ENVIRONMENTAL RESEARCH
LETTERS

The role of terrain-mediated hydroclimate in vegetation recovery after wildfire

To cite this article: Ryan W Webb *et al* 2023 *Environ. Res. Lett.* **18** 064036

ENVIRONMENTAL RESEARCH
LETTERS

CrossMark

OPEN ACCESS

RECEIVED
23 January 2023

REVISED
15 May 2023

ACCEPTED FOR PUBLICATION
23 May 2023

PUBLISHED
2 June 2023

LETTER

The role of terrain-mediated hydroclimate in vegetation recovery after wildfire

Ryan W Webb[1,*], **Marcy E Litvak**[2] and **Paul D Brooks**[3]

[1] Department of Civil and Architectural Engineering and Construction Management, University of Wyoming, Laramie, WY 82071, United States of America
[2] Department of Biology, University of New Mexico, Albuquerque, NM 87131, United States of America
[3] Geology & Geophysics, University of Utah, Salt Lake City, UT 84112, United States of America
* Author to whom any correspondence should be addressed.

E-mail: Ryan.Webb@uwyo.edu

Keywords: wildfire, forest recovery, plant available water, hydrologic redistribution

Abstract

Throughout communities and ecosystems both within and downstream of mountain forests, there is an increasing risk of wildfire. After a wildfire, stakeholder management will vary depending on the rate and spatial heterogeneity of forest re-establishment. However, forest re-establishment and recovery after a wildfire is closely linked to interactions between the temporal evolution of plant-available water (PAW) and spatial patterns in available energy. Therefore, we propose a conceptual model that describes spatial heterogeneity in long-term watershed recovery rate as a function of topographically-mediated interactions between available energy and the movement of water in the subsurface (i.e. subsurface hydrologic redistribution). As vegetation becomes re-established across a burned landscape in response to topographic and subsurface controls on water and energy, canopies shade the ground surface and reduce wind speed creating positive feedbacks that increase PAW. Furthermore, slope aspect differentially impacts the spatial patterns in regrowth and re-establishment. South aspect slopes receive high solar radiation, and consequently are warmer and drier, with lower standing biomass and greater drought stress and mortality compared to north aspect slopes. To date, most assessments of these impacts have taken a bulk approach, or an implicitly one-dimensional conceptual approach that does not include spatial heterogeneity in hydroclimate influenced by topography and vegetation. The presented conceptual model sets a starting point to further our understanding of the spatio-temporal evolution of PAW storage, energy availability, and vegetation re-establishment and survival in forested catchments after a wildfire. The model also provides a template for collaboration with diverse stakeholders to aid the co-production of next generation management tools to mitigate the negative impacts of future wildfires.

1. Introduction

Wildfire impacts on water resources are an increasing risk for communities and ecosystems in and downstream of mountain forests. Climate change has increased the frequency and burned area of wildfire in the western US over recent decades, altering the land surface energy balance resulting in surprising impacts on mountain snowpacks, ecosystem water availability, and streamflow generation (Kampf *et al* 2022). While the immediate impacts of fire on air quality, carbon storage, peak streamflow, and sediment delivery are well quantified, the long-term impacts are poorly understood (Wine *et al* 2018). In large part, this long-term uncertainty arises from spatial and temporal heterogeneity with respect to if and how vegetation recovers from disturbance in a warmer and likely drier climate where water limitation becomes more widespread, especially during late summer. Because vegetation both responds to and alters local hydroclimate, predicting recovery requires more complex and nuanced representations of the water cycle in complex terrain. Here, we review what is known and present a new conceptual model about terrain-mediated interactions between water, energy, and vegetation that can be expected to result in spatial heterogeneity in forest recovery and water resources in the western US.

As climate change increases the frequency, duration, and area under water stress, forest re-establishment and recovery after a wildfire will be closely linked to interactions between the temporal evolution of plant-available water (PAW) and spatial patterns in available energy (Brooks *et al* 2015, Fan *et al* 2019). High intensity wildfires remove surface vegetation and soil organic matter, leaving landscapes barren. The removal of organic matter and development of hydrophobic compounds alters the structure of the soil reducing infiltration and decreasing surface water storage. Consequently, immediately following a wildfire the landscape is prone to: (a) high spatial variability in infiltration (Onda *et al* 2008), (b) increased runoff response to input (Moody *et al* 2008), and the resulting (c) high rates of erosion which rapidly changes the physiography of the landscape (Kampf *et al* 2016). The altered geomorphology creates spatial and temporal patterns of hydrologic, sediment, and nutrient connectivity different from that of the pre-burn landscape. While these short-term responses have been studied at the plot (Benavides-Solorio and MacDonald 2001), hillslope (Schmeer *et al* 2018), and watershed scales (Saxe *et al* 2018), few studies have considered how these changes influence PAW storage across complex terrain at longer-term timescales.

We propose a conceptual model that describes spatial heterogeneity in long-term watershed recovery rate as a function of topographically-mediated interactions between available energy and the movement and storage of water in the shallow subsurface (i.e. subsurface hydrologic redistribution). Subsurface hydrologic redistribution acts as the connection between short- and long-term recovery timescales because it controls the distribution of PAW across complex terrain (McNamara *et al* 2005, Hwang *et al* 2012, McGuire *et al* 2018). The distribution of PAW then controls the spatial patterns of vegetation establishment and survival after a wildfire (e.g. Rodriguez-Iturbe 2000, Litaor *et al* 2008, Zapata-Rios *et al* 2015, Boisramé *et al* 2018). Spatially variable and temporally dynamic subsurface hydrologic redistribution has only recently been incorporated into predictive ecohydrological models. We argue that expansion of work in this area is required for models to get the ‘right answers for the right reasons’ (Kirchner 2006). In particular, understanding the temporally and spatially variable evolution of PAW after a wildfire will improve predictive capabilities on (1) how and where seedlings establish in the short term, and (2) the likelihood of seedling successful re-establishment and survival across dry years which are likely to become more frequent in a warming climate.

2. Hydrologic redistribution and PAW heterogeneity

The processes that control the post-wildfire spatial heterogeneity of water availability in complex terrain determines the patterns of long-term biomass accumulation (Swetnam *et al* 2017, Boisramé *et al* 2018), annual gross primary production (Tai *et al* 2021), and vegetation resilience to drought and insect attack (Tai *et al* 2021). These patterns are widespread throughout western US forests and are driven by subsurface hydrological redistribution from ridgeline to valley and at locations where local slope decreases (Rodriguez-Iturbe 2000, Litaor *et al* 2008, Zapata-Rios *et al* 2015, Swetnam *et al* 2017, Boisramé *et al* 2018). Similarly, antecedent soil moisture influences the partitioning of incoming precipitation amongst runoff, groundwater recharge, and evapotranspiration (e.g. Hwang *et al* 2012). The interactions between spatially variable and temporally dynamic subsurface hydrologic redistribution and topographically-driven patterns in energy availability have only recently begun to be incorporated into ecohydrologic models. Thus, the influence of these processes has yet to be fully explored in relation to vegetation re-establishment after a wildfire.

Many ecohydrologic studies have investigated post-wildfire recovery as bulk responses across scales (i.e. plot to watershed). This implicit one-dimensional conceptual model of a system likely lacks transferability to other locations due to differences in complex physiographic characteristics that influence hydroclimate experienced by vegetation during recovery. Topography complicates the post-wildfire recovery processes through the redistribution of water both above and below the ground surface. Mountain snowpack is often redistributed from exposed areas and deposited on leeward slopes or where physical wind breaks occur such as surviving vegetation. During spring snowmelt, increased infiltration occurs where snow accumulates on leeward slopes, solar shaded areas, and the leeward sides of forest stands (Musselman *et al* 2012, Broxton *et al* 2015, Harpold *et al* 2015, Webb 2017, Webb *et al* 2020). Following spring snowmelt, rain events create an additional distinct infiltration pattern from runoff and run-on around vegetation driven largely by gravity flow and upslope contributing areas (Hwang *et al* 2012, Rossi *et al* 2018). However, the seasonally variable patterns of water input to the system also has seasonally varying output associated with the increased demand during the growing season. These complex processes of spatially and temporally variable patterns of water input, subsurface hydrologic redistribution, and water output result in spatially heterogeneous distribution of PAW and energy availability across a landscape.

As vegetation re-establishes across a burned landscape in response to topographic and subsurface controls on PAW, inputs of organic matter and increases in surface roughness promote infiltration of upslope runoff, limit erosion (Boisramé *et al* 2018), and increase the rate of soil development (Brooks *et al* 2015) creating positive feedbacks that increase PAW storage. Vegetation regrowth in these favored locations alter boundary layer characteristics that influence evaporation from the ground surface, specifically reducing wind speed and shading the ground surface (Gouttevin *et al* 2015, Rossi *et al* 2018). During winter, shading and sheltering of the snowpack by regrowth reduces sublimation and evaporation, increasing the snow volume in these locations (Rinehart *et al* 2008, Musselman *et al* 2012). This shading also delays the onset of snowmelt and slows the rate of melt, thus shading alters the volume and timing of soil water input (Moeser *et al* 2020). During summer, shading and wind sheltering of the ground surface limits evaporation further, indirectly increasing PAW and decreasing the ratio of evaporation to transpiration. Consequently, there is the potential for positive feedback where initial vegetation re-establishment in topographically favored micro-hydroclimates increases the likelihood of longer-term survival.

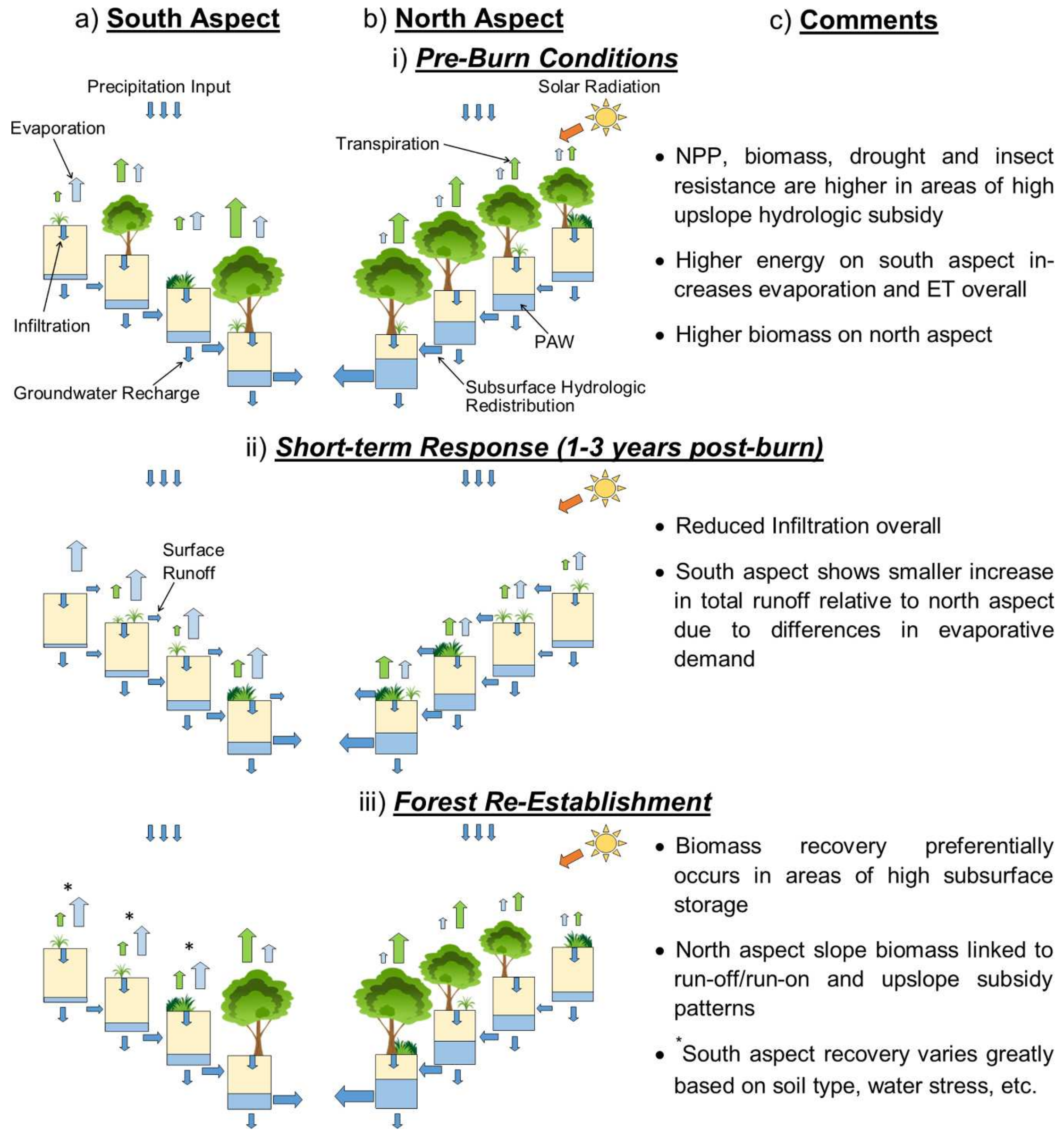
Furthermore, slope aspect should differentially impact the spatial patterns in regrowth and re-establishment via topographically driven hydrologic redistribution. In the northern Hemisphere, south and west aspect slopes receive high solar radiation, and consequently are warmer and drier, with lower standing biomass (Wilcox *et al* 2003, Swetnam *et al* 2017, Boisramé *et al* 2018) and greater drought stress and mortality (Tai *et al* 2021) compared to north and east aspect slopes. Thus, topographically driven hydrologic subsidy should result in greater spatial variability in vegetation recovery in higher energy south and west aspect environments than on lower energy north and east aspect slopes or slopes shaded by adjacent topography. This is particularly important in predicting rates and trajectory of recovery in a watershed from wildfire in drought conditions compared to the climate when pre-burn vegetation patterns were established.

3. Conceptual model and testable hypothesis

The inferential evidence for hydrologic redistribution in complex terrain driving ecosystem structure and function is strong and widespread. These observations present both a notable challenge and opportunity to predict vegetation response and recovery after wildfire in complex terrain. To address this challenge, we propose a conceptual model that includes interactions between terrain-mediated subsurface hydrologic redistribution, energy availability, and vegetation structure (e.g. Rinehart *et al* 2008, Thompson *et al* 2011, Swetnam *et al* 2017) that differentially influences both short-term responses and long-term forest re-establishment after a wildfire (figure 1). Thus, we present figure 1 as a new conceptual model of topographically driven hydrologically redistributed PAW and vegetation recovery after a wildfire for generic hillslopes. Just as productivity, species composition, and drought response vary in undisturbed forests, we expect that the vegetation recovery rate and spatial heterogeneity will vary predictably between a southerly aspect (figure 1(a)) and northerly aspect (figure 1(b)) due to differences in energy availability. It is important to note that the influence of complex terrain and resulting distribution of PAW also alters the timeline of vegetation re-establishment and survival depending on physiographic parameters yet to be fully constrained. Therefore, we also present a timeline of four stages for post-wildfire vegetation recovery and associated ecohydrologic impacts in the form of a testable vegetation recovery hypothesis (table 1).

This testable hypothesis focuses on the temporal evolution of vegetation recovery driven by interactions between spatial patterns in water availability as a function of slope position, spatial patterns in available energy related to aspect, and vegetation influences on local microclimate. Specifically, the proposed four stage vegetation recovery focuses on the ecohydrologic response of evaporation, transpiration, canopy interception, infiltration, soil moisture, and energy demand reaching the ground surface. As vegetation establishes and survives, tree canopies will increase interception of incoming precipitation. However, the shading of radiation and increase in surface roughness overcomes these interception losses, resulting in an increase in PAW as previously described (Musselman *et al* 2008, Veatch *et al* 2009, O'Donnell *et al* 2021). Initial ground cover recovery (Stage 2) will be shallow rooted vegetation that utilizes shallow soil moisture, allowing deeper soil moisture retention (Tromp-van Meerveld and McDonnell 2006). As saplings establish (Stage 3), vegetation will access PAW from both shallow and deep soil moisture. We hypothesize that vegetation adolescence (Stage 4) will take approximately 5–10 years and the long-term spatial patterns of vegetation will emerge during this stage. However, long-term recovery beyond 10 years is an outstanding question due to uncertainty with respect to how vegetation recovers in a warmer, drier climate.

One example of our conceptual model and timeline is the recovery from the Thompson Ridge fire which occurred during the summer of 2013 in the Jemez mountains, New Mexico USA. Vegetation recovery from this fire has occurred on the north aspect but remains lacking on south aspect slopes



- NPP, biomass, drought and insect resistance are higher in areas of high upslope hydrologic subsidy
- Higher energy on south aspect increases evaporation and ET overall
- Higher biomass on north aspect

- Reduced Infiltration overall
- South aspect shows smaller increase in total runoff relative to north aspect due to differences in evaporative demand

- Biomass recovery preferentially occurs in areas of high subsurface storage
- North aspect slope biomass linked to run-off/run-on and upslope subsidy patterns
- *South aspect recovery varies greatly based on soil type, water stress, etc.

Figure 1. Conceptual model of the hydrologic redistribution of plant available water (PAW) for (a) a south aspect slope, (b) a north aspect slope, and (c) comments on some of the main processes. Conceptual models are displayed for the time periods (i) pre-burn conditions (ii) short-term response (1–3 years post-burn), and (iii) long-term forest re-establishment.

(figure 2). It remains unclear if the forest will recover on south aspect slopes. This supports the aspect controls presented in figure 1 and timeline in table 1. Past studies further support the influence of drought and aspect on vegetation establishment (e.g. Tai *et al* 2021, Marsh *et al* 2022). However, there remains a need to systematically evaluate these processes at multiple sites in a variety of conditions. Our presented conceptual figure (figure 1) and testable vegetation recovery hypothesis (table 1) are posed as a starting point to conduct such a systematic evaluations in future investigations that incorporate multiple eco-regions.

Post-wildfire recovery will vary between eco-regions due to differences in vegetation species, phenology, latitude, geology, and climate patterns. However, further work is necessary to constrain the physiographic and environmental factors that constrain PAW and the associated vegetation re-establishment and survival. Once vegetation is re-established and survives (figure 1(iii)), the spatial patterns of infiltration, depth to groundwater, and evapotranspiration will vary in a predictable seasonal manner that may be projected into the future (e.g. Boisramé *et al* 2018). These time-scales of recovery are likely to vary based on seasonality and form (rain vs snow) of precipitation relative to the growing season, different topographic thresholds such as hillslope angle, and geological impacts on subsurface water storage and transmissivity. Additionally, the distance to seed source and distribution mechanism (e.g. Kiel and Turner 2022) as well as hillslope angle influencing geomorphic changes (e.g. Kampf *et al* 2016) are likely important drivers in recovery after a

Table 1. A description of the four-stage vegetation recovery hypothesis with timeline for each stage and ecohydrologic impacts.

	Vegetation status	Timeline	Ecohydrologic response
Stage 1	Immediately after fire—no vegetation	Initial weeks to months	• Minimal transpiration • Minimal canopy interception • Minimal infiltration • Minimal shallow soil moisture
Stage 2	Ground cover recovery	Years 1–3	• Minimal canopy interception • High solar radiation and wind on ground surface • Increased evapotranspiration • Low near surface soil moisture • Shallow roots allow retention of deeper soil moisture
Stage 3	Sapling establishment	Years 2–5	• Moderate canopy interception • Moderate transpiration • Moderate solar radiation and wind • Reduced shallow and deep soil moisture
Stage 4	Adolescence	Years 5–10	• High canopy interception • High transpiration • Low solar radiation and wind on ground surface • Moderate soil moisture

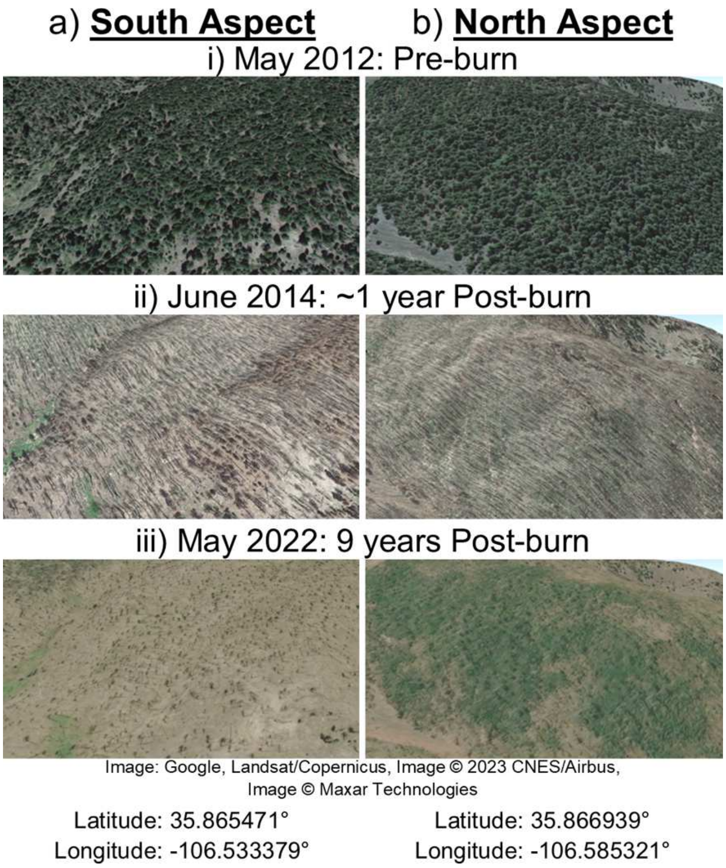


Image: Google, Landsat/Copernicus, Image © 2023 CNES/Airbus, Image © Maxar Technologies

Figure 2. Satellite imagery of (a) south aspect and (b) north aspect hillslopes in the Jemez Mountains, New Mexico USA. These hillslopes burned during summer 2013 in the Thompson Ridge fire. (Landsat Imagery gathered via Google Earth Pro v. 7; Google Earth 2023a, 2023b).

wildfire. Thus, further understanding of the influence of complex topography across multiple eco-regions on the subsurface hydrologic redistribution of PAW and association with vegetation establishment and survival will improve models for long-term predictive capabilities.

Long-term predictive capabilities in vegetation recovery may also vary across scales. While this paper focuses on the headwater catchment and hillslopes, larger scale processes are important to consider. At the mountain range scale, windward sides of mountains may receive higher amounts of precipitation due to orographic lifting, increasing PAW differently than at the hillslope scale as described in this paper. This may result in recovery patterns that vary by scale, though further investigations are necessary.

Considering the transferability of the presented conceptual model, the physical processes described in this paper will also drive recovery elsewhere. However, differences in climate and vegetation type, as previously mentioned, may alter the timeline. For example, wildfire in the mountains of south Africa have been linked to similar PAW storage processes as described herein (van der Werf *et al* 2008, Andela and van der Werf 2014, Li *et al* 2023). Grassland biomes in North America have high resilience in wildfire recovery, but drought intensity has resulted in declines in vegetation cover and tree abundance (Donovan *et al* 2020). A non-water limited site in the northeastern US has shown biomass and productivity varies with topography and micro-climate (e.g. Smith *et al* 2016) that may be linked to hydrologic redistribution of nutrients seen at another site (Weintraub *et al* 2017). Beyond individual sites, studies have found that water limitation during dry years can be widespread across ecosystem types (Brooks *et al* 2011, Voepel *et al* 2011) and warm dry air masses impact tree growth across the entire northern Hemisphere (Lee and Dannenberg 2023). Thus, our presented conceptual model for hydrologic redistribution of PAW may be transferable to other regions as well, with appropriate modifications for location-specific conditions.

4. Concluding remarks

Burned areas experience both short- and long-term alterations to runoff and water quality that can be costly for municipalities and landowners, with large uncertainties associated with planning and recovery efforts. One of the largest uncertainties, particularly in seasonally water-limited forests characteristic of much of western North America, is understanding the mechanisms driving both spatial and temporal variability in vegetation re-establishment and survival after a wildfire and the ecohydrological impacts of this variability. Constraining these uncertainties in the face of climate change and more extreme wildfires will serve as an important link between science and resource management for ecosystems and communities that rely on these water supplies.

To date, most assessments of these impacts have taken a bulk approach, or an implicitly one-dimensional conceptual approach that does not include spatial heterogeneity in hydroclimate influenced by topography and vegetation. Understanding of the natural heterogeneity of these processes across space and time in complex terrain is a major gap in current understanding. The presented conceptual model that includes influences of complex terrain in addition to the testable vegetation recovery hypothesis associated with time of recovery will address this knowledge gap. This sets a starting point to further our understanding of the spatio-temporal evolution of PAW storage and vegetation re-establishment and survival in forested catchments after a wildfire. The presented conceptual model also provides a template for discussions with diverse stakeholders to help integrate multiple interests and assist in the co-production of knowledge to develop next generation management tools to mitigate the negative impacts of future wildfires.

Data availability statement

No new data were created or analyzed in this study.

ORCID iD

Ryan W Webb https://orcid.org/0000-0002-1565-909X

References

Andela N and van der Werf G R 2014 Recent trends in African fires driven by cropland expansion and El Niño to La Niña transition *Nat. Clim. Change* **4** 791–5

Benavides-Solorio J and MacDonald L 2001 Post-fire runoff and erosion from simulated rainfall on small plots, Colorado front range *Hydrol. Process.* **15** 2931–52

Boisramé G, Thompson S and Stephens S 2018 Hydrologic responses to restored wildfire regimes revealed by soil moisture-vegetation relationships *Adv. Water Resour.* **112** 124–46

Brooks P D, Troch P A, Durcik M, Gallo E and Schlegel M 2011 Quantifying regional scale ecosystem response to changes in precipitation: not all rain is created equal *Water Resour. Res.* **47** W00J08

Brooks P, Chorover J, Fan Y, Godsey S, Maxwell R, McNamara J and Tague C 2015 Hydrological partitioning in the critical zone: recent advances and opportunities for developing transferable understanding of water cycle dynamics *Water Resour. Res.* **51** 6973–87

Broxton P D, Harpold A A, Biederman J A, Troch P A, Molotch N P and Brooks P D 2015 Quantifying the effects of vegetation structure on snow accumulation and ablation in mixed-conifer forests *Ecohydrology* **8** 1073–94

Donovan V M, Twidwell D, Uden R D, Tadesse T, Wardlow B D, Bielski C H, Jones M O, Allred B W, Naugle D E and

Allen C R 2020 Resilience to large, 'Catastrophic' wildfires in North America's grassland biome *Earth's Future* **8** e2020EF001487

Fan Y *et al* 2019 Hillslope hydrology in global change research and earth system modeling *Water Resour. Res.* **55** 1737–72

Google Earth Pro 2023a v 7.3.6.9345: Jemez Mountains, NM, 35.865471° N, −106.533379° W 4 April

Google Earth Pro 2023b v 7.3.6.9345: Jemez Mountains, NM, 35.866939° N, −106.585321° W 4 April

Gouttevin I, Lehning M, Jonas T, Gustafsson D and Molder M 2015 A two-layer canopy model with thermal inertia for an improved snowpack energy balance below needle leaf forest (model SNOWPACK, version 3.2.1, revision 741) *Geosci. Model Dev.* **8** 2379–98

Harpold A A, Molotch N P, Musselman K N, Bales R C, Kirchner P B, Litvak M and Brooks P D 2015 Soil moisture response to snowmelt timing in mixed-conifer subalpine forests *Hydrol. Process.* **29** 2782–98

Hwang T, Band L, Vose J and Tague C 2012 Ecosystem processes at the watershed scale: hydrologic vegetation gradient as an indicator for lateral hydrologic connectivity of headwater catchments *Water Resour. Res.* **48** W06514

Kampf S, Brogan D, Schmeer S, MacDonald L and Nelson P 2016 How do geomorphic effects of rainfall vary with storm type and spatial scale in a post-fire landscape? *Geomorphology* **273** 39–51

Kampf S, McGrath D, Sears M, Fassnacht S, Kiewiet L and Hammonds J 2022 Increasing wildfire impacts on snowpack in the western U.S. *Proc. Natl Acad. Sci. USA* **119** e2200333119

Kiel N and Turner M 2022 Where are the trees? Extent, configuration, and drivers of poor forest recovery 30 years after the 1988 Yellowstone fires *For. Ecol. Manage.* **524** 120536

Kirchner J 2006 Getting the right answers for the right reasons: linking measurements, analyses, and models to advance the science of hydrology *Water Resour. Res.* **42** W03S04

Lee C C and Dannenberg M P 2023 Frequencies of multivariate air masses drive tree growth *J. Geophys. Res. Biogeosci.* **128** e2022JG007064

Li F *et al* 2023 AttentionFire_v1.0: interpretable machine learning fire model for burned-area predictions over tropics *Geosci. Model Dev.* **16** 869–84

Litaor M I, Williams M and R T 2008 Seastedt: topographic controls on snow distribution, soil moisture, and species diversity of herbaceous alpine vegetation, Niwot Ridge, Colorado *J. Geophys. Res.* **113** G02008

Marsh C, Crockett J L, Krofcheck D, Keyser A, Allen C D, Litvak M and Hurteau M D 2022 Planted seedling survival in a post-wildfire landscape: from experimental planting to predictive probabilistic surfaces *For. Ecol. Manage.* **525** 120524

McGuire L, Rengers F, Kean J, Staley D and Mirus B 2018 Incorporating spatially heterogeneous infiltration capacity into hydrologic models with applications for simulating post-wildfire debris flow initiation *Hydrol. Process.* **32** 1173–87

McNamara J P, Chandler D, Seyfried M and Achet S 2005 Soil moisture states, lateral flow, and streamflow generation in a semi-arid, snowmelt-driven catchment *Hydrol. Process.* **19** 4023–38

Moeser C, Broxton P, Harpold A and Robertson A 2020 Estimating the effects of forest structure changes from wildfire on snow water resources under varying meteorological conditions *Water Resour. Res.* **56** e2020WR027071

Moody J, Martin D, Haire S and Kinner D 2008 Linking runoff response to burn severity after a wildfire *Hydrol. Process.* **22** 2063–74

Musselman K N, Molotch N P and Brooks P D 2008 Effects of vegetation on snow accumulation and ablation in a mid-latitude sub-alpine forest *Hydrol. Process.* **22** 2767–76

Musselman K N, Molotch N P, Margulis S A, Kirchner P B and Bales R C 2012 Influence of canopy structure and direct beam solar irradiance on snowmelt rates in a mixed conifer forest *Agric. For. Meteorol.* **161** 46–56

O'Donnell F C, Donager J, Sankey T, Masek Lopez S and Springer A E 2021 Vegetation structure controls on snow and soil moisture in restored ponderosa pine forests *Hydrol. Process.* **35** e14432

Onda Y, Dietrich W and Booker F 2008 Evolution of overland flow after a severe forest fire, Point Reyes, California *Catena* **72** 13–20

Rinehart A J, Vivoni E R and Brooks P D 2008 Effects of vegetation, albedo, and solar radiation sheltering on the distribution of snow in the Valles Caldera, New Mexico *Ecohydrol* **1** 253–70

Rodriguez-Iturbe I 2000 Ecohydrology: a hydrologic perspective of climate-soil-vegetation dynamies *Water Resour. Res.* **36** 3–9

Rossi M, Ares J, Jobbagy E, Vivoni E, Vervoort R, Schreiner-McGraw A and Saco P 2018 Vegetation and terrain drivers of infiltration depth along a semiarid hillslope *Sci. Total Environ.* **644** 1399–408

Saxe S, Hogue T and Hay L 2018 Characterization and evaluation of controls on post-fire streamflow response across western US watersheds *Hydrol. Earth Syst. Sci.* **22** 1221–37

Schmeer S, Kampf S, MacDonald L, Hewitt J and Wilson C 2018 Empirical models of annual post-fire erosion on mulched and unmulched hillslopes *Catena* **163** 276–87

Smith L A, Eissenstat D M and Kaye M W 2016 Variability in aboveground carbon driven by slope aspect and curvature in an eastern deciduous forest, USA *Can. J. For. Res.* **47** 149–58

Swetnam T L, Brooks P D, Barnard H R, Harpold A A and Gallo E L 2017 Topographically driven differences in energy and water constrain climatic control on forest carbon sequestration *Ecosphere* **8** e01797

Tai X, Venturas M, Mackay S, Brooks P and Flanagan L B 2021 Lateral subsurface flow modulates forest mortality risk to future climate and elevated CO_2 *Environ. Res. Lett.* **16** 084015

Thompson S E, Harman C J, Troch P A, Brooks P D and Sivapalan M 2011 Spatial scale dependence of ecohydrologically mediated water balance partitioning: a synthesis framework for catchment ecohydrology *Water Resour. Res.* **47** W00J03

Tromp-van Meerveld H J and McDonnell J J 2006 On the interrelations between topography, soil depth, soil moisture, transpiration rates and species distribution at the hillslope scale *Adv. Water Resour.* **29** 293–310

van der Werf G R, Randerson J T, Giglio L, Gobron N and Dolman A J 2008 Climate controls on the variability of fires in the tropics and subtropics *Glob. Biogeochem. Cycles* **22** GB3028

Veatch W, Brooks P, Gustafson J and Molotch N 2009 Quantifying the effects of forest canopy cover on net snow accumulation at a continental, mid-latitude site *Ecohydrology* **2** 115–28

Voepel H, Ruddell B, Schumer R, Troch P A, Brooks P D, Neal A, Durcik M and Sivapalan M 2011 Quantifying the role of climate and landscape characteristics on hydrologic partitioning and vegetation response *Water Resour. Res.* **47** W00J09

Webb R W 2017 Using ground penetrating radar to assess the variability of snow water equivalent and melt in a mixed canopy forest, Northern Colorado *Front. Earth Sci.* **11** 482–95

Webb R W, Raleigh M S, McGrath D, Molotch N P, Elder K, Hiemstra C, Brucker L and Marshall H P 2020 Within-stand boundary effects on snow water equivalent distribution in forested areas *Water Resour. Res.* **56** e2019WR024905

Weintraub S R, Brooks P D and Bowen G J 2017 Interactive effects of vegetation type and topographic position on nitrogen availability and loss in a temperate montane ecosystem *Ecosystems* **20** 1073–88

Wilcox B, Breshears D and Allen C 2003 Ecohydrology of a resource-conserving semiarid woodland: effects of scale and disturbance *Ecol. Monogr.* **73** 223–39

Wine M, Makhnin O and Cadol D 2018 Nonlinear long-term large watershed hydrologic response to wildfire and climatic dynamics locally increases water yields *Earths Future* **6** 997–1006

Zapata-Rios X, McIntosh J, Rademacher L, Troch P A, Brooks P D, Rasmussen C and Chorover J 2015 Climatic and landscape controls on water transit times and silicate mineral weathering in the critical zone *Water Resour. Res.* **51** 6036–51