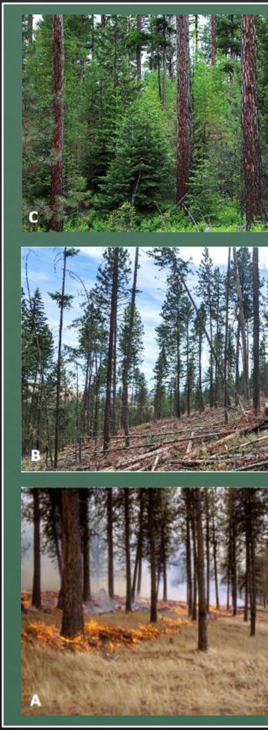


Fig. 1. Across western North America, fire frequency decreased substantially following expansion of colonization by Europeans, intensive livestock grazing, decimation of Indigenous populations and suppression of Indigenous burning in the late 19th century. The combined record of fire occurrence from more than 800 forest and woodland sites, the largest network of tree-ring-based fire-scar chronologies in the world, illustrates this regionwide decrease in fire frequency. Reprinted from Swetnam et al. (2016) with the author's permission.

From Hagmann et al. 2021

Theme 1: Impacts to Forest Ecology

- Contemporary, high-intensity wildfires **reduce both the structural and compositional heterogeneity** of forests, and this reduction in heterogeneity increases a forests susceptibility insects, disease, and subsequent fire (Cassell et al. 2019).
- Higher tree densities dominated by younger and smaller trees create high-risk conditions which reduce the options for management or restoration (Hagmann et al. 2022).
- Current management policies call for aggressive suppression techniques and therefore the fires that do escape suppression often occur during extreme fire conditions, **resulting in greater burn area and a higher burn severity** (Prichard et al. 2021).
- The severity of these fires often leaves few trees alive and the larger burn areas mean that **seed sources for forest regeneration are further away, resulting in sparse or non-existent natural regeneration** (Prichard et al. 2021).



From Prichard et al. 2021

Theme 2: Impacts to Air Quality

- Smoke from wildfires contains both particulate matter (PM) and hundreds of gaseous compounds **making it more complex than most industrial smoke** and can travel hundreds of miles (Jaffe et al. 2020).
- Emissions from wildfires vary based on the type and amount of fuel and by the meteorological conditions present during the time of the fire (Prichard et al. 2019).
- **PM has been shown to be up to 10x higher during wildfire** and is the component that poses the greatest health risk. $PM_{2.5}$ affects immediate and long-term health because their size allows them to pass through the nose and throat and into the lungs, causing serious health effects (Liu et al. 2015, McCaffrey 2022).
- While **it is difficult to separate the effects of wildfire from other airborne pollutants**, wildfire is associated with increased risk of respiratory and cardiovascular diseases, and this effect is elevated for children and the elderly (Liu et al. 2015).

Satellite View of Wildfire Smoke (above) and AQI measurements (below). From Jaffa et al. 2020

Figure 1. (A) (top) Observed smoke on September 4, 2017. (Top) NASA Worldview (https://worldview.earthdata.nasa.gov/) image showing fire hotspot detections from the VIIRS and MODIS satellite instruments, along with visible satellite imagery from the VIIRS instrument between 1200–1400 local time. Bright white areas are clouds; grayer areas are smoke. (B) (Bottom) 24-hour average $PM_{2.5}$, shown as the corresponding Air Quality Index (AQI) level category colors, based on surface PM sensors collected in the EPA's AirNow system (https://www.airnow.gov/).

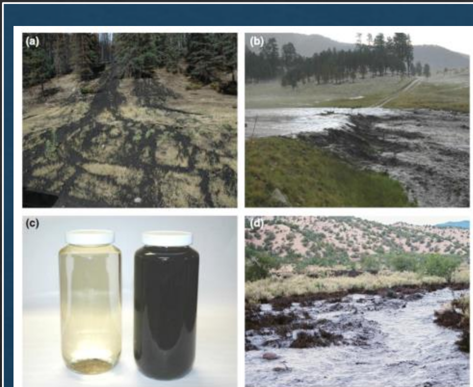
Theme 3: Soil Degradation

- Soil is considered a non-renewable resource on human timescales because of its vulnerability and slow rate of formation (Lal 2015).
- Low to moderate intensity fires generally result in ash deposition on soil surfaces which benefits **soil chemistry** while high intensity fires cause complete combustion of organic matter, nutrient volatilization-particularly Nitrogen-and little ash deposition (Agbeshie et al. 2022).
- High intensity wildfires also effect **soil structure** by degrading soil aggregate stability, increasing soil bulk density, and increasing soil hydrophobicity, which results in decreased infiltration and increased erosion (Agbeshie et al. 2022).
- Wildfire impacts **soil microbial life** causing extracellular enzyme activity (EEA) to decrease by 20%-40% through reduction of soil microbial biomass volatilization of nitrogen (Ginzburg and Steinberger 2012, Zhou et al. 2022).

Overland flow of burnt soil, Australia 2003 (Above) and rill formation after Buffalo Creek Fire, Denver CO, 2006. From Shakesby and Doerr 2006.

Theme 4: Impacts to Water Quality

- High intensity wildfires reduce soil aggregate stability and increase soil bulk density, **both of which contribute to a higher runoff and the potential degradation of water quality** (Agbeshie et al. 2022, Paul et al. 2022).
- It is generally accepted that higher runoff on post-burn hillsides produce higher streamflows in the watershed (Hallema et al. 2017, Shakesby and Doerr 2006).
- This increase in streamflow from post-burn landscapes can **mobilize a variety of pollutants**-including sediment, dissolved organic compounds, and metals-which threaten the quality of drinking water sources (Dahm et al. 2015, Hohner et al 2019, Paul et al. 2022, Smith et al. 2011).
- These water quality impacts may persist after high-intensity fires, at least until vegetative recovery can provide soil stability. In some cases DOC and nitrogen levels have remained elevated for up to 15 years (Hohner et al. 2019).



Runoff from Vallas Caldera National Preserve, New Mexico, during monsoon rains after the Las Conchas Fire

Conclusions

- The relationship between forest management practices and the resulting fire regime is complex with many feedback loops (Cassell et al. 2019).
- Contemporary, high-severity wildfires are becoming more common, and these damaging wildfires degrade the environment in ways that low to moderate severity wildfires do not. (Agbeshie et al. 2022, Cassell et al. 2019, Hagmann et al. 2022).
- The environmental damage caused by contemporary wildfires poses human health risks, particularly the impacts to air and water quality (Hohner et al 2019, Jaffe et al. 2020, Liu et al. 2015, McCaffrey et al. 2022, Paul et al. 2022, Smith et al. 2011).

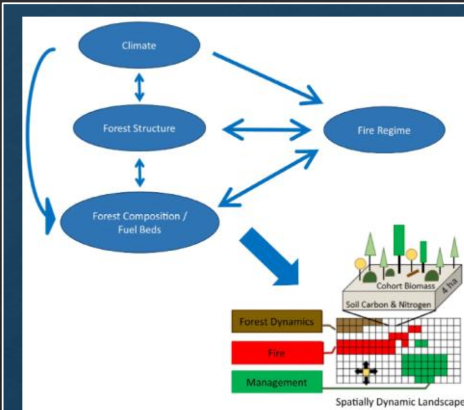


Fig. 3. Conceptual model and dynamic modeling design. Relationships among climate, forest structure, forest composition and fuel beds, and fire regimes are complex, operating at multiple temporal and spatial scales and with feedbacks. These inter-related factors are modeled in the LANDIS-II forest landscape model (FLM), which integrates forest successional dynamics with management and disturbance events across space and time. Processes occur within and across each 4-ha cell. The Net Ecosystem Carbon and Nitrogen Succession extension simulates complex biophysical above- and belowground processes.

From Cassell et al. 2019

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