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Short communication

Wildfire and climate change amplify knowledge gaps linking mountain source-water systems and agricultural water supply in the western United States

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ABSTRACT

Agricultural production in the western United States relies on water supplies from mountain source-water systems that are sensitive to impacts from wildfire and a changing climate. The resultant challenges to water supply forecasting directly impact agricultural producers and irrigation managers who rely on snowmelt and streamflow forecasts for crop selection and irrigation scheduling. To date, much research has focused on source-water system processes and agricultural production separately, but in this short communication we highlight a substantial need for new research connecting these disparate systems to improve forecasting accuracy. We identify key knowledge and data gaps regarding the functioning of source watersheds and their contributions to agricultural water resources with associated uncertainties in the context of wildfire and changing climate. In doing so, we encourage researchers, resource managers, and agricultural producers to consider the interdependency of water supply source and sink relationships through improved observations, monitoring, and modeling to ensure sustainable food production in the western US.

1. Agriculture in the western US relies on mountain source-water systems

Increasingly limited water supplies threaten agricultural production, especially in the western United States where irrigated crops use ~80% of all surface water withdrawals (Maupin, 2018). Surface water supplies for irrigation come from rivers and reservoirs fed by seasonal melt of high-elevation snowpacks that have declined over recent decades and are further impacted by increasing wildfire (Fassnacht and López-Moreno, 2020; Kampf et al., 2022; Li et al., 2017; McGrath et al., 2023; Viviroli et al., 2007). There is limited research linking ecohydrological change in mountain source-water systems to water availability for agricultural production, despite a growing reliance on snowmelt and streamflow forecasting for crop and irrigation planning (Wallander et al., 2022). This knowledge gap, combined with a changing climate, increases uncertainties with decision making and planning for reservoirs, aquifers, and agricultural irrigation management (Harmel et al., 2020; Mankin et al., 2022a; Musselman et al., 2021).

Roughly 75% of total precipitation in the western US falls in forested mountain watersheds (Liu et al., 2022) where wildfire severity and extent is increasing (Abatzoglou and Williams, 2016). Climate change could amplify the impacts of wildfire and subsequent ecohydrological

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feedbacks (Fig. 1). These changes and their interactions can lead to uncertainty in various factors, such as streamflow predictions, flood risk and sedimentation, biogeochemistry, soil microbial and ecosystem functioning, and snow accumulation and melt timing (Kampf et al., 2020; Kampf et al., 2022; Nelson et al., 2022; Rhoades et al., 2011; Williams et al., 2022). Moreover, the impacts of fires can vary broadly based on hydrological scale and fire size, but need further characterization to refine downstream impacts on agricultural production (Heindel et al., 2022; Riggan et al., 1994; Rust et al., 2018). When combined, these uncertainties complicate water supply forecasting for agricultural production (Qin et al., 2020). Wildfire may further affect water supply infrastructure through sedimentation and altered flows, impacting diversion and ditch networks regardless of streamflow volumes and reservoir levels. In addition, wildfire patterns are changing (Andela et al., 2017), with increasing encroachment on urban and agricultural areas previously free from the threat of fire. Hence, research is needed to link change and disturbance in source-water systems to water availability for agriculture and other downstream users to ensure sustainable food production in the future.

2. Uncertainty in estimating snowpack water content highlights spatiotemporal scaling issues and data gaps

Snow monitoring stations are not always representative of surrounding areas (Mankin et al., 2022a). Moreover, snow station data are fine-scale point measurements that are typically more sparsely distributed than what would be ideal for forecasting (Blöschl, 1999). Especially to inform agricultural water management downstream of mountainous regions (Kaune et al., 2020; Tennant et al., 2017). Western US water supply forecasts are commonly made using statistical models developed to historical runoff volumes and snow water equivalent (SWE) from SNOTEL stations or snow courses (Helms et al., 2008). While more complex methods have been developed, including advanced machine learning and artificial intelligence algorithms, their testing has been too limited to justify broad adoption at operational-scales thus far (Fleming et al., 2021). Nevertheless, these models trained to past data have become less reliable as the climate increasingly deviates from historical norms (Lehner et al., 2017; Livneh and Badger, 2020). Remotely sensed snow data, such as airborne lidar, have increased the spatial resolution of basin-wide snow metrics (Painter et al., 2016). However, landscape factors, such as vegetation and topography can affect these estimates, especially when snowpack depth exceeds 50 cm (Deems et al., 2013; Raleigh and Small, 2017). Additionally, the high costs of airborne lidar flights and data processing restrict widespread adoption of these methods, continuing a reliance on sparsely distributed sensor networks that may delay improvements to snowmelt and streamflow forecasting.

3. An uncertain future, measurement gaps, and incomplete understanding further complicate snowmelt and streamflow forecasting

The impacts of wildfire and other disturbances (e.g. deforestation from bark beetle outbreaks) on snow accumulation and melt timing in forested areas are highly variable and amplified by a changing climate. Although snowpacks are generally declining across the western US (Fassnacht and López-Moreno, 2020), reduced canopy interception of snow due to fire or disturbance can increase snowpack accumulation and reduce canopy sublimation losses (Moeser et al., 2020). However, these same canopy changes can also result in higher insolation and turbulent fluxes at the snow surface, increasing melt rate (Harpold et al., 2014; McGrath et al., 2023). Characterizing these factors across the landscape can be challenging as they vary by topographic position and can be affected by decreased albedo from ash or dust on the snow surface (Fassnacht et al., 2022; Gleason et al., 2013). As a result, continued research is needed to improve the understanding of these interactive factors and reduce uncertainty in predictions of snowmelt rate and timing and streamflow generation from burned watersheds (Giovando and Niemann, 2022; Holden et al., 2012; Pomeroy et al., 2012; Smoot and Gleason, 2021).

Similarly, the magnitude of wildfire impacts on hydrologic function

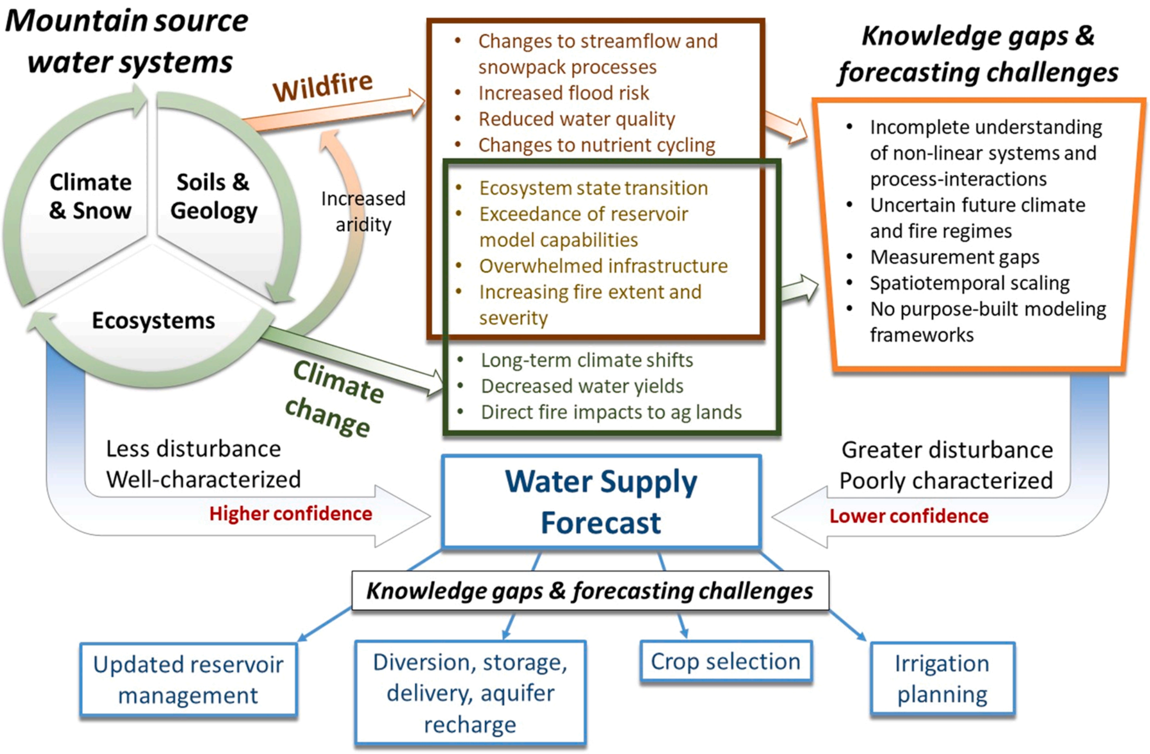

Fig. 1. Conceptual diagram of mountain source water system functioning and water supply forecasting including complications due to the impacts of climate change and wildfire.

is spatially variable, depending on burn severity, topography, soils, climate, and changes to vegetation (Goeking and Tarboton, 2020; Hallema et al., 2017). Higher burn severity increases soil hydrophobicity and reduces soil organic matter and surface roughness, reducing soil infiltration and increasing overland flow (Ebel and Moody, 2017; Shakesby et al., 2000). This can lead to “flashier” streamflow responses with faster and higher peak-flows, especially after high-intensity rain storms (Moeser and Douglas-Mankin, 2021; Moody and Martin, 2001). Moreover, vegetation mortality reduces evapotranspiration losses post-fire, potentially increasing baseflow (Bart and Tague, 2017; Kinoshita and Hogue, 2015). Conversely, rapid vegetation recovery post-fire can increase soil-water uptake (Buckley et al., 2012). These interactive and multifaceted effects can lead to both acute (2–3 years post-fire) and chronic (decadal) changes that can vary across burn areas (Hallema et al., 2018).

Water supply reservoirs are especially important in snow-dominated river basins. This includes larger reservoirs with declining operating capacities (e.g. Lake Mead, Lake Powell) and smaller regional reservoirs that are more likely to fill to capacity each year. However, wildfires and a changing climate are highlighting limitations with reservoir capacity, operating levels, and release rates that were designed based on historical climate and pre-fire landcover. The combination of unique streamflow responses, flash floods, and sediment and debris loading that may emerge post-fire are often outside of the ranges of historical variability used during reservoir design (Basso et al., 2021; Floyd et al., 2019; Nyman et al., 2019). Therefore critical research is needed to quantify the potential impacts of wildfire and climate change on streamflow variability impacts to reservoir design and irrigation water distribution networks.

Reservoir operating criteria are further challenged by uncertainty in the timing of watershed hydrologic recovery which can range from 3 to 45 years after fire (Hampton and Basu, 2022; Wine and Cadol, 2016). Increasing aridity and uncertain future wildfire regimes can further confound these predictions. For example, decreasing precipitation and increasing wildfire extent and severity in the western US may result in reduced vegetation recovery or shifts in ecological states slowing hydrologic recovery, or shifting to a new hydrologic regime altogether (Lian et al., 2021; Rodman et al., 2020; Stevens-Rumann and Morgan, 2019).

4. Forest soils moderate wildfire effects on nutrient cycling, water quality, and ecosystem recovery

Severe wildfires combust forest vegetation and organic soil layers and expose mineral soils to surface runoff and leaching with direct consequences for downstream water quality (Rhoades et al., 2011; Rhoades et al., 2019b). However, little is known about these effects on irrigated agriculture. Sediment and ash mobilization are the primary short-term water quality concerns after severe wildfires. Ash is alkaline and often contains high levels of nitrogen, phosphorus, potassium, and trace metals with lasting effects at local and regional scales (Rhoades et al., 2019a; Rust et al., 2018). Although additions of char in irrigation water from burned lands may benefit crop production through nutrient enrichment (Spokas et al., 2012), char may also contribute to eutrophication and harmful algal production in water bodies (Hohner et al., 2019) and foul irrigation infrastructure. For water treatment and pre-treatment of water for high-efficiency irrigation systems, particulates are an important concern, especially following high intensity rainstorms (Hohner et al., 2016). Nutrients, metals, and char deposited within reservoirs and floodplain sediments can also be longer-term concerns for agricultural water quality when remobilized during high flows (Martens et al., 2019).

Microbial communities fill essential roles in nutrient cycling and forest soil and vegetation functioning that are altered by wildfire. The resilience of soil microbiomes regulates the rate of post-fire vegetation recovery and nutrient cycling, with downstream effects on agricultural water quality. For example, microbial communities can frequently transform ammonium (abundant after fire), to nitrate, which can leach into adjacent fluvial systems. Microbes can also play critical roles in the methylation of mercury that is exported from burned watersheds and can bioaccumulate in the food web (Jensen et al., 2017). Additionally, fire can substantially deplete ectomycorrhizal fungi (EMF), which are critical symbiotic partners to many plant species, including dominant pine vegetation in the western US. Recent studies have indicated that EMF populations are mostly absent one-year post fire, especially following high severity fires (Nelson et al., 2022). These changes likely affect the ability of seedlings to establish and grow (Rhoades et al., 2021), with subsequent impacts on hydrology and the trajectory of ecosystem recovery. Widespread regeneration failures and state transitions in the forests and shrublands of the western US (Mahood and Balch, 2019; Shriver et al., 2019) are likely to lead to alterations in the pools and fluxes of soil nutrients (Mahood et al., 2022), for which the role of EMF reductions are largely unexplored. Moreover, the full extent of post-fire changes to microbial communities and their impacts on soil health, vegetation recovery, water quality, and source-water yields remain to be identified.

5. Modeling and data limitations lower confidence in water supply forecasts

Wildfire impacts are often considered in the context of local utilities and land disturbance (Blount and Kroepsch, 2019). However, downstream impacts on agriculture can be indirect, difficult to quantify, and as a result, remain poorly investigated. Process-based hydrologic models can simulate future risks related to climate change, and are thus important tools for improving our understanding of hydrologic responses (Hay et al., 2011; Mankin et al., 2022b). However, no models have been developed specifically to represent fire effects or post-fire recovery on ecohydrologic processes (Ebel et al., 2023). Instead, integrating measurements and simulations “from fire to farm” involves many challenges including conceptual and data gaps. For example, complex terrain and spatially variable climate, vegetation, and geology in mountain systems confound observations and simulations of surface and groundwater flow paths (Frisbee et al., 2011; Somers and McKenzie, 2020; Viviroli et al., 2007). Water management and water supply forecasts downstream would benefit from research that improves systems-level understanding of the inputs, feedbacks, and alterations in system dynamics due to disturbance and climate change.

6. Farm-level impacts of a decreasing yet uncertain water supply

Planning crop irrigation requirements is increasingly difficult due to multi-year droughts, variable precipitation, wildfire, and disturbance in source-water areas. Water managers and ditch companies that supply irrigation water rely on snowpack reports and streamflow monitoring for short-term planning, and extended weather forecasts and reservoir reports for long-term planning (Wallander et al., 2022). However, without reliable long-term climate outlooks and a comprehensive modeling framework (as described above), high-resolution water supply forecasts are limited to short-term (i.e. 7–10 days). Insufficient water supplies, post-fire sediment impacts on irrigation infrastructure, or poor confidence in forecasts will compel curtailments to surface and groundwater extractions. This will lead producers to reduce irrigated acreage or the amount of irrigation applied, or to select more drought tolerant (but less productive) crops (Schneekloth and Andales, 2017). It is worth noting, however, that water user organizations and irrigation ditch companies are attempting to coordinate water supplies (river diversions, reservoir releases, groundwater pumping) to effectuate exchanges, trades, and leases to maximize basin water use and address future uncertainties. These efforts will be further aided by improved understanding of crop water requirements and new research focused on the development of comprehensive modeling frameworks and improved weather forecasting.

The timing of water delivery is also essential for planning irrigation to maximize crop yield and economic return. However, timing water delivery to crop requirements becomes challenging post-fire and under increasing aridity as supply limitations often coincide with peak irrigation demand. Many modern crop hybrids (e.g. maize) have been bred with specific growth phase timing (Abendroth et al., 2011). Water limitations at key growth stages can cause substantial yield losses, especially during the middle and end of season (Comas et al., 2019; Zhang et al., 2019). Hence, peak streamflow from snowmelt and reservoir releases earlier in the season, resulting in less water being available later, are unlikely to provide sufficient water supply for these crops. Farm-level water management, as a result, may require a shift away from full irrigation of crops with large water requirements later in the season (e.g., maize, alfalfa) to crops with more flexible timing of water requirements (e.g., sorghum, sunflower).

Regulated deficit irrigation (RDI; strategic irrigation shortfalls during targeted growth stages), to a degree, can maintain crop yields while saving crop water use (Comas et al., 2019; Zhang et al., 2019). Many producers, however, lack flexibility in their irrigation systems to apply RDI. Sprinkler systems often lack the capacity to rapidly replenish soil moisture after the root zone is depleted. Furrow systems require water to reach the end of the field but could achieve RDI by supplying fewer well-timed irrigations if the ditch schedule allows. If farms must use less water, fully irrigating a smaller portion of a farm for a crop with high water requirements and producing an alternative crop with lower water requirements on the remainder of the farm may provide better options. Ultimately, more advanced tools are needed for evaluating farm management options if farms are able to use RDI to save water for leasing (Manning et al., 2018; Trout and Manning, 2019; Wichelns, 2015). New research and development of adaptable decision support tools that can evaluate alternative cropping choices, decision making tools (e.g. using soil moisture, evapotranspiration estimates), and management options will be critical for effective management of irrigation water on farms and for the development of municipal drought response plans.

Sedimentation in water supplies can also negatively impact irrigation systems. While most surface water supplies non-pressurized irrigation systems, pressurized systems (sprinkler and drip irrigation) require settling ponds or filtration of fine sediments to prevent clogging of nozzles and emitters. Sediment yields post-fire can reach 1000 mg/L, far exceeding the 50 mg/L thresholds for emitter function (Capra and Scicolone, 2007; Murphy et al., 2012).

7. Thinking outside the box will advance agricultural adaptation to an uncertain future

There is a critical shortage of research linking source-water systems to irrigation for downstream agricultural production. This has resulted in a substantial knowledge gap and a clear opportunity to develop resilient systems that can respond to uncertain agriculture water supplies in the western US. Snowpacks are declining, and wildfire size, extent, and severity are increasing, with large destructive fires extending into winter months and encroaching on agricultural land and the wildland-urban interface (e.g. Marshall fire in Colorado and the Kansas grassland fire outbreak in December of 2021). A new perspective on agricultural production is now needed that encompasses both farm-level decision support and broader preparation for modeling and forecasting unpredictable water supply and delivery.

Increased focus on state-of-the-art technology to characterize spatial distributions of snowpack water (e.g. airborne lidar) and improved snowmelt models will reduce uncertainty in the timing and volume of snowmelt. An increase in resources for mitigating risk pre-fire (e.g. fuels reduction treatments, prescribed burning) and for post-fire recovery (e.g. mulching treatments, stream channel restoration) will benefit downstream water users through improvements to water quality, increasing the predictability of post-fire hydrologic functioning, and decreasing time to watershed recovery. Flexibility and constraints in the management of infrastructure used to store and distribute source waters to agricultural users must be included explicitly in systems-level research. At the farm level, improved irrigation management and crop genetics and selection may sustain or improve current levels of crop production but must also be considered in the context of water shortages and uncertainties in water supply.

Numerous watershed partnerships and water management organizations have emerged across the western US with broad focus on these aspects of water resources in semi-arid regions, although few have drought or fire built into management models (Wallander et al., 2022). Increased interactions among the research community, watershed partnerships, conservation agencies, water and resource managers, and agricultural producers will enhance a broader understanding of water supply issues, develop innovative management strategies, and grow relationships among disparate groups of stakeholders toward new, effective water management strategies.

Declaration of Competing Interest

The authors declare no known competing financial or personal relationships or interests that could appear to have influenced the work reported in this paper.

Data availability

No data was used for the research described in the article.

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