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Forests in the upper Colorado basin: linkages between forests, snow cover, and runoff

Introduction

Forests in the western U.S. have seen dramatic changes in forest structure and ecosystem processes in response to climate change and altered disturbance regimes. Changes in forests influences precipitation dynamics and runoff of water from snow, which is critical because the seasonal snowpack of the western U.S. is a “natural water tower” that provides 53% of all runoff across the west and 75% of water in the Colorado River (Li et al. 2017). Snow dynamics are essential to understand given that 1/6 of the world’s population depends on surface water supplies from snowmelt systems (Barnett et al. 2005), including 40 million people who rely on the Colorado River for water (Deems et al. 2013). Most of the snow in the western U.S. falls in forested areas, where vegetation controls accumulation and ablation of snow (Varhola et al. 2010, Trujillo and Molotch 2014). Warming climate is expected to both decrease the fraction of precipitation falling as snow and increase evapotranspiration due to higher surface energy (Foster et al. 2016). Understanding the complex feedbacks between vegetation and snow is essential for predicting how climate and forest cover changes will influence water supply (Goulden and Bales 2014). Because water provision is a crucial ecosystem service from these forests that millions of people rely on, predictions and uncertainty for how climate change, disturbances, and management actions may influence water should be considered in management planning. This is an active area of research (i.e. Goulden and Bales 2014, Fassnacht et al. 2018), and this paper will review the research for the western U.S. and the Colorado Basin in particular.

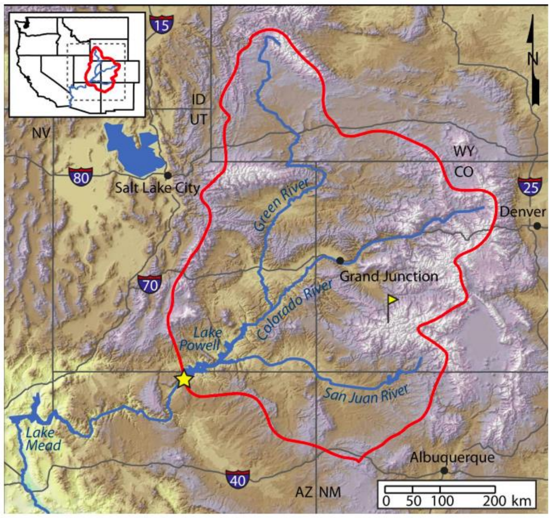

Figure 1. Map of the Upper Colorado River Basin. Source: Deems et al. 2013

Western forests and water flows

Forests in the western United States provide many essential ecosystem services, including carbon sequestration, habitat for animals, and the protection of water resources. In the Colorado Basin alone, there are 15 million acres of conifer forests and 3.3 million acres of aspen forests that receive more than half of the precipitation in snow. Of these, 6.8 million acres are subalpine forest, which receive more than two thirds of the precipitation as snow (Hibbert 1979). The upper basin of the Colorado River is the part of the watershed that runs off to the river before Lee’s Ferry; 75% of the river’s water comes from the snowmelt, with the vast majority falling in the high elevations of the Rocky Mountains (Li et al. 2017). and that processes of snow melt and runoff interact with vegetation and climate in complex ways.

The western U.S. has historically seen peak flows April through July, with 50-80% of water flow in this time due to the storage of water in snow (Lundquist et al. 2009). Because the west has relatively dry summers, snow is the most important water source for many ecosystems to survive the seasonal drought, especially at high elevations (Monson et al. 2002, Hu et al. 2010). Increasing temperatures have led to earlier snowmelt across the western states, with peak annual flow occurring 1-4 weeks earlier in 2002 than 1948 (Dettinger and Cayan 1995, Stewart et al. 2005, Lundquist et al. 2009). This can lead to changes in vegetation due to increasing stress of late summer drought (Hu et al. 2010). While rivers downstream of dams do not see the natural pattern of high April-July flows, earlier snowmelt poses challenges to water management systems. Rainwater systems are less predictable due to flashier water availability and sometimes the need to release water earlier in the year to prevent flood risk (Stewart et al. 2005). This paper will focus on another challenge, that of complex interactions between forests, snow, and climate that can lead to changes in the amount of runoff.

Snow deposition is controlled mainly by winter temperatures, while spring temperatures are the strongest driver of snow melt (Knowles et al. 2006). Snow water equivalent is a measure of the amount of water held in snow. The reduction in snow water equivalent is called ablation, which may occur through melting, evaporation, transpiration, sublimation, and wind, for example. When snow melts, water seeps into the ground, runs down to bedrock, and comes out downslope into rivers, which is why snowpack is an essential reservoir of water for the semi-arid and summer-dry western U.S. (Cole and Moore 2009).

Increases in minimum temperature have led to decreases in the amount of snow deposited and earlier disappearance of snow across the western U.S. since the mid 1900s (Knowles et al. 2006). In the inter-mountain west (the Great Basin and Colorado River Basin), this earlier disappearance of snow may be due in part to increased sublimation due to raised temperatures being able to hold more water vapor, leading to a faster rate of melt rather than earlier onset of melt (Harpold et al. 2012). In the Sierra Nevada, which has overall warmer temperatures, research has shown a larger effect of state transitions from snow to rain as causing the declines in snow water equivalent (Mote et al. 2005). The difference between regions is likely due to differences in winter temperatures and the amount of buffer an area has for dealing with increased temperatures. For example, the higher elevation southern Sierra Nevada has not seen the same declines in snowpack due to colder temperatures at the higher elevations than in the northern Sierra Nevada (Mote et al. 2005, Das and Stephenson 2013). These regional and elevational differences are important to consider as environmental conditions may mediate change.

Evapotranspiration and climate

Increased temperature is expected to be a primary driver of change in the amount of water runoff, due largely to the influence of temperature on evapotranspiration (Foster et al. 2016). Evapotranspiration is increased by greater energy availability both for evaporation and for plant transpiration, and is therefore driven both by increasing air temperatures as well as earlier snowmelt and the rate of snowmelt. Multiple theories exist for how change in snowmelt rate influences evapotranspiration. One theory is that earlier snowmelt due to warmer atmosphere will lead to greater evapotranspiration due to increased vapor pressure deficit. A second theory posits that early snowmelt will lead to asynchrony between water availability and vegetation growth, leading to more runoff. Similarly, some results have shown that earlier snowmelt is associated with slower snowmelt (Trujillo and Molotch 2014), while others show faster snowmelt (Harpold et al. 2012). Faster snowmelt would mean that soil would saturate and then more water would be available to runoff, faster than the rate of evapotranspiration; this would lead to increased infiltration and greater subsurface drainage (Barnhart et al. 2016). Conversely, slower melt may be more able to be taken up by vegetation, leading to increases in evapotranspiration. Snowmelt rate is therefore important for controlling how much water is evaporated or transpired and how much becomes subsurface drainage or surface flows.

Annual evapotranspiration is very closely related to canopy density. In addition to high elevation forests being the forest type that receives the most snowfall, high elevation forests are especially important for runoff because low vegetation cover means there's less ET than if there were very dense forest (Goulden and Bales 2014). They also have a very short growing season and so are only taking up water (therefore transpiring) for a short part of the year. High elevation forests such as the subalpine are energy limited rather than water limited like in lower elevation forests; that means that they have the water capacity to increase ET if they had more energy (Goulden et al. 2012, Foster et al. 2016). Increasing temperatures can release the forests from that control, leading to increased transpiration with warming temperatures, which has already been seen in some western U.S. watersheds including in the Sierra Nevada and the Rocky Mountains (Goulden and Bales 2014). Increased temperatures can lead to rapid vegetation shifts in high elevation forests, including increases in subalpine tree growth (Dolanc et al. 2013b), densification (Dolanc et al. 2013a), rising tree-line altitude (Camarero et al. 2017, Smithers et al. 2018), and changes in species distribution (Millar et al. 2004, Slaton 2015). Increasing temperatures can therefore cause changes in forest structure that lead to increased transpiration, which can minimize the amount of water available downstream (Foster et al. 2016).

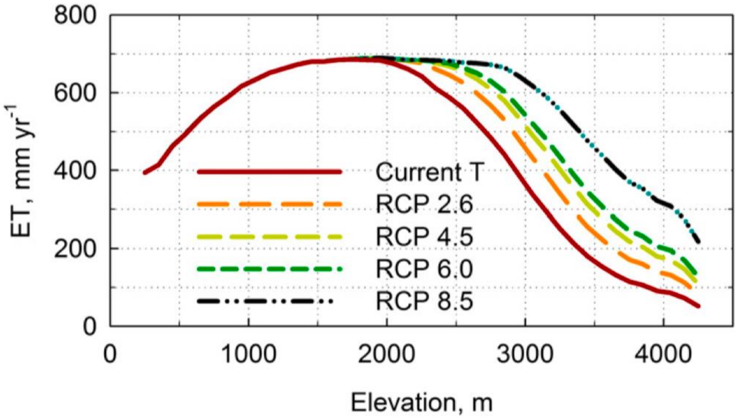

Figure 2. Evapotranspiration across elevational gradient in the Sierra Nevada, with current amount and predictions of increases under future climate models. Similar increases in ET have been observed and are expected to continue across the western U.S. Source: Goulden and Bales, 2014.

Tree-snow interactions across scales

Forests and trees also interact with snow accumulation and melt via energy transfer. Trees can shade snow on the ground from shortwave radiation, but they also emit longwave radiation down to the surface. Some snow is additionally caught in the tree, where it will either sublimate, melt to the floor, or fall. Whether a forest leads to snowpack protection in the spring or to earlier snowmelt is complicated. One pattern comes with average air temperature: in places with mean winter temperature > -1°C (Dec-Feb), melt occurs during winter more under forest than in clearings due to greater net radiation (Lundquist et al. 2013). That means that in warmer areas, including much of the continental western U.S., midwinter melt is higher under forests than in clearings. In colder areas, such as higher latitudes, the opposite occurs, with greater melt in open clearings. In general, this means that streamflow timing in areas that are warmer would be more sensitive to climate change under forests than in clearings – that change in snowmelt timing would be greater under trees than in clearings (Lundquist et al. 2013). Of course, this is general, and snowmelt is influenced by many other factors, including aspect, slope, and rain-on-snow events. One implication of this research is that areas with mortality or decreasing canopy cover could be a positive thing for streamflow in warmer climates. It is also an interesting idea for forest management in warmer areas such as the continental western U.S.; for example, forest management history, such as fire suppression and logging, has led to very dense forests. Thinning for purposes such as fire and fuel reduction could have additional benefits of increasing streamflow.

Forest disturbance interactions with snow

The general observation from Lundquist et al. (2013) that tree cover in relatively warm-winter snow areas causes increased melt is complicated by other research that investigates the tree-snow interaction at different scales. Snow intercepted by canopies may sublimates more than snow on the forest floor, but canopies also intercept wind which can reduce sublimation and wind scour. Much of the research investigating effects at multiple scales has been conducted in the context of forest disturbances.

One active front of research on snow-forest interactions deals with forest disturbances. This is useful for comparing snowmelt from areas with and without disturbance as well as incorporating changing disturbance regimes into predictions for future forest cover and runoff. Mountain pine beetle is a native beetle that in recent decades has caused widespread mortality due to favorable climatic conditions for reproduction and dispersal along with increased stress for trees (Raffa et al. 2008). Research has investigated the difference in snow accumulation in forests with live trees and forests with beetle-caused mortality after all of the needles have dropped but the trees still stand. These studies have reported variable findings about how mountain pine beetle mortality has influenced snowpack and highlighted the importance of the scale of observation (Biederman et al. 2014). For example, multiple studies have found greater peak snowpack after mortality due to the decrease in sublimation of attenuated snow in canopies (Pugh and Small 2012, Boon 2012). Biederman et al. (2014), also observed that there was decreased snow interception in canopies (more snow fell on the ground) when snow was measured by continuous snow sensors installed at plots. However, when snow accumulation was studied using transect measurements and isotope analyses at a larger forest stand scale, they found that the decreased interception was offset by higher sublimation, leading to no noticeable change between stands with and without high mortality from mountain pine beetles (Biederman et al. 2014). This result highlights the importance of investigating multiple scales for snow measurements in response to high severity disturbances.

Over the last half century, fires have increased in area and severity across the western U.S. (Westerling et al. 2006, Safford and Van de Water 2013, Parks et al. 2018). In northern Rocky Mountain lodgepole pine forests, the fire regime is characterized by high severity, infrequent fire, with return intervals of 100-300 years (Turner et al. 2003). For these systems, 20th century fire suppression has played little role in building fuels that would lead to larger or more severe fires, but increasing spring and summer temperatures and earlier spring snowmelt are strongly associated with the large increase in large fires (Westerling et al. 2006). While large high severity burns such as the 1988 Yellowstone fires are not unusual for that system, the fire return interval is expected to shorten dramatically, potentially to 30 years by the mid-21st century (Westerling et al. 2011). Lodgepole pine of the northern Rocky Mountains are fire adapted and many have serotinous cones that open after fire, but serotinous cones take many decades to produce, which could limit succession after repeated frequent fire (Romme et al. 2011). This is expected to lead to state changes away from lodgepole pine and into treeless systems (Westerling et al. 2011), which in a windy system like the Rocky Mountains could lead to additional wind-scour and lower snow accumulation (Woods et al. 2006). The southern Rocky Mountains, which are part of the Colorado River Basin, also have lodgepole pine forests and a variety of fire regimes, leading to a variety of potential management strategies to deal with changes in climate, fuel loads, and tree cover. Potential changes in forest cover or transitions to other vegetation systems have not been incorporated into hydrological predictions for the Colorado River, but could play an important role in determining snow ablation (Bales et al. 2006).

In the Sierra Nevada, Stevens (2017) found that increasing fire severity had a strong negative effect on snowpack depth, with unburned forest having the deepest snowpack. This seems to run counter to the trend of warm-winter forests (with average temperature > -1C) have greater snowpack in clearings (Lundquist et al. 2013), and indicates that ablation from sunlight hitting the ground is still an important driver of snowpack. At the individual tree scale, however, snowpack depth *was* greater in canopy openings than under trees. Variation in canopy cover creates smaller areas for snow accumulation while reducing ablation with shading (Stevens 2017). This research emphasizes the importance of heterogeneity in forest structure, which is essential for many other aspects of ecosystem function in addition to snowpack, and has increasingly been incorporated into ecosystem management in federal land management agencies (North et al. 2009, North 2012).

Forest Management Uses and Implications

Forest management has long been thought of as a tool for managing runoff (Hibbert 1979). With increasing temperatures, lengthening growing seasons, carbon and nitrogen deposition, and fire suppression occurring over vast areas of the western U.S., many forested areas have increased in density over the past century which may lead to declines in snow accumulation and water yield (Hibbert 1979, Anderson and Goulden 2011, Dolanc et al. 2013a). Tree removal during harvest or fuel reduction efforts may change the amount of snow accumulation, depending on the relative gains due to lower snow interception and losses due to increased wind scour and sublimation (Stegman 1996). An experimental treatment in the Rocky Mountains of Montana found that peak snow water equivalent was increased in a silvicultural prescription that left residual trees evenly spaced, while a harvest in patches, leaving residual groups of trees, caused no change in snow water equivalent (Woods et al. 2006). The potential exists for forest management to improve both water runoff amounts while enhancing forest resistance to high severity fire or disease and reducing drought stress.

Conclusions

Forest and snow interact in complex ways, mediated by climatic conditions such as temperature and timing of snow events. Interactions differ across global, regional, and microclimate scales, and observations of patterns or processes also can depend on the amount of snow between years (Varhola et al. 2010). Because of warmer temperatures, increases in evapotranspiration can reduce overall flows to the Colorado River along with all of the river systems in the western U.S. These patterns could be complicated or mediated by changes in forest cover and disturbance regimes that can lead to state changes (Turner 2010). While water agencies have historically been reluctant to engage in forest management funding or operations (personal communication, Dr. Hugh Safford), there are strong connections between forest resilience and water yields, leading to the natural question of whether or how water agencies could help to protect the sources of much of the water in the western U.S..

In summary, forest interactions with snow are very complex. It is difficult to model changes due to cross-scale interactions and feedbacks, but researchers are in agreement that climate change will lead to decreases in runoff due to a variety of factors including decreased snowpack from warming temperatures and increasing evapotranspiration. This is an active area of research from multiple angles, including the interactions between forest disturbances and snow. Forest management agencies recognize the importance of preserving forest heterogeneity at multiple scales as a part of ecosystem management (North et al. 2009, North 2012), which for now seems to be the best course of action while research progresses and continues to work out the underlying processes that drive runoff.

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