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Forests and Water Yield: A Synthesis of Disturbance Effects on Streamflow and Snowpack in Western Coniferous Forests

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Abstract

In coniferous western forests, recent widespread tree mortality provided opportunities to test the long-held theory that forest cover loss increases water yield. We reviewed 78 studies of hydrologic response to standing-replacing (severe wildfire, harvest) or nonstand-replacing (drought, insects, low-severity wildfire) disturbances, and reassessed the question: Does water yield or snowpack increase after forest disturbance? Collective results indicate that postdisturbance streamflow and snowpack may increase, not change, or even decrease, and illuminate factors that may help improve predictability of hydrologic response to disturbance. Contrary to the expectation that tree mortality reduces evapotranspiration, making more water available as runoff, postdisturbance evapotranspiration sometimes increased—particularly following nonstand-replacing disturbance—because of (a) increased evaporation resulting from higher subcanopy radiation, and (b) increased transpiration resulting from rapid postdisturbance growth. Postdisturbance hydrologic response depends on vegetation structure, climate, and topography, and new hypotheses continue to be formulated and tested in this rapidly evolving discipline.

Keywords: forest disturbance, forest hydrology, water yield, streamflow, snow water equivalent, snowpack, coniferous forests

In 1967, Alden Hibbert concisely formulated three long-lived hypotheses about the relation between forest cover and water yield: “1. Reduction of forest cover increases water yield. 2. Establishment of forest cover on sparsely vegetated land decreases water yield. 3. Response to treatment is highly variable, and, for the most part, unpredictable” (Hibbert 1967, p. 535). Decades of subsequent research have supported these hypotheses (Hibbert 1967, Bosch and Hewlett 1982, Troendle 1983, Troendle and King 1985, Andréassian 2004). However, recent studies suggest that the variability of water yield response is a fundamental characteristic of semiarid western watersheds and raise questions about the universality of the first hypothesis regarding the relation between forest cover and water yield (Pugh and Gordon 2013, Biederman et al. 2015).

Recent reviews have highlighted differences in the magnitude of water-yield increases following disturbance, as well as variability in individual hydrologic processes that drive water-yield response (Buttle et al. 2005, Moore and Wondzell 2005, Adams et al. 2012, Mikkelson et al. 2013, Pugh and Gordon 2013). The magnitude of postdisturbance water yield change varied widely in these reviews, from −50 percent to more than +200 percent, although such large increases are questionable (Adams et al. 2012), and Pugh and Gordon (2013) predict either no change or increases up to +25 percent. However, even more recently,

Management and Policy Implications

Previous research on the link between forest management and water yield led to the expectation that water yield would increase following recent tree mortality in the Western United States. This paper presents a review of papers published during 2000–19 on the effects of forest disturbance on streamflow in western coniferous forests. Although some studies observed postdisturbance increases in water yield, as expected, in many cases water yield did not change or even decreased. Decreases were generally observed in areas with the following characteristics: high total radiation and high solar radiation (i.e., at low latitudes and south-facing aspects); rapid growth of postdisturbance vegetation; and nonstand-replacing disturbances, such as drought and insect-caused mortality. Although one objective of forest management may be to increase water yield, another might be to encourage postdisturbance forest recovery and resilience by optimizing growing-season soil moisture, which depends on snow accumulation and retention. The ability to meet such goals, and the treatments to accomplish them, depends on residual vegetation, latitude, and aspect. Our review suggests that recommendations for meeting specific management objectives in forested watersheds of the semiarid West—and the best available scientific information about the link between forest cover and water yield—are changing rapidly.

studies have concluded that water yield decreases following forest disturbance in semiarid western watersheds (Biederman et al. 2014, Biederman et al. 2015, Bart et al. 2016, Slinski et al. 2016, Bennett et al. 2018). Because these recent studies contradict Hibbert's (1967) first hypothesis, additional review is needed to identify where and why decreases in water yield may occur and thus improve the predictability of postdisturbance hydrologic response.

Previous studies that observed increases in postdisturbance water yield, as expected, illuminated the mechanisms responsible (Hibbert 1967, Bosch and Hewlett 1982, Troendle 1983). Water yield is constrained by the amount of precipitation minus evapotranspiration, where vegetation affects the partitioning of precipitation into runoff versus evapotranspiration. When forest cover is decreased, two components of evapotranspiration decline (Figure 1). First, less precipitation is intercepted and subsequently sublimated (snow) or evaporated (rain) by tree canopies. Sublimation losses of canopy-intercepted snow can be as high as 20–30 percent of snowfall in western watersheds where a substantial fraction of precipitation falls as snow (Schmidt et al. 1998, Montesi et al. 2004), thus substantially reducing the amount of water available for streamflow. Second, transpiration decreases following death or removal of trees (Wilm 1948, Hibbert 1967, Troendle 1983, Troendle and King 1985, Adams et al. 2012).

As expected from these mechanisms, standing-replacing disturbances such as clearcut harvests often lead to increased streamflow (Troendle 1983, Troendle and King 1985, Troendle and King 1987, Stednick 1996, Hubbart et al. 2007). However, nonstand-replacing disturbances may differ with respect to individual hydrologic processes such as interception of precipitation, radiation transmission, accumulation and retention of snowpack, and evapotranspiration from the overstory and understory. Partial-cut harvesting has both increased water yield (Hubbart et al. 2007) and failed to produce significant increases (Troendle and King 1987). Opportunistic studies of previous insect outbreaks concluded that streamflow increased following mortality (Figure 1a) (Bethlahmy 1974, Potts 1984), particularly after salvage clearcuts (Cheng 1989), although the increase was hypothesized to be modulated by radiation exposure (Bethlahmy 1975). Higher radiation exposure—which is related to a combination of slope, latitude, aspect, and temperature—translates to higher evaporative demand and thus higher potential evapotranspiration. In contrast to earlier studies, recent research has observed unchanged or even decreased streamflow following insect outbreaks, likely because increased evapotranspiration from understory vegetation overcompensated for decreased evapotranspiration from the overstory (Figure 1b) (Biederman et al. 2015).

Recent widespread tree mortality across the western United States (Breshears et al. 2005, van Mantgem et al. 2009, Anderegg et al. 2013, Huang et al. 2015) has provided opportunities to test hypotheses about the linkage between forest cover, disturbance, and water yield. Contemporary studies differ from historical watershed experiments in several important ways. First, recent mortality was caused by multiple factors that did not typically kill or remove 100 percent of trees in affected stands (Hicke et al. 2015), whereas most previous studies and reviews (Troendle 1983, Troendle and King 1985, Stednick 1996, Hubbart et al. 2007) focused on stand-replacing disturbances, mainly clearcut harvesting and severe wildfire. Second, the spatial scale of analysis can be much broader,

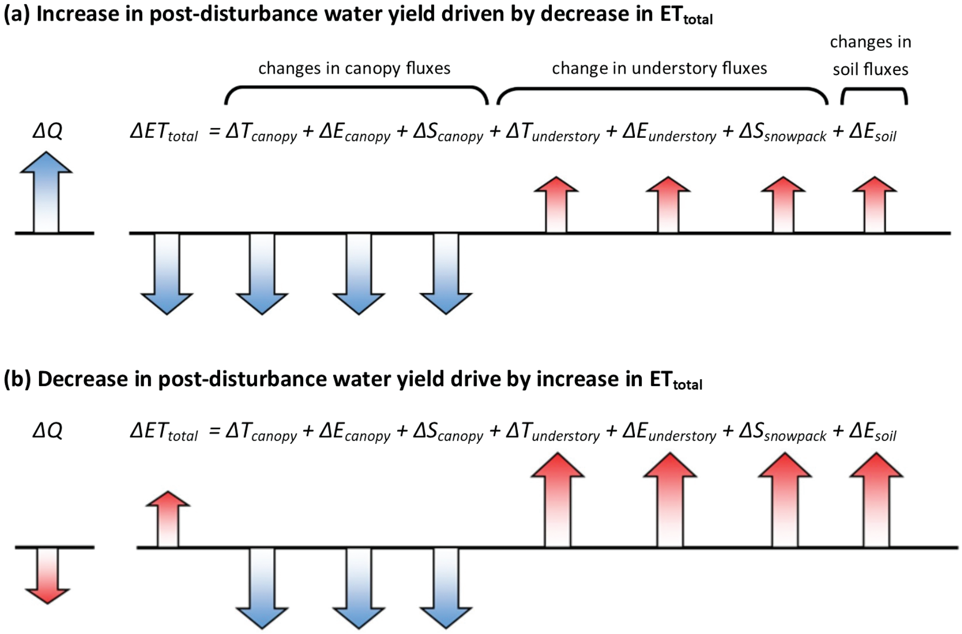

Figure 1. Postdisturbance decrease (a) versus increase (b) in net evapotranspiration (ET) that determine water yield response, as determined by changes in individual components of ET relative to predisturbance fluxes. Red arrows contribute to higher total ET and lower water yield; blue arrows contribute to lower total ET and higher water yield. Arrow sizes correspond to relative sizes of change in flux; in (a), blue arrows are larger than red arrows and drive a net decrease in ET, whereas in (b), red arrows are larger than blue arrows and drive a net increase in ET. ΔQ = change in water yield; ΔET_{total} = net change in evapotranspiration; ΔT_{canopy} = canopy transpiration; ΔE_{canopy} = canopy (overstory) evaporation of liquid water; ΔS_{canopy} = sublimation of canopy-intercepted snow; $\Delta T_{understory}$ = understory transpiration; $\Delta E_{understory}$ = understory evaporation; $\Delta S_{snowpack}$ = sublimation of ground snowpack; and ΔE_{soil} = soil evaporation.

given the widespread mortality and rapidly evolving spatial analysis tools, than most historical studies of watersheds smaller than 25 km^2 (Bosch and Hewlett 1982, Andréassian 2004). Third, the current state of physically based, spatially distributed models—as well as spatially explicit input data on elevation, soil, and climate—enables disentangling climate versus vegetation effects (Biederman et al. 2015; Hallema et al. 2017; Perry and Jones 2017), assessment of multiple alternative climate and land-cover scenarios (Du et al. 2016), and examination of large watersheds using a water budget approach (Andréassian 2004). This capability contrasts with paired-watershed studies that typically focus on small watersheds using before/after-control/impact experimental designs, and use streamflow data as the primary and often sole catchment-scale response variable (Hibbert 1967, Hewlett 1971, Bethlahmy 1974, 1975, Bosch and Hewlett 1982, Troendle 1983, Potts 1984, Troendle and King 1985, Cheng 1989, Biederman et al. 2015). Fourth, quantifying evaporation is notoriously difficult, and eddy-covariance methods enable assessment of seasonal evapotranspiration (Biederman et al. 2014, Biederman et al. 2014).

Our objective was to synthesize recent findings and reassess the question: Does water yield increase following forest disturbance in western coniferous forests? We expected that water yield response may differ for stand-replacing versus nonstand-replacing disturbances because of different process-level responses (Adams et al. 2012, Mikkelson et al. 2013, Pugh and Gordon 2013). A second objective was to assess whether the predictability of hydrologic response—particularly decreases in streamflow or snowpack—following forest cover loss has improved since Hibbert's (1967) review. Our review included both stand-replacing disturbances, such as severe wildfire and clearcutting, and nonstand-replacing disturbances such as drought, insects, and low- to moderate-severity fire. We included literature that identified the physical processes and components of the hydrologic cycle that drove overall hydrologic response, as well as studies that explicitly assessed annual streamflow (i.e., water yield). Although we did not seek to focus specifically on studies in catchments that receive most precipitation as snow, we found that the recent widespread tree mortality in western coniferous forests occurred primarily in regions with seasonal snowpack. Given the relatively recent, post-2000 time frame of widespread natural forest disturbance in the West (Breshears et al. 2005, Williams et al. 2013, Huang et al. 2015), we focused on papers published after 2000.

Scope and Approach

To address our objectives, we first cast a wide net to include as many recent papers as possible, and then eliminated papers that did not focus on recent disturbances in western coniferous forests and also added papers that were not returned in our initial search that were recommended by colleagues and reviewers. The first step consisted of a Scopus search (scopus.com) resulting in 182 papers. Criteria for this search included titles, abstracts, or keywords that included "forest"; at least one term describing forest cover (forest cover, tree cover, or canopy cover); at least one term describing forest disturbance (tree mortality, forest disturbance, drought, water stress, fire, insects, beetle, drought, harvest, or thinning); at least one term describing hydrologic or ecohydrologic response (transpiration, evapotranspiration, snowpack, snow accumulation, snow retention, streamflow, water yield, or runoff); and publication in peer-reviewed journals in year 2000 or later, given the relatively recent increase in widespread tree mortality in the western United States (Breshears et al. 2005, Williams et al. 2013, Huang et al. 2015). In the second step, we eliminated papers that did not focus on disturbance in coniferous forests or did not include an explicit evaluation of the effects of forest disturbance on hydrologic processes, and also added several papers that were cited in studies within our search or suggested by reviewers.

Our search resulted in a set of 78 papers (Table 1) published in 30 journals, plus older seminal papers and reviews on the relation between forest cover, disturbance, and streamflow or snowpack in western forests. The number of papers published per year was higher in 2012–17 than in 2000–11, and was higher than expected given the rate of increase in all published papers during this period (Figure 2). This trend possibly corresponds to increased tree mortality in the western United States (van Mantgem et al. 2009), much of which was due to drought and insects (Meddens et al. 2012), and may reflect increased societal concern and scientific interest in water issues related to forest management. For each paper, we assessed several questions about how "forest" and "disturbance" were characterized, how hydrologic impacts were characterized, and whether confounding factors such as climate variability and postdisturbance recovery were considered. We also determined whether the disturbance under consideration was stand-replacing or nonstand-replacing, what specific disturbance agents were considered (e.g., insects, drought, wildfire), and whether conclusions were based on observations, simulations, or both.

In the next section, we highlight unexpected hydrologic responses and the process-level mechanisms (e.g., postdisturbance transpiration and sublimation) that explain such responses. Subsequent sections provide a broader interpretation of the results that incorporates earlier (pre-2000) papers to highlight where recent studies reframe or underscore previous work. The section "Linkage between Forest Disturbance and Water Yield" section summarizes our conclusions and addresses our objectives of assessing Hibbert's (1967) first and third hypotheses in the context of recent, post-2000 tree mortality in the West. In the "Improving Predictability" section, we highlight the strengths of selected papers and summarize needs for research that will improve predictive capabilities and facilitate future meta-analyses on the linkage between forest dynamics and water resources. The "Implications for Forest Management" section recognizes that managing for water yield and forest resilience may be distinct and not always compatible goals.

Postdisturbance Hydrologic Response

The 78 papers included in this review were based on observations (42 papers), simulations (18), a combination of observations and simulations (14), and conceptual models (4) of hydrologic fluxes. Here we summarize the findings with respect to postdisturbance water yield (i.e., annual streamflow), peak flows (magnitude and timing), low flow magnitude, snow water equivalent (SWE), and evapotranspiration.

Water Yield

Contrary to Hibbert's (1967) review, water yield decreased in nine of 31 studies that directly assessed streamflow response to disturbance (Table 2). Many studies found variable responses, such as both increases and decreases in different catchments. Collectively, recent research indicates that water yield is more likely to decrease following nonstand-replacing disturbance (eight of 19 studies) than following stand-replacing disturbance (three of 17 studies; Table 3). Note that some studies found variable responses (e.g., increases, no change, or decreases in streamflow) given different disturbance scenarios, and some studies assessed both

Table 1. Summary characteristics of 78 papers that met our search criteria.

Author	Year	Journal*	Location[†]	Type of study[‡]
Adams et al.	2012	*Ecohydrology*[o]	NA (conceptual)	Both
Bart et al.	2016	*Plos ONE*[O]	CA	Simulations
Bearup et al.	2014	*Nature Climate Change*[O]	CO	Observations
Bennett et al.	2018	*Hydrology & Earth System Sciences*[H]	AZ, CO, NM, UT	Simulations
Bewley et al.	2010	*Journal of Hydrology*[H]	BC	Simulations
Biederman et al.	2014	*Ecohydrology*[O]	CO, WY	Observations
Biederman et al.	2014	*Water Resources Research*[H]	CO, WY	Observations
Biederman et al.	2015	*Water Resources Research*[H]	CO	Observations
Boisramé et al.	2017	*Ecosystems*[O]	CA	Both
Boon	2009	*Hydrological Processes*[H]	BC	Both
Boon	2012	*Ecohydrology*[o]	BC	Observations
Bright et al.	2013	*Journal of Geophysical Research: Biogeosciences*[o]	CO	Observations
Broxton et al.	2015	*Ecohydrology*[O]	CO, NM	Both
Buma and Livneh	2015	*Forest Science*[F]	CO	Simulations
Buma and Livneh	2017	*Environmental Research Letters*[O]	Entire US	Observations
Burles and Boon	2011	*Hydrological Processes*[H]	AB	Both
Buttle et al.	2005	*Hydrological Processes*[H]	Canada (review)	Both
Chen et al.	2015	*Journal of Hydrometeorology*[H]	WY	Both
Concilio et al.	2009	*Climatic Change*[O]	CA	Observations
Cristea et al.	2014	*Hydrological Processes*[H]	CA	Simulations
Du et al.	2016	*Hydrological Processes*[H]	ID	Simulations
Eaton et al.	2010	*Earth Surface Processes & Landforms*[O]	BC	Observations
Ellis et al.	2011	*Canadian Journal of Forest Research*[F]	AB	Observations
Ellis et al.	2013	*Water Resources Research*[H]	AB	Observations
Gleason et al.	2013	*Geophysical Research Letters*[H]	OR	Observations
Grant et al.	2013	*Frontiers in Ecology & Environment*[O]	NM	Both
Green and Alila	2012	*Water Resources Research*[H]	BC, CO, ID, UT, WY	Both
Guardiola-Claramonte et al.	2011	*Journal of Hydrology*[H]	AZ, CO, NM, UT	Observations
Hallema et al.	2017	*Ecohydrology*[O]	AZ, CA	Observations
Hallema et al.	2017	*Hydrological Processes*[H]	Western United States	Observations
Harpold et al.	2014	*Ecohydrology*[O]	NM	Observations
Harpold et al.	2015	*Hydrological Processes*[H]	CA, CO, NM	Observations
Hernandez et al.	2018	*Forests*[F]	ID, MT	Simulations
Hubbart et al.	2015	*Forest Science*[F]	ID	Observations
Huff et al.	2000	*Journal of Forestry*[F]	CA	Both
Jackson and Prowse	2009	*Hydrological Processes*[h]	BC	Observations
Jacobs	2015	*Ecohydrology*[o]	NM	Observations
Li et al.	2018	*Journal of Hydrology*[H]	BC, WA	Observations
Livneh et al.	2015	*Journal of Hydrology*[H]	CO	Both
Lundquist et al.	2013	*Water Resources Research*[H]	CA	Observations
Mahat and Anderson	2013	*Hydrology & Earth System Sciences*[H]	AB	Simulations
Maxwell et al.	2019	*Forest Ecology & Management*[F]	UT	Observations
Meyer et al.	2017	*Forest Ecology & Management*[F]	BC	Simulations
Mikkelson et al.	2013	*Biogeochemistry*[O]	NA (review)	Both
Moore and Scott	2005	*Canadian Water Resources Journal*[H]	BC	Observations
Moore and Wondzell	2005	*Journal of American Water Resources Association*[H]	AK, BC, ID, OR, WA	Observations

Table 1. Continued

Author	Year	Journal*	Location†	Type of study‡
Morillas et al.	2017	*Journal of Geophysical Research: Biogeosciences*^{O}	NM	Observations
Penn et al.	2016	*Water Resources Research*^{H}	CO	Simulations
Perrot et al.	2014	*Ecohydrology*^{O}	CO	Observations
Perry and Jones	2017	*Ecohydrology*^{O}	OR	Observations
Pomeroy et al.	2012	*Hydrological Processes*^{H}	AB	Simulations
Poon and Kinoshita	2018	*Journal of Hydrology*^{H}	NM	Simulations
Pugh and Gordon	2013	*Hydrological Processes*^{H}	Western North America	Simulations
Pugh and Small	2012	*Ecohydrology*^{O}	CO	Observations
Pugh and Small	2013	*Hydrology Research*^{H}	CO	Observations
Reed et al.	2014	*Environmental Research Letters*^{O}	WY	Observations
Reed et al.	2016	*Theoretical & Applied Climatology*^{O}	WY	Observations
Robles et al.	2014	*PLoS ONE*^{O}	AZ	Simulations
Saksa et al.	2017	*Water Resources Research*^{H}	CA	Simulations
Sankey et al.	2015	*Remote Sensing of Environment*^{O}	AZ	Observations
Sexstone et al.	2018	*Water Resources Research*^{H}	CO	Both
Slinski et al.	2016	*Environmental Research Letters*^{O}	ID, MT, OR, UT, WA, WY	Observations
Stevens	2017	*Ecological Applications*^{O}	CA	Observations
Sun et al.	2018	*Hydrological Processes*^{H}	ID, WA	Simulations
Svoma	2017	*Journal of Geophysical Research: Atmospheres*^{O}	AZ	Simulations
Tennant et al.	2017	*Water Resources Research*^{H}	CA, CO, NM, ID	Observations
Tonina et al.	2008	*Hydrological Processes*^{H}	ID	Simulations
Vanderhoof and Williams	2015	*Agricultural & Forest Meteorology*^{O}	CO, WY	Both
Varhola et al.	2010	*Canadian Journal of Forest Research*^{F}	BC	Both
Wei and Zhang	2010	*Water Resources Research*^{H}	BC	Observations
Wine and Cadol	2016	*Environmental Research Letters*^{O}	NM	Both
Wine et al.	2018	*Environmental Research Letters*^{O}	Western United States	Both
Winkler et al.	2005	*Hydrological Processes*^{H}	BC	Observations
Winkler et al.	2014	*Hydrological Processes*^{H}	BC	Observations
Winkler et al.	2015	*Hydrology Research*^{H}	BC	Observations
Winkler et al.	2017	*Ecohydrology*^{O}	BC	Observations
Yazzie and Chang	2017	*Climate*^{O}	OR	Simulations
Zhang and Wei	2012	*Hydrology & Earth System Sciences*^{H}	BC	Observations

* Primary discipline of journal (F = forestry, H = hydrology, and O = other/cross-disciplinary).

† Locations are abbreviated using standard US state and Canadian province abbreviations.

‡ Results based on observations, simulations, or both observations and simulations.

stand-replacing and nonstand-replacing disturbance. Among the 31 studies that assessed annual streamflow response, 14 used direct flow measurements, nine used simulation models, five used a combination of observations and simulations, and three presented conceptual models based on previous literature.

When nonstand-replacing disturbances result in decreased streamflow, it is because total postdisturbance evapotranspiration increases (Figure 1b), as a result of increased transpiration in the understory, increased sublimation from snowpack, or increased soil evaporation because of more radiation reaching the surface (Biederman et al. 2014, Bennett et al. 2018)—all of which decrease the proportion of precipitation available for streamflow. Previous reviews concluded that streamflow response to nonstand-replacing disturbance may be highly variable, relative to stand-replacing disturbances, and cite the competing responses of decreased overstory transpiration and decreased canopy interception losses, versus increased evapotranspiration from the understory and ground (Figure 1) (Moore and Wondzell 2005, Adams et al. 2012, Mikkelson et al. 2013, Pugh and Gordon 2013). The variable responses found by other studies, many of which were published after these reviews, found a combination of increases and no change (Huff et al. 2000, Winkler et al. 2015, Penn et al. 2016, Boisramé et al. 2017), a combination of all possible responses (Slinski et al. 2016, Boisramé et al. 2017), and either decreases or no change (Biederman et al. 2015). Eight studies found consistent water-yield responses, including both consistent increases (Robles et al. 2014, Livneh et al. 2015, Buma and Livneh 2017, Li et al. 2018, Wine et al. 2018) and consistent decreases (Guardiola-Claramonte et al. 2011, Biederman et al. 2014, Bennett et al. 2018).

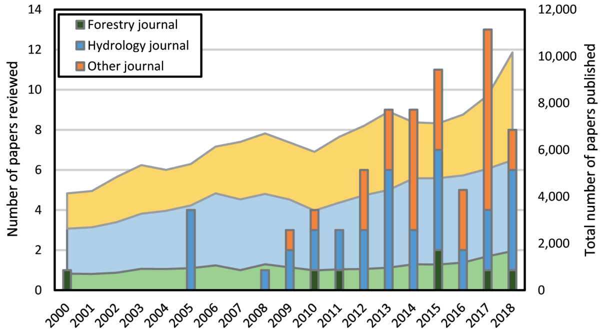

Figure 2. Publication year and journal discipline (forestry, hydrology, or "other" cross-disciplinary journal) of the 78 papers included in our review (vertical bars; left axis) and the total number of papers in each discipline (horizontal shaded areas; right axis). (Note that the journal *PLoS ONE*, which began publishing in 2006, is categorized as "other" yet omitted in the total number of papers (lines) because within 5 years of its founding, it published several times as many papers as all other journals in aggregate. Two papers in this review were published in *PLoS ONE*: one in 2014 and one in 2016.)

Studies of stand-replacing disturbances, such as clearcutting or severe wildfire, confirm that water yield typically increases following stand-replacing disturbances, as expected from the previous reviews (Hibbert 1967, Bosch and Hewlett 1982, Troendle 1983, Troendle and King 1985, Andréassian 2004). However, they also suggest that postdisturbance vegetation characteristics determine the direction of response. Two of the three studies with decreases in annual streamflow following stand-replacing disturbances provide similar explanations for their results: water yield decreases

Table 2. Metrics of hydrologic response used in the 78 papers in this review, as well as the number of papers that found increases, no change, or decreases in each metric.

Response	Total no. of studies	Increase	No change	Decrease
Streamflow (annual water yield)	31	26	16	9
Peak flow magnitude	22	19	10	7
Peak flow timing*	18	14	7	4
Low flow magnitude	25	14	9	9
Maximum snow water equivalent	42	34	10	10

Note: Totals do not always equal the sum of the papers across each row because many studies found variable responses (e.g., increases, no change, or decreases in streamflow given different disturbance scenarios). Similarly, the sum of the total number of papers does not equal 78 because many studies assessed multiple response metrics (e.g., both streamflow and evapotranspiration).

* Peak flow timing "increase" represents earlier peak flows; "decrease" represents later peak flows.

Table 3. Response of annual streamflow (i.e., water yield) to disturbance.

Type of disturbance	Total no. of studies	Increase	No change	Decrease
Stand-replacing	17	15	7	3
Nonstand-replacing*	19	15	10	9

Note: Totals do not equal the sum of the papers across each row and column because many studies found variable responses (e.g., increases, no change, or decreases in streamflow given different disturbance scenarios), and some studies assessed both stand-replacing and nonstand-replacing disturbance.

* Papers focused on nonstand-replacing disturbances included three papers based on conceptual models, which predicted an increase (three papers), no change (three papers), or decreases (one paper) in streamflow.

when trees are replaced with shrubs with high leaf area and high transpiration rates (Figure 1b) (Bart et al. 2016, Bennett et al. 2018). The third study found decreases in streamflow within a geographically constrained region of rain-dominated catchments of the coastal Pacific Northwest, where decreases in water yield occur because of a decline in fog interception (Moore and Wondzell 2005). In contrast to these three studies, most studies concluded that water yield consistently increases following stand-replacing disturbance (Figure 1a) (Wei and Zhang 2010, Zhang and Wei 2012, Buma and Livneh 2015, Winkler et al. 2015, Du et al. 2016, Hallema et al. 2017, Winkler et al. 2017, Hernandez et al. 2018, Li et al. 2018, Sun et al. 2018), although several studies found variable streamflow response, depending on the disturbance scenario (Moore and Wondzell 2005, Bart et al. 2016, Wine and Cadol 2016, Hallema et al. 2017, Wine et al. 2018).

Among the simulation models used to assess postdisturbance water yield, only physically based models predicted any decreases in water yield following disturbance, whereas simpler models consistently predicted increases. Simulation-based studies that found decreases in postdisturbance streamflow are in similar types of catchments (i.e., those with high total radiation at low latitudes, and with dense postdisturbance vegetation) to observational studies that found decreases in streamflow because of net increases in evapotranspiration. Given that some observational studies also concluded that streamflow may decrease following disturbance, particularly following nonstand-replacing disturbance, the ability to simulate postdisturbance decreases is a strength of physically based models. Thus, physically based models can complement paired-catchment studies to robustly assess the impacts of forest disturbance on streamflow (Moore and Scott 2005), whereas more empirically based models may be incapable of simulating the conditions that lead to postdisturbance decreases in water yield. The degree of spatial distribution and the number of physical processes in the models varied, from the point-based WRENSS model applied to grid cells (Huff et al. 2000), to catchment-scale empirical or statistical models (Wine and Cadol 2016, Boisramé et al. 2017, Robles et al. 2017, Wine et al. 2018), semidistributed models such as the Soil and Water Assessment Tool (Hernandez et al. 2018), and several fully distributed, physically based models such as the Distributed Hydrology Soil Vegetation Model (Green and Alila 2012, Buma and Livneh 2015, Livneh et al. 2015, Du et al. 2016, Sun et al. 2018); Regional Hydro-Ecological Simulation System (Bart et al. 2016, Saksa et al. 2017); ParFlow (Penn et al. 2016); and Variable Infiltration Capacity (Bennett et al. 2018).

Peak Flows

Twenty-two studies evaluated peak flow magnitudes, and most found that postdisturbance peak flows exceed predisturbance peaks (Table 2), regardless of whether disturbance is stand-replacing. However, three studies found that peak flows sometimes increase, do not change, or decrease (Slinski et al. 2016, Buma and Livneh 2017, Bennett et al. 2018), depending on disturbance severity and extent, postdisturbance vegetation recovery, and radiation budgets—all of which affect snowmelt rates (Moore and Wondzell 2005, Mikkelson et al. 2013, Pugh and Gordon 2013). For example, snowmelt occurs more rapidly—and thus produces higher peak flows—at sites with higher total radiation, which tend to occur on sites at lower latitudes, lower elevations, and south-facing slopes. Snowmelt in undisturbed forested watersheds is typically asynchronous by elevation (i.e., lower elevations melt earlier and higher elevations melt later), whereas postdisturbance synchronization of snowmelt leads to higher peak flows (Bewley et al. 2010, Pomeroy et al. 2012). Thus, variable responses in peak flows may be explained by the degree of synchronicity of snowmelt rates throughout a watershed (Pomeroy et al. 2012), and disturbance that reduces synchronicity of snowmelt can lead to smaller peak flows. Another factor that may reduce postdisturbance peak flows is a simultaneous shift in climate that results in more precipitation falling as rain versus snow (Jacobs 2015).

Postdisturbance peak flows typically occur earlier than predisturbance peaks (Table 2), as expected from previous reviews (Andréassian 2004). However, seven studies found variable responses with respect to peak flow timing, including later peaks in some cases (Moore and Wondzell 2005, Pomeroy et al. 2012, Pugh and Gordon 2013, Cristea et al. 2014, Livneh et al. 2015, Du et al. 2016, Slinski et al. 2016, Bart et al. 2016, Buma and Livneh 2017). Later peak flows are more likely to occur when snow accumulation increases following forest cover loss (Cristea et al. 2014); note that snow accumulation does not always increase following disturbance (Table 2). As with peak flow magnitude, peak flow timing may be affected by the degree of synchronization of snowmelt across elevation zones (Bewley et al. 2010, Pomeroy et al. 2012).

Low Flows

The response of low flows to forest disturbance is related to snow accumulation, snowmelt rates, and summer evapotranspiration rates. Low flows typically increase when more snow accumulates, snow melts more slowly, and/or summer evapotranspiration declines. Low flows can also be sensitive to time since disturbance. In the Pacific Northwest, conversion of mature forests to timber plantations may initially result in higher summer flows but then switch to lower low flows by 15 years postharvest, and this decrease may persist for several decades (Perry and Jones 2017). Most of the studies considered here did not cover this length of time, and it is noteworthy that Perry and Jones (2017) concluded that initially inflated seasonal low flows may switch to deficits several years after disturbance. Moore and Wondzell's (2005) review concluded that water yield may initially increase but then decrease in the longer term. In both papers, long-term streamflow declines were attributed to rapid postdisturbance vegetation growth.

Among the remaining studies, postdisturbance seasonal low flows increased in 14 of the 19 studies that evaluated low flows, nine studies found no change, and eight studies found decreases (Table 2). However, given the rigor of Perry and Jones's (2017) long-term study, which ruled out climate variability as a cause of observed decreases in low flows, future research into the effects of disturbance on seasonal low flows must consider that the response may vary over decadal timescales.

SWE

Although 34 of 42 studies that assessed SWE concluded that annual maximum SWE increases following forest disturbance, 10 studies concluded that it decreases (Table 2). Contributors to the variable response of SWE include the timing and magnitude of precipitation, as well as disturbance type (stand-replacing versus nonstand-replacing) and forest structure—which both affect radiation and thus sublimation (described in the next section) and SWE. In some studies, SWE in disturbed versus undisturbed stands differs in low-snow years but not in high-snow years, when the amount of snowfall presumably overwhelms trees' interception capacity (Boon 2012, Winkler et al. 2014). Several studies concluded that SWE in stands affected by nonstand-replacing, insect-caused disturbances is more similar to undisturbed forests than to sites with recent stand-replacing disturbances (Boon 2009, 2012, Burles and Boon 2011, Pomeroy et al. 2012, Winkler et al. 2014). This suggests that SWE responds to a continuum of disturbance levels, and that quantitative characterization of forest density—such as regressions between leaf area index (LAI) or canopy cover and SWE (Varhola et al. 2010)—could lead to improved quantitative predictions of disturbance effects on SWE.

Patterns of SWE response vary geographically, with more consistent postdisturbance increases at higher latitudes and more variable responses at lower latitudes. Of 13 studies of SWE conducted in Canada and the northern United States, nine consistently found higher SWE following disturbance (Winkler et al. 2005, Boon 2009, Jackson and Prowse 2009, Varhola et al. 2010, Burles and Boon 2011, Ellis et al. 2013, Gleason et al. 2013, Chen et al. 2015, Hubbart et al. 2015, Du et al. 2016), whereas four found variable response—i.e., a combination of increases, no change, and decreases (Ellis et al. 2011, Boon 2012, Winkler et al. 2014, 2015). Among the 13 studies conducted farther south in the United States, only five consistently found that SWE increases in disturbed stands (Pugh and Small 2013, Biederman et al. 2014, Broxton et al. 2015, Harpold et al. 2015, Livneh et al. 2015). Four studies found that SWE responds variably to reduced canopy density (Pugh and Small 2012, Lundquist et al. 2013, Perrot et al. 2014, Tennant et al. 2017). The remaining studies concluded that SWE does not change (Biederman et al. 2014, Sexstone et al. 2018, Maxwell et al. 2019) or decreases following disturbances (Harpold et al. 2014, Stevens 2017). Thus, postdisturbance SWE is more often observed to decrease or respond variably at low latitudes than at high latitudes, where it typically increases. Unexpected decreases in postdisturbance SWE are attributed to increased shortwave radiation, which results in increased ablation of the snowpack (Harpold et al. 2014, Stevens 2017), as well as decreased albedo following accumulation of needles, bark, and other organic matter on the snow surface, which also leads to snowpack ablation (Gleason et al. 2013, Pugh and Gordon 2013, Winkler et al. 2014). It is important to note that dividing ablation into sublimation versus melt is a difficult yet important task for estimating water budgets, because whereas melt clearly contributes to streamflow, sublimation represents evapotranspiration losses that can contribute to reduced streamflow.

Twenty-six studies quantified at least one component of radiation budgets that influences snowpack. Disturbance affects both shortwave (i.e., solar) and longwave radiation, which increase and decrease, respectively, as a result of reduced tree cover (Adams et al. 2012, Mikkelson et al. 2013, Pugh and Gordon 2013, Sun et al. 2018). Postdisturbance changes in the relative contributions of shortwave and longwave radiation are not linear, and their relative contributions vary throughout the seasonal snowpack season as sun angle changes (Boon 2009, Burles and Boon 2011, Ellis et al. 2011, 2013, Harpold et al. 2014, Sun et al. 2018). Total radiation available for snowmelt sometimes increases by more than the increase in insolation alone, particularly when organic debris (i.e., needles, bark, branches) falls on the snowpack following tree mortality because of insects or wildfire (Gleason et al. 2013, Pugh and Gordon 2013). Debris-covered snowpack has a lower albedo than debris-free snowpack, and thus absorbs more radiation and melts or sublimates faster (Gleason et al. 2013, Pugh and Gordon 2013, Winkler et al. 2014). In the Sierra Nevada, disturbance severity is negatively related to SWE (Stevens 2017), presumably because denser, less disturbed stands shade the snowpack and slow snowmelt. Although trees shade the snowpack from shortwave radiation, they also emit longwave radiation—which presents a tradeoff between shortwave and longwave radiation, as snowmelt is affected by total radiation (Lundquist et al. 2013, Sun et al. 2018). At temperatures near freezing, medium-density forests are likely to retain more snow than higher-density forests (with higher longwave radiation) or lower-density forests (with higher shortwave radiation) (Lundquist et al. 2013, Hubbart et al. 2015). For example, forest thinning in Arizona may decrease longwave radiation while having little effect on shortwave radiation reaching snowpack, resulting in decreased net radiation and thus increased SWE (Svoma 2017). In contrast, in areas with average winter temperatures below freezing, longwave radiation may be insufficient to melt midwinter snowpack, and shading becomes more important for snow retention in later winter (Ellis et al. 2011, Lundquist et al. 2013, Stevens 2017). The impact of radiation budgets on SWE suggests that physically based models that include components of radiation could improve the predictability of hydrologic response to disturbance.

Several studies concluded that topographic aspect controls the effects of trees on snowmelt via its effects on shortwave radiation. In the Canadian Rockies, snow disappearance date either increases or decreases in clearings, relative to intact forest stands, depending on aspect (Ellis et al. 2011). Snowpack under undisturbed forests on south-facing slopes is shaded and thus receives less shortwave radiation—and retains snow longer because of slower snowmelt—than adjacent clearings, even though clearings may initially have a higher total snowpack. In contrast, trees on north-facing slopes have higher late-winter snowmelt rates than clearings because of higher longwave radiation within forested stands (Ellis et al. 2011). In central Utah, which is at a lower latitude and thus has a higher solar angle, stand-replacing wildfire results in earlier snow disappearance on both north- and south-facing slopes, relative to unburned stands (Maxwell et al. 2019). Two studies—one west-wide (Tennant et al. 2017) and one in New Mexico (Harpold et al. 2014)—concurred that in areas with relatively high solar radiation, e.g., at low latitudes, aspect exerts a greater control on SWE than vegetation characteristics.

Evapotranspiration

The long-held expectation that postdisturbance water yield will increase is based on the assumption that evapotranspiration will decrease (Figure 1a), thus making more water available for streamflow (Adams et al. 2012, Pugh and Gordon 2013). Here we examine three components of evapotranspiration that have been cited as driving gains in streamflow following disturbance: transpiration; sublimation of snow, both from canopies and from snowpack; and evaporation from soil (Figure 1). All were found to respond variably to disturbance, as described below.

Few studies have asked whether the expectation of reduced postdisturbance transpiration holds true for nonstand-replacing disturbances such as the widespread recent die-off (Hicke et al. 2015). Two case studies highlight mechanisms that may result in unexpected increases in evaporation. First, although mountain pine beetle epidemics kill overstory trees and thus lead to declines in overstory transpiration, increased transpiration of surviving vegetation, including advance regeneration (i.e., seedlings and saplings that were present in the understory prior to the epidemic), can lead to increased total evapotranspiration and decreased streamflow (Biederman et al. 2014). Another study concluded that decreases in postdisturbance transpiration may be offset by increased soil evaporation, resulting in a net increase in evapotranspiration (Reed et al. 2016).

The assumption that reduced canopy interception will lead to a net decrease in postdisturbance sublimation, and thus an increase in SWE, is supported by stand-replacing disturbances such as clearcutting (Stednick 1996). However, two observational studies—one in Colorado (Biederman et al. 2014) and one in New Mexico (Harpold et al. 2014)—and one simulation study (Sexstone et al. 2018) found that increased sublimation from the snowpack can offset decreases in canopy sublimation. High radiation reaching the snowpack surface, as well as increased turbulence beneath the reduced postdisturbance canopy, can cause unexpectedly high sublimation from snowpack (Biederman et al. 2014, Sexstone et al. 2018).

Finally, evaporation from soil represents not only a component of evapotranspiration but also a constraint on forest regeneration and growth. Most of the 18 studies that assessed postdisturbance soil moisture evaluated nonstand-replacing disturbances. Approximately equal numbers of studies concluded that soil evaporation increases, decreases, or does not change following disturbance, and several studies found variable responses (Adams et al. 2012, Grant et al. 2013, Pugh and Gordon 2013, Reed et al. 2014, Harpold et al. 2015, Bart et al. 2016, Boisramé et al. 2017). Postdisturbance soil moisture may increase because of decreased transpiration (Concilio et al. 2009, Mikkelson et al. 2013, Penn et al. 2016, Saksa et al. 2017, Reed et al. 2016), but it may also decrease, particularly during the growing season, because of increased evaporative demand driven by higher solar radiation following overstory canopy loss (Biederman et al. 2014, Chen et al. 2015, Bennett et al. 2018). Soil moisture response may vary because of differences in snow retention—the date of complete snow disappearance (Grant et al. 2013, Harpold et al. 2015)—and depletion of soil moisture by growing-season evapotranspiration (Bart et al. 2016, Bennett et al. 2018). As with seasonal low flows, soil moisture response to disturbance may vary over long timescales (Perry and Jones 2017).

Linkage between Forest Disturbance and Water Yield

This synthesis of recent literature indicates that forest disturbance may increase or decrease water yield, leading to two important conclusions about the linkage between forest disturbance and water yield in semiarid western watersheds: (1) the hypothesis that forest cover reduction leads to increased water yield is not universally true, and in some cases postdisturbance water yield may actually decrease, and (2) although the "response to treatment [or disturbance] is highly variable" (Hibbert 1967, p. 535), the ability to predict where water yield may increase versus decrease following disturbance is improving. Thus, this review contributes insights beyond those of other recent reviews by identifying circumstances that may exhibit decreased postdisturbance water yield. Silvicultural prescriptions such as fuels treatments and forest thinning often mimic nonstand-replacing disturbances such as those summarized here, and therefore they may fail to increase water yield in semiarid western watersheds.

Studies that found decreases in water yield highlight important exceptions to Hibbert's (1967) first hypothesis that forest cover loss leads to increased water yield. Two previous reviews (Adams et al. 2012, Pugh and Gordon 2013) hypothesized that water yield could actually decrease following nonstand-replacing tree die-off, and several studies have now confirmed this response. These unexpected results facilitate formulation of new hypotheses about when water yield—and potentially snowpack—might actually decrease following forest disturbance. First, all of these studies occurred in a semiarid region. Second, two factors that lead to decreased postdisturbance water yield and snowpack are: (1) high density and growth rates, and thus transpiration, of postdisturbance vegetation (Guardiola-Claramonte et al. 2011, Biederman et al. 2014, Bart et al. 2016, Bennett et al. 2018), and (2) high total radiation (Harpold et al. 2014, Biederman et al. 2015, Stevens 2017), which leads to increased sublimation from the snowpack (Biederman et al. 2014, Harpold et al. 2014), and increased evaporation of soil moisture (Biederman et al. 2014, Chen et al. 2015, Bennett et al. 2018). In short, increases in evapotranspiration (Figure 1b, red arrows) more than compensate for the decreases (Figure 1b, blue arrows). The relative magnitudes of the responses exhibited by individual components of evapotranspiration (Figure 1) are related both to the type and density of postdisturbance vegetation, and also to net radiation, which drives evaporative demand. Net radiation is partly a function of latitude and aspect, which have long been identified as a control on the magnitude of water-yield increases following harvest in wetter areas such as Coweeta, NC, and Fernow, WV (Hibbert 1967).

Previous reviews provided rule-of-thumb thresholds for when and where forest disturbance is likely to increase water yield: in watersheds where at least 20 percent of tree cover is removed (Stednick 1996, Brown et al. 2005, Adams et al. 2012) and precipitation is at least 500 mm/year (Adams et al. 2012). Given that most studies reviewed here characterized predisturbance conditions categorically rather than quantitatively (Table 4), the interpretation of the 20 percent rule of thumb is likely to be applied to entire stands (e.g., 20 percent of area within a catchment,

Table 4. Metrics used to describe forest conditions and disturbance.

Metric	Forest condition	Disturbance
Percentage of area forested/disturbed	3	14
Percentage of canopy cover at catchment scale	5	1
Categorical	41	44
Leaf area index/plant area index	15	8
Standard forestry measurements	11	5
Tree growth and/or mortality rates	1	4
NA (review papers)	2	2
Total	78	78

Note: More than half of papers described forests and disturbances in categorical terms rather than quantitative ones; the most common quantitative metric was leaf or plant area index.

based on delineation of polygons) rather than to the density within individual stands (e.g., 20 percent density reduction in stands of known density). However, the relation between forest cover and streamflow response is complex and nonlinear (Moore and Wondzell 2005). An "area affected" characterization can mask the variability of stand densities within a catchment, where density is known to affect snow accumulation and retention (Lundquist et al. 2013), and perpetuates the categorical characterization of forests and disturbance (e.g., "disturbed" versus "undisturbed"), as described below. In regard to precipitation thresholds, decreases in postdisturbance water yield occurred in watersheds with precipitation greater than the rule of thumb of 500 mm/year (Table 5).

Two recent high-profile papers underscore the ongoing interest and uncertainty regarding the factors that determine water yield response to forest disturbance and recovery. In an analysis of 251 catchments worldwide, Evaristo and McDonnell (2019) report that among catchments where streamflow increased following removal of forest cover, the best predictor of the magnitude of streamflow increase was subsurface storage potential (i.e., depth to bedrock). However, a subsequent critique (Kirchner et al. 2019) of Evaristo and McDonnell (2019) illuminates the obstacles inherent in amassing reliable broad-scale datasets, building robust models, and extending findings to new watersheds. As suggested by Kirchner et al. (2019), shortcomings in the ability to predict streamflow response to forest cover change could result in forest policy and management that may have unquantified effects over both short- and long-term timescales, and also at spatial scales ranging from watersheds to continental-scale linkages between cover type and downwind precipitation. Thus, the disciplines of forestry and hydrology have much work to do, both individually and collectively, to improve the predictability of the effects of forest dynamics on water resources, as discussed below.

Improving Predictability of Hydrologic Response to Disturbance

Extending recent findings to forest and watershed management, and predicting the response of any given watershed to disturbance, requires an improved quantitative framework linking forest conditions, disturbance severity, and hydrologic response. Despite the recent increase in the number of papers focused on this linkage, less than half of studies characterized forest cover and forest disturbance quantitatively rather than categorically (Table 4). Given that individual components of the hydrologic cycle are affected by vegetation composition (Bart et al. 2016, Bennett et al. 2018), structure (Broxton et al. 2015), density (Lundquist et al. 2013, Hubbart et al. 2015), and radiation exposure (i.e., aspect) (Ellis et al. 2011, Harpold et al. 2014, Tennant et al. 2017), a more precise understanding of the linkage between disturbance and hydrologic response requires analysis of quantitative (e.g., LAI, basal area, canopy cover) rather than categorical or qualitative (e.g., forest versus nonforest, disturbed versus undisturbed) attributes.

Among the majority of studies that characterized forests and disturbance categorically rather than quantitatively (Table 4), descriptors of "forest" (i.e., predisturbance conditions) included three types of categories: forest versus nonforest; forest type or cover type; or forest density classes. The most common categorical characterizations of forest disturbance (Table 4) consisted of simply "disturbed" versus "not disturbed" (17 papers), where disturbance thresholds were defined either within the study or by an external

Table 5. Summary of studies that detected decreased water yield following disturbance.

Paper	Type of study	Location	Annual precipitation	Magnitude of water yield change	Extent of disturbance	Type of disturbance	Factors leading to decreased *Q*
Adams et al. 2012	Review paper	NA (review)	NA (review)	–50 percent to +250 percent (highest values not realistic: Adams et al. 2012)	20 percent forest loss	Nonstand-replacing mortality due to drought and insects (<100 percent mortality)	Precipitation <~500 mm/yr, not snowmelt-dominated, rapid understory growth that results in increased evapotranspiration
Bart et al. 2016	Simulation (Regional Hydro-Ecological Simulation System)	Sierra Nevada, CA	1297 mm/yr	–30 percent to +155 percent	50–100 percent forest loss	Stand-replacing wildfire	High transpiration by dense postdisturbance shrubs
Bennett et al. 2018	Simulation (Variable Infiltration Capacity)	San Juan Basin, AZ/CO/NM/UT	666 mm/yr	–21 percent to –15 percent	>50 percent forest loss	Multiple agents (disturbance projections based on climate), including stand-replacing and nonstand-replacing mortality	High transpiration by dense postdisturbance shrubs
Biederman et al. 2014	Observation	Rocky Mountains, CO/WY	600–800 mm/yr	–74 percent to –62 percent	Up to 80 percent of area affected	Nonstand-replacing mortality due to insects (<100 percent mortality)	Increased postdisturbance evapotranspiration, including sublimation from snowpack
Biederman et al. 2015	Observation	Rocky Mountains, CO	730–830 mm/yr	–29 percent to –11 percent	35–50 percent of area affected	Nonstand-replacing mortality due to insects (<100 percent mortality)	Increased postdisturbance evapotranspiration, mainly due to transpiration of understory vegetation
Guardiola-Claramonte et al. 2011	Observation	Colorado Plateau, AZ/CO/NM/UT	208–480 mm/yr	Up to –50 percent	3–21 percent mortality of trees	Nonstand-replacing mortality due to drought (<100 percent mortality)	Increased transpiration by herbaceous understory vegetation and increased soil evaporation due to increased insolation of the soil surface
Pugh and Gordon 2013	Review paper	NA (review)	NA (review)	Decreases recognized in conceptual model	Not specified	Nonstand-replacing mortality due to insects (<100 percent mortality)	Increased postdisturbance evapotranspiration
Slinski et al. 2016	Observation	CO, ID, MT, OR, SD, UT, WY	NA (not reported across 33 catchments)	Not reported	21–72 percent	Nonstand-replacing mortality due to insects (<100 percent mortality)	Increased postdisturbance evapotranspiration

Note: Where rain versus snow domination of precipitation regime was found to be important, it is noted under “Factors leading to decreased *Q*” (*Q* = water yield). Note that most studies also detected increases or no change in some circumstances; only conditions leading to decreased *Q* are indicated.

dataset (e.g., Aerial Detection Surveys). For mountain pine beetle disturbance, some studies further distinguished between green, red, and gray phases of infestation (see Pugh and Gordon 2013, for phase definitions), which were expected to differentially affect SWE via their effects on snowpack albedo, shading, and interception (Winkler et al. 2005, Pugh and Small, 2012, 2013, Pugh and Gordon 2013, Biederman et al. 2014, Biederman et al. 2014, Perrot et al. 2014, Penn et al. 2016). Other papers included scenarios of either multiple disturbance agents or multiple severities of a single agent, as well as one study that characterized cover type conversion from forest to multiple nonforest scenarios with varying vegetation densities (Bart et al. 2016).

Several studies concluded that forests affected by nonstand-replacing disturbance should be considered a distinct cover type, based on observations that nonstand-replacing disturbances exhibit a range of hydrologic responses between those observed in undisturbed forests and those subject to stand-replacing disturbances such as clearcut harvests or severe wildfire (Boon 2009, Boon 2012, Pomeroy et al. 2012, Winkler et al. 2014). One of these studies (Boon 2012) proposed the concept of a “forest structure continuum” (p. 284), which represents a step toward quantifying forests and forest disturbance numerically rather than applying categories of disturbance or cover. This recommendation underscores the importance of characterization forests and disturbance quantitatively rather than categorically.

Quantitative Characterization of Forests and Disturbance

Among the minority of studies that quantitatively related forest conditions to hydrologic fluxes (Table 4), the most common metric for characterizing forest conditions was LAI. Process-based simulation models, such as the Regional Hydro-Ecological Simulation System (Tague and Band 2004) and Distributed Hydrology Soil Vegetation Model (Wigmosta et al. 1994) ecohydrologic models and one snowpack model (Broxton et al. 2015), include the capability to represent forest canopy densities in terms of LAI. Because standard forestry assessments do not include LAI (Härkönen et al. 2015, USDA 2017; plus the majority of studies in this review), a disconnect exists between standard forestry measurements and quantitative forest metrics used in hydrology. Future efforts to improve quantitative predictions of disturbance effects on water resources should thus include spatially explicit estimation of LAI. Abundant research has improved the ability to estimate LAI on the ground using light sensors or hemispherical photography (Jonckheere et al. 2004), or remotely via airborne or space-based light detection and ranging (Tang et al. 2014), as efficient alternatives to destructive sampling that may have the added benefit of separating understory from overstory LAI. In recent studies, both the scale and grain (e.g., ability to distinguish overstory from understory LAI) of LAI assessments have varied widely, depending mainly on data availability. At the broadest scale of assessment, a single LAI value represented each cover or disturbance class (Perrot et al. 2014, Broxton et al. 2015, Penn et al. 2016, Svoma 2017, Sexstone et al. 2018). Other studies spatially averaged LAI within disturbance severity classes (Pomeroy et al. 2012, Reed et al. 2016). The most data-intensive studies represented spatially and temporally explicit LAI in empirical analysis (Bewley et al. 2010), process-based numerical models (Reed et al. 2014, Chen et al. 2015), or ecohydrologic simulation models (Huff et al. 2000, Livneh et al. 2015, Saksa et al. 2017, Bennett et al. 2018).

Of the studies that collected detailed forestry measurements, exclusive of LAI, the majority did not quantitatively analyze those data relative to hydrologic effects and presented quantitative data only in a site-descriptive context. Only a single study related quantitative forestry measurements to hydrologic response, using correlations of forest cover against maximum SWE and snowpack ablation rate (Varhola et al. 2010). Standard forestry measurements included stand-level quantitative metrics such as basal area, tree density, and tree volume, as well as tree-level attributes such as diameter, height, and species. Although allometric equations allow estimation of LAI based on standard forestry measurements, they are typically applicable only in the localized regions and for the species for which they were developed (Jonckheere et al. 2004). The scale of forest characterization also ranged from site-specific evaluation to watershed-scale assessment based on maps or remote sensing. Two studies in Table 1 (Zhang and Wei 2012, Li et al. 2018) quantified disturbance effects in terms of equivalent clearcut area (ECA) (King 1989)—which accounts for the density and extent of disturbed areas for the purpose of predicting peak flow changes—and one paper presented a brief critical review of the concept (Varhola et al. 2010). As discussed above, hydrologic response to disturbance is influenced by stand structure, density, and radiation exposure, which all affect snow accumulation, snowmelt rates, and evapotranspiration. Because these influences are almost certainly nonlinear (Moore and Wondzell 2005), it is unlikely that ECA can accurately represent the hydrologic impacts of spatially heterogeneous, nonstand-replacing forest disturbances.

Direct and Indirect Hydrologic Effects of Forest Disturbance and Climate

Aside from the most data-intensive LAI assessments, nearly all other studies in our review assumed postdisturbance LAI to be time-invariant, therefore not accounting for growth of postdisturbance vegetation. Applying new findings to management requires not only improving our quantitative representation of vegetation in hydrologic analyses, but also accounting for postdisturbance vegetation dynamics and response to future climate (Andréassian 2004, Buma and Livneh 2015, Bennett et al. 2018). Future disturbance and climate will have both direct effects on streamflow (e.g., warmer temperatures will result in more precipitation falling as rain rather than snow) and indirect effects as mediated through vegetation changes (e.g., warmer temperatures lead to tree die-off, which in turn affects evapotranspiration). Accounting for postdisturbance vegetation dynamics and climate scenarios is possible given the current state of physically based ecohydrologic modeling (Wigmosta et al. 1994, Tague and Band 2004), which again requires better quantitative characterization of forest conditions.

Postdisturbance recovery and regrowth can cause streamflow to either increase or decrease, depending on seasonality, time since disturbance, and density and rate of regrowth (Perry and Jones 2017). Twenty-six of the 78 studies considered in this review incorporated either past or future climate forcing data, whereas only 21 included multiannual forest dynamics, i.e., regeneration or regrowth, in their assessments of hydrologic response to disturbance. Beyond timescales of about a decade, initial hydrologic responses, such as seasonal low flows or water yield, may return to baseline conditions or even differ in sign (increase versus decrease) from the immediate postdisturbance response (Perry and Jones 2017). However, in studies focused on sufficiently short timelines (<10 years), the assumption of static vegetation may be acceptable in the slow-growing coniferous forests of the western United States. Studies that accounted for vegetation dynamics used a variety of methods, ranging from time-based thresholds for reversion from "disturbed" to "undisturbed" (Hernandez et al. 2018) to classification of stands or catchments in various stages of recovery, as observed either through ground observations or through remote sensing (Wei and Zhang 2010, Zhang and Wei 2012, Robles et al. 2014, Winkler et al. 2014, Vanderhoof and Williams 2015, Boisramé et al. 2017, Meyer et al. 2017, Li et al. 2018) or simulation of future vegetation growth (Grant et al. 2013, Buma and Livneh 2015, Bart et al. 2016, Penn et al. 2016, Saksa et al. 2017). Simulations of vegetation recovery vary from species-specific bioclimatic envelopes (Buma and Livneh 2015) to species-invariant simulated canopy growth (Grant et al. 2013, Bart et al. 2016, Saksa et al. 2017).

Interannual climate variability can also mask streamflow and snowpack responses to disturbance. The largest differences in snowpack between disturbed versus undisturbed stands occur in low-snowfall years (Boon 2012, Winkler et al. 2014), which are expected to become more common in western North America (Fyfe et al. 2017), as larger snowfall overwhelms the interception capacity of the overstory. Additionally, tree mortality is likely to increase because of drought- and heat-related factors (Adams et al. 2009, Allen et al. 2010, Anderegg et al. 2013, Williams et al. 2013, McDowell et al. 2016). Simulations that include both vegetation dynamics and climate projections suggest that vegetation may have a stronger influence on the future water yield than climate alone in dry regions (Bart et al. 2016, Bennett et al. 2018). In contrast, interannual precipitation variability in wetter areas exerts a stronger control than forest conditions on streamflow (Burt et al. 2015).

Finally, future studies can help improve the predictability of hydrologic response to disturbance by quantifying and reporting the magnitude of changes in both forest conditions and hydrologic fluxes. Such quantification will allow differentiation of initial forest densities or structures, disturbance severities, and subsequent hydrologic response. In Bosch and Hewlett's (1982) review, their figure 1 presented a quantitative relation between the percentage reduction in forest cover and the annual streamflow increase. Their review differed from this paper in that it focused on stand-replacing disturbances—primarily harvesting—while our review included numerous cases of both stand-replacing and nonstand-replacing disturbances, which we conclude may exhibit different hydrologic responses. Although we initially sought to quantify the magnitude of increases or decreases in snowpack and water yield that were observed in different studies, too few of the papers reviewed here reported magnitudes of change in a way that enabled meta-analysis. Therefore, we recommend that future papers explicitly report the following metrics: quantitative forest density (e.g., in terms of LAI, basal area per acre, or canopy cover percentage), quantitative disturbance effects (e.g., reduction in LAI, area affected), scale of assessment (e.g., stand, hillslope, or catchment), annual precipitation, annual maximum SWE, and magnitude of hydrologic change as well as results of any statistical significance tests.

Implications for Forest Management: Balancing Water Yield and Forest Resilience

Given that tree mortality in the West is likely to continue at a historically high rate in the future (Allen et al. 2010, Anderegg et al. 2013, Williams et al. 2013), management objectives may seek to maximize the adaptive capacity of forested watersheds by optimizing growing-season soil moisture (Grant et al. 2013), e.g., by maximizing snow retention. The same factors that affect postdisturbance water yield also may affect snow retention and soil moisture. Although soil moisture sometimes increases in the years following harvest in relatively wet areas (Ziemer 1964, Perry and Jones 2017), it may decline if snowpack decreases or melts earlier. Decreases in snow accumulation, snow retention, or soil moisture most often occur at lower latitudes and south-facing aspects where solar radiation dominates the radiation budget (Ellis et al. 2011, Lundquist et al. 2013, Biederman et al. 2014, Harpold et al. 2014, Chen et al. 2015, Bennett et al. 2018). At such sites, stand structure and density can have important effects on snow accumulation and retention (Lundquist et al. 2013, Broxton et al. 2015), which in turn affect growing-season soil moisture (Tague et al. 2009, Grant et al. 2013, Harpold et al. 2015).

The studies that found decreases in postdisturbance water yield (Table 5) or snowpack mainly occurred in catchments that coincide with regions that are expected to receive less precipitation as snow in the future (Fyfe et al. 2017). Even in catchments receiving more rain than snow, die-off may increase the vulnerability of surviving trees to future mortality if understory transpiration and soil evaporation overcompensate for the decrease in canopy evapotranspiration (Morillas et al. 2017). In stands already affected by natural, nonstand-replacing disturbance such as drought- or insect-related die-off, postdisturbance salvage logging in high-radiation environments may allow increased solar radiation to drive earlier snowmelt and subsequent depletion of soil moisture, either through soil evaporation or through transpiration by understory vegetation (Boon 2009, Gleason et al. 2013, Perrot et al. 2014, Winkler et al. 2015, Morillas et al. 2017). Such treatments in high-radiation environments may not only lead to reduced summer flows and possibly reduced water yield, but also hinder future forest recovery and resilience if soil moisture decreases as a result of increased solar radiation reaching the soil surface. Additionally, harvest treatments have additional effects if they include road-building, which can affect infiltration and both surface and subsurface runoff pathways and rates (Moore and Wondzell 2005).

Toward the goal of optimizing soil moisture, studies summarized here provide some guidelines for maximizing snow retention. In areas where average winter temperature is less than –1° C, longwave radiation in dense forests is typically insufficient to melt midwinter snowpack, and dense canopies provide shade that slows spring snowmelt (Lundquist et al. 2013). Thus, retaining moderately dense forest cover should be a goal in colder areas if forest resilience is a management objective, particularly on south-facing slopes where they provide solar shading (Ellis et al. 2011). However, snow retention at relatively windy sites in cold regions may be controlled more by winds (i.e., with longer retention in forests than in clearings where wind scours the snowpack) (Dickerson-Lange et al. 2017). In warmer areas, i.e., those where mean winter temperature is warmer than –1° C, sparser tree cover may optimize snow retention by providing solar shading with minimal longwave radiation emittance (Lundquist et al. 2013). For example, maximum snow retention was observed in Arizona at sites that were thinned and burned to about 24–30 percent of initial density (Sankey et al. 2015, Svoma 2017), where treatments provided the added benefit of lower fire risk. In such warm areas, or in colder areas on north-facing slopes (Ellis et al. 2011), managing for less dense forests may minimize total melt energy—i.e., by blocking shortwave radiation while emitting less longwave radiation than denser stands—and thus maximize snow retention.

Future management-driven research should attempt to improve predictions of when snow retention will respond positively or negatively to silvicultural treatments such as thinning or salvage harvests. Physically based models already include the capability for simulating the effects of canopy density (typically in terms of LAI) on radiation, snowpack, and evaporation (Wigmosta et al. 1994, Tague and Band 2004), and may thus serve as tools for comparing management alternatives. At finer scales that are relevant to individual forest-management projects, physically based models can be used to comparatively assess alternative silvicultural prescriptions—including site aspect, elevation, and the number and size of harvest gaps—for maximizing hydrologic objectives such as snow retention, water yield, or seasonal low flow targets (Ellis et al. 2013, Sun et al. 2018).

Conclusions

A review of 78 studies on hydrologic response to forest disturbance indicates that this topic has received increased attention in the literature, and that new hypotheses continue to be formulated as understanding increases in this rapidly evolving discipline. Although one long-held hypothesis—that forest cover loss results in increased water yield because of decreased evapotranspiration—still applies in many cases, it was found to be incorrect under some conditions, and identifying these conditions will improve predictability of streamflow response to forest disturbance. Water yield and snowpack are more likely to decrease or not change in areas with rapid postdisturbance growth and in watersheds where net radiation is greater, such as at lower latitudes and south-facing aspects. Both observational and simulation studies concluded that postdisturbance streamflow and snowpack may decrease under these conditions, yet only physically based models were able to simulate any reductions in yield, underscoring the importance of continued investment in physically based modeling to support forest management. The use of such models to evaluate management alternatives will require improved quantitative characterization of forest density and disturbance effects, particularly in terms of leaf area index, which is the metric currently used for most quantitative linkages between forests and hydrologic response.

Supplementary Materials

Supplementary data are available at *Journal of Forestry* online.

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Literature Cited

Adams, H.D., M. Guardiola-Claramonte, G.A. Barron-Gafford, J.C. Villegas, D.D. Breshears, C.B. Zou, P.A. Troch, and T.E. Huxman. 2009. Temperature sensitivity of drought-induced tree mortality portends increased regional die-off under global-change-type drought. *Proc. Natl. Acad. Sci. USA* 106(17):7063–7066.

Adams, H.D., C.H. Luce, D.D. Breshears, C.D. Allen, M. Weiler, V.C. Hale, A.M. Smith, and T.E. Huxman. 2012. Ecohydrological consequences of drought-and infestation-triggered tree die-off: Insights and hypotheses. *Ecohydrology* 5:145–159.

Allen, C.D., A.K. Macalady, H. Chenchouni, D. Bachelet, N. McDowell, M. Vennetier, T. Kitzberger, et al. 2010. A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. *For. Ecol. Manag.* 259:660–684.

Anderegg, W., J. Kane, and L. Anderegg. 2013. Consequences of widespread tree mortality triggered by drought and temperature stress. *Nat. Clim. Change* 3:30–36.

Andréassian, V. 2004. Waters and forests: From historical controversy to scientific debate. *J. Hydrol.* 291:1–27.

Bart, R., C. Tague, and M. Moritz. 2016. Effect of tree-to-shrub type conversion in lower montane forests of the Sierra Nevada (USA) on streamflow. *PLoS ONE* 11(8):e0161805.

Bearup, L., R. Maxwell, D. Clow, and J. McCray. 2014. Hydrological effects of forest transpiration loss in bark beetle-impacted watersheds. *Nat. Clim. Change* 4:481–486.

Bennett, K.E., T.J. Bohn, K. Solander, N.G. McDowell, C. Xu, E. Vivoni, and R.S. Middleton. 2018. Climate-driven disturbances in the San Juan River sub-basin of the Colorado River. *Hydrol. Earth Syst. Sci.* 22(1):709–725.

Bethlahmy, N. 1974. More streamflow after a bark beetle epidemic. *J. Hydrol.* 23:185–189.

Bethlahmy, N. 1975. A Colorado episode: Beetle epidemic, ghost forests, more streamflow. *Northwest Sci.* 49:95–105.

Bewley, D., Y. Alila, and A. Varhola. 2010. Variability of snow water equivalent and snow energetics across a large catchment subject to Mountain Pine Beetle infestation and rapid salvage logging. *J. Hydrol.* 388(3–4):464–479.

Biederman, J.A., P.D. Brooks, A.A. Harpold, D.J. Gochis, E. Gutmann, D.E. Reed, E. Pendall, and B.E. Ewers. 2014. Multiscale observations of snow accumulation and peak snowpack following widespread, insect-induced lodgepole pine mortality. *Ecohydrology* 7(1):150–162.

Biederman, J.A., A.A. Harpold, D.J. Gochis, B.E. Ewers, D.E. Reed, S.A. Papuga, and P.D. Brooks. 2014. Increased evaporation following widespread tree mortality limits streamflow response. *Water Resour. Res.* 50(7):5395–5409.

Biederman, J.A., A.J. Somor, A.A. Harpold, E.D. Gutmann, D.D. Breshears, P.A. Troch, D.J. Gochis, R.L. Scott, A.J. Meddens, and P.D. Brooks. 2015. Recent tree die-off has little effect on streamflow in contrast to expected increases from historical studies. *Water Resour. Res.* 51(12):9775–9789.

Boisramé, G., S. Thompson, B. Collins, and S. Stephens. 2017. Managed wildfire effects on forest resilience and water in the Sierra Nevada. *Ecosystems* 20(4):717–732.

Boon, S. 2009. Snow ablation energy balance in a dead forest stand. *Hydrol. Process.* 23(18):2600–2610.

Boon, S. 2012. Snow accumulation following forest disturbance. *Ecohydrology* 5(3):279–285.

Bosch, J., and J. Hewlett. 1982. A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. *J. Hydrol.* 55:3–23.

Breshears, D.D., N.S. Cobb, P.M. Rich, K.P. Price, C.D. Allen, R.G. Balice, W.H. Romme, et al. 2005. Regional vegetation die-off in response to global-change-type drought. *Proc. Natl. Acad. Sci. USA* 102:15144–15148.

Bright, B., J. Hicke, and A. Meddens. 2013. Effects of bark beetle-caused tree mortality on biogeochemical and biogeophysical MODIS products. *J. Geophys. Res. Biogeosci.* 118:974–982.

Brown, A.E., L. Zhang, T.A. McMahon, A.W. Western, and R.A. Vertessy. 2005. A review of paired catchment studies for determining changes in water yield resulting from alterations in vegetation. *J. Hydrol.* 310:28–61.

Broxton, P.D., A.A. Harpold, J.A. Biederman, P.A. Troch, N.P. Molotch, and P.D. Brooks. 2015. Quantifying the effects of vegetation structure on snow accumulation and ablation in mixed-conifer forests. *Ecohydrology* 8(6):1073–1094.

Buma, B., and B. Livneh. 2015. Potential effects of forest disturbances and management on water resources in a warmer climate. *For. Sci.* 61(5):895–903.

Buma, B., and B. Livneh. 2017. Key landscape and biotic indicators of watersheds sensitivity to forest disturbance identified using remote sensing and historical hydrography data. *Environ. Res. Lett.* 12(7):074028.

Burles, K., and S. Boon. 2011. Snowmelt energy balance in a burned forest plot, Crowsnest Pass, Alberta, Canada. *Hydrol. Process.* 25(19):3012–3029.

Burt, T.P., N.J.K. Howden, J.J. McDonnell, J.A. Jones, and G.R. Hancock. 2015. Seeing the climate through the trees: Observing climate and forestry impacts on streamflow using a 60-year record. *Hydrol. Process.* 29(3):473–480.

Buttle, J., I. Creed, and R. Moore. 2005. Advances in Canadian forest hydrology. 1999–2003. *Hydrol. Process.* 19(1):169–200.

Chen, F., G. Zhang, M. Barlage, Y. Zhang, J.A. Hicke, A. Meddens, G. Zhou, W.J. Massman, and J. Frank. 2015. An observational and modeling study of impacts of bark beetle-caused tree mortality on surface energy and hydrological cycles. *J. Hydrometeorol.* 16(2):744–761.

Cheng, J. 1989. Streamflow changes after clear-cut logging of a pine beetle-infested watershed in southern British Columbia, Canada. *Water Resour. Res.* 25:449–456.

Concilio, A., J. Chen, S. Ma, and M. North. 2009. Precipitation drives interannual variation in summer soil respiration in a Mediterranean-climate, mixed-conifer forest. *Climatic Change* 92(1–2):109–122.

Cristea, N.C., J.D. Lundquist, S.P. Loheide, C.S. Lowry, and C.E. Moore. 2014. Modelling how vegetation cover affects climate change impacts on streamflow timing and magnitude in the snowmelt-dominated upper Tuolumne Basin, Sierra Nevada. *Hydrol. Process.* 28(12):3896–3918.

Dickerson-Lange, S.E., R.F. Gersonde, J.A. Hubbart, T.E. Link, A.W. Nolin, G.H. Perry, T.R. Roth, N.E. Wayand, and J.D. Lundquist. 2017. Snow disappearance timing is dominated by forest effects on snow accumulation in warm winter climates of the Pacific Northwest, United States. *Hydrol. Process.* 31:1846–1862.

Du, E., T. Link, L. Wei, and J. Marshall. 2016. Evaluating hydrologic effects of spatial and temporal patterns of forest canopy change using numerical modelling. *Hydrol. Process.* 30:217–231.

Eaton, B., R. Moore, and T. Giles. 2010. Forest fire, bank strength and channel instability: The 'unusual' response of Fishtrap Creek, British Columbia. *Earth Surf. Process. Landf.* 35:1167–1183.

Ellis, C., J. Pomeroy, R. Essery, and T. Link. 2011. Effects of needleleaf forest cover on radiation and snowmelt dynamics in the Canadian Rocky Mountains. *Can. J. For. Res.* 41(3):608–620.

Ellis, C., J. Pomeroy, and T. Link. 2013. Modeling increases in snowmelt yield and desynchronization resulting from forest gap-thinning treatments in a northern mountain headwater basin. *Water Resour. Res.* 49(2):936–949.

Evaristo, J., and J. McDonnell. 2019. Global analysis of streamflow response to forest management. *Nature* 570:455–461.

Fyfe, J.C., C. Derksen, L. Mudryk, G.M. Flato, B.D. Santer, N.C. Swart, N.P. Molotch, et al. 2017. Large near-term projected snowpack loss over the western United States. *Nat. Commun.* 8:14996.

Gleason, K.E., A.W. Nolin, and T.R. Roth. 2013. Charred forests increase snowmelt: Effects of burned woody debris and incoming solar radiation on snow ablation. *Geophys. Res. Lett.* 40(17):4654–4661.

Grant, G., C. Tague, and C. Allen. 2013. Watering the forest for the trees: An emerging priority for managing water in forest landscapes. *Front. Ecol. Environ.* 11(6):314–321.

Green, K., and Y. Alila. 2012. A paradigm shift in understanding and quantifying the effects of forest harvesting on floods in snow environments. *Water Resour. Res.* 48:W10503.

Guardiola-Claramonte, M., P.A. Troch, D.D. Breshears, T.E. Huxman, M.B. Switanek, M. Durcik, and N.S. Cobb. 2011. Decreased streamflow in semi-arid basins following drought-induced tree die-off: A counter-intuitive and indirect climate impact on hydrology. *J. Hydrol.* 406:225–233.

Hallema, D.W., G. Sun, K.D. Bladon, S.P. Norman, P.V. Caldwell, Y. Liu, and S.G. McNulty. 2017. Regional patterns of postwildfire streamflow response in the Western United States: The importance of scale-specific connectivity. *Hydrol. Process.* 31:2582–2598.

Hallema, D.W., G. Sun, P.V. Caldwell, S.P. Norman, E.C. Cohen, Y. Liu, E.J. Ward, and S.G. McNulty. 2017.

Assessment of wildland fire impacts on watershed annual water yield: Analytical framework and case studies in the United States. *Ecohydrology* 10:e1794.

Härkönen, S., A. Lehtonen, T. Manninen, S. Tuominen, and M. Peltoniemi. 2015. Estimating forest leaf area index using satellite images: Comparison of k-NN based Landsat-NFI LAI with MODIS-RSR based LAI product for Finland. *Boreal Environ. Res.* 20:181–195.

Harpold, A.A., J.A. Biederman, K. Condon, M. Merino, Y. Korgaonkar, T. Nan, L.L. Sloat, M. Ross, and P.D. Brooks. 2014. Changes in snow accumulation and ablation following the Las Conchas Forest Fire, New Mexico, USA. *Ecohydrology* 7(2):440–452.

Harpold, A.A., N.P. Molotch, K.N. Musselman, R.C. Bales, P.B. Kirchner, M. Litvak, and P.D. Brooks. 2015. Soil moisture response to snowmelt timing in mixed-conifer subalpine forests. *Hydrol. Process.* 29(12):2782–2798.

Hernandez, A., S. Healey, H. Huang, and R. Ramsey. 2018. Improved prediction of stream flow based on updating land cover maps with remotely sensed forest change detection. *Forests* 9(6):317.

Hewlett, J. 1971. Comments on the catchment experiment to determine vegetal effects on water yield. *J. Am. Water Resour. Assoc.* 7:376–381.

Hibbert, A. 1967. Forest treatment effects on water yield. P. 527–543 in *International symposium on forest hydrology*, Sopper, W.A.L.H. (ed.). Pergamon, Oxford.

Hicke, J., A. Meddens, and C. Kolden. 2015. Recent tree mortality in the western United States from bark beetles and forest fires. *For. Sci.* 62:141–153.

Huang, K., C. Yi, D. Wu, T. Zhou, X. Zhao, W.J. Blanford, S. Wei, H. Wu, D. Ling, and Z. Li. 2015. Tipping point of a conifer forest ecosystem under severe drought. *Environ. Res. Lett.* 10(2):024011.

Hubbart, J., T. Link, and J. Gravelle. 2015. Forest canopy reduction and snowpack dynamics in a Northern Idaho watershed of the continental-maritime region, United States. *For. Sci.* 61(5):882–894.

Hubbart, J., T. Link, J. Gravelle, and W. Elliot. 2007. Timber harvest impacts on water yield in the continental/maritime hydroclimatic region of the United States. *For. Sci.* 53:169–180.

Huff, D., B. Hargrove, M. Tharp, and R. Graham. 2000. Managing forests for water yield: The importance of scale. *J. For.* 98(12):15–19.

Jackson, S., and T. Prowse. 2009. Spatial variation of snowmelt and sublimation in a high-elevation semi-desert basin of western Canada. *Hydrol. Process.* 23(18):2611–2627.

Jacobs, B. 2015. Restoration of degraded transitional (piñon-juniper) woodland sites improves ecohydrologic condition and primes understory resilience to subsequent disturbance. *Ecohydrology* 8(8):1417–1428.

Jonckheere, I., S. Fleck, K. Nackaerts, B. Muys, P. Coppin, M. Weiss, and F. Baret. 2004. Review of methods for in situ leaf area index determination: Part I. Theories, sensors and hemispherical photography. *Agr. Forest Meteorol.* 121:19–35.

King, J. 1989. *Streamflow responses to road building and harvesting: A comparison with the equivalent clearcut area procedure*. USDA Forest Service Res. Pap. INT-401, Intermountain Research Station, Ogden, UT.

Kirchner, J.W., W.R. Berghuijs, S.T. Allen, M. Hrachowitz, R. Hut, and D.M. Rizzo. 2019. Comment on Evaristo and McDonnell, global analysis of streamflow response to forest management. *EarthArXiv* preprint doi: 10.31223/osf.io/8jpx6.

Li, Q., X. Wei, M. Zhang, W. Liu, Giles-K. Hansen, and Y. Wang. 2018. The cumulative effects of forest disturbance and climate variability on streamflow components in a large forest-dominated watershed. *J. Hydrol.* 557:448–459.

Livneh, B., J.S. Deems, B. Buma, J.J. Barsugli, D. Schneider, N.P. Molotch, K. Wolter, and C.A. Wessman. 2015. Catchment response to bark beetle outbreak and dust-on-snow in the Colorado Rocky Mountains. *J. Hydrol.* 523:196–210.

Lundquist, J. Dickerson-S. Lange, J. Lutz, and N. Cristea. 2013. Lower forest density enhances snow retention in regions with warmer winters: A global framework developed from plot-scale observations and modeling. *Water Resour. Res.* 49(10):6356–6370.

Mahat, V., and A. Anderson. 2013. Impacts of climate and catastrophic forest changes on streamflow and water balance in a mountainous headwater stream in Southern Alberta. *Hydrol. Earth Syst. Sci.* 17(12):4941–4956.

Maxwell, J., A. Call, and S. Clair. 2019. Wildfire and topography impacts on snow accumulation and retention in montane forests. *For. Ecol. Manag.* 432:256–263.

McDowell, N.G., A.P. Williams, C. Xu, W.T. Pockman, L.T. Dickman, S. Sevanto, R. Pangle, et al. 2016. Multi-scale predictions of massive conifer mortality due to chronic temperature rise. *Nat. Clim. Change* 6:295.

Meddens, A., J. Hicke, and C. Ferguson. 2012. Spatiotemporal patterns of observed bark beetle-caused tree mortality in British Columbia and the western United States. *Ecol. Appl.* 22:1876–1891.

Meyer, G., T.A. Black, R.S. Jassal, Z. Nesic, N.J. Grant, D.L. Spittlehouse, A.L. Fredeen, et al. 2017. Measurements and simulations using the 3-PG model of the water balance and water use efficiency of a lodgepole pine stand following mountain pine beetle attack. *For. Ecol. Manag.* 393:89–104.

Mikkelson, K.M., L.A. Bearup, R.M. Maxwell, J.D. Stednick, J.E. McCray, and J.O. Sharp. 2013. Bark beetle infestation impacts on nutrient cycling, water quality and interdependent hydrological effects. *Biogeochemistry* 115(1–3):1–21.

Montesi, J., K. Elder, R. Schmidt, and R. Davis. 2004. Sublimation of intercepted snow within a subalpine forest canopy at two elevations. *J. Hydrometeorol.* 5:763–773.

Moore, R., and D. Scott. 2005. Camp Creek revisited: Streamflow changes following salvage harvesting in a medium-sized, snowmelt-dominated catchment. *Water Resour. Res.* 30:331–344.

Moore, R., and S. Wondzell. 2005. Physical hydrology and the effects of forest harvesting in the Pacific Northwest: A review. *J. Am. Water Resour. Assoc.* 41:763–784.

Morillas, L., R.E. Pangle, G.E. Maurer, W.T. Pockman, N. McDowell, C.W. Huang, D.J. Krofcheck, et al. 2017. Tree mortality decreases water availability and ecosystem resilience to drought in piñon–juniper woodlands in the Southwestern US. *J. Geophys. Res. Biogeosci.* 122:3343–3361.

Penn, C., L. Bearup, R. Maxwell, and D. Clow. 2016. Numerical experiments to explain multiscale hydrological responses to mountain pine beetle tree mortality in a headwater watershed. *Water Resour. Res.* 52:3143–3161.

Perrot, D., N. Molotch, K. Musselman, and E. Pugh. 2014. Modelling the effects of the mountain pine beetle on snowmelt in a subalpine forest. *Ecohydrology* 7(2):226–241.

Perry, T.D., and J.A. Jones. 2017. Summer streamflow deficits from regenerating Douglas-fir forest in the Pacific Northwest, USA. *Ecohydrology* 10:1–13.

Pomeroy, J., X. Fang, and C. Ellis. 2012. Sensitivity of snowmelt hydrology in Marmot Creek, Alberta, to forest cover disturbance. *Hydrol. Process.* 26(12):1892–1905.

Poon, P., and A. Kinoshita. 2018. Spatial and temporal evapotranspiration trends after wildfire in semi-arid landscapes. *J. Hydrol.* 559:71–83.

Potts, D. 1984. Hydrologic impacts of a large-scale mountain pine beetle (*Dendroctonus ponderosae* Hopkins) epidemic. *J. Am. Water Resour. Assoc.* 20:373–377.

Pugh, E., and E. Gordon. 2013. A conceptual model of water yield effects from beetle-induced tree death in snow-dominated lodgepole pine forests. *Hydrol. Process.* 27:2048–2060.

Pugh, E., and E. Small. 2012. The impact of pine beetle infestation on snow accumulation and melt in the headwaters of the Colorado River. *Ecohydrology* 5:467–477.

Pugh, E., and E. Small. 2013. The impact of beetle-induced conifer death on stand-scale canopy snow interception. *Hydrol. Res.* 44(4):644–657.

Reed, D., B. Ewers, and E. Pendall. 2014. Impact of mountain pine beetle induced mortality on forest carbon and water fluxes. *Environ. Res. Lett.* 9(10):105004.

Reed, D.E., B.E. Ewers, E. Pendall, J. Frank, and R. Kelly. 2016. Bark beetle-induced tree mortality alters stand energy budgets due to water budget changes. *Theor. Appl. Climatol.* 131:153–165.

Robles, M.D., R.M. Marshall, F. O'Donnell, E.B. Smith, J.A. Haney, and D.F. Gori. 2014. Effects of climate variability and accelerated forest thinning on watershed-scale runoff in southwestern USA ponderosa pine forests. *PLoS ONE* 9(10):e111092.

Robles, M., D. Turner, and J. Haney. 2017. A century of changing flows: Forest management changed flow magnitudes and warming advanced the timing of flow in a southwestern US river. *PLoS ONE* 12(11):e0187875.

Saksa, P.C., M.H. Conklin, J.J. Battles, C.L. Tague, and R.C. Bales. 2017. Forest thinning impacts on the water balance of Sierra Nevada mixed-conifer headwater basins. *Water Resour. Res.* 53(7):5364–5381.

Sankey, T., J. Donald, J. McVay, M. Ashley, F. O'Donnell, S.M. Lopez, and A. Springer. 2015. Multi-scale analysis of snow dynamics at the southern margin of the North American continental snow distribution. *Remote Sens. Environ.* 169:307–319.

Schmidt, R., C. Troendle, and J. Meiman. 1998. Sublimation of snowpacks in subalpine conifer forests. *Can. J. For. Res.* 28:501–513.

Sexstone, G.A., D.W. Clow, S.R. Fassnacht, G.E. Liston, C.A. Hiemstra, J.F. Knowles, and C.A. Penn. 2018. Snow sublimation in mountain environments and its sensitivity to forest disturbance and climate warming. *Water Resour. Res.* 54(2):1191–1211.

Slinski, K., T. Hogue, A. Porter, and J. McCray. 2016. Recent bark beetle outbreaks have little impact on streamflow in the Western United States. *Environ. Res. Lett.* 11(7):074010.

Stednick, J. 1996. Monitoring the effects of timber harvest on annual water yield. *J. Hydrol.* 176:79–95.

Stevens, J. 2017. Scale-dependent effects of post-fire canopy cover on snowpack depth in montane coniferous forests. *Ecol. Appl.* 27(6):1888–1900.

Sun, N., M. Wigmosta, T. Zhou, J. Lundquist, Dickerson-S. Lange, and N. Cristea. 2018. Evaluating the functionality and streamflow impacts of explicitly modelling forest-snow interactions and canopy gaps in a distributed hydrologic model. *Hydrol. Process.* 32:2128–2140.

Svoma, B. 2017. Canopy effects on snow sublimation from a central Arizona basin. *J. Geophys. Res.* 122(1):20–46.

Tague, C., and L. Band. 2004. RHESSys: Regional hydro-ecologic simulation system—an object-oriented approach to spatially distributed modeling of carbon, water, and nutrient cycling. *Earth Interactions* 8:1–42.

Tague, C., K. Heyn, and L. Christensen. 2009. Topographic controls on spatial patterns of conifer transpiration and net primary productivity under climate warming in mountain ecosystems. *Ecohydrology* 2:541–554.

Tang, H., M. Brolly, F. Zhao, A.H. Strahler, C.L. Schaaf, S. Ganguly, G. Zhang, and R. Dubayah. 2014. Deriving and validating Leaf Area Index (LAI) at multiple spatial scales through lidar remote sensing: A case study in Sierra National Forest, CA. *Remote Sens. Environ.* 143:131–141.

Tennant, C.J., A.A. Harpold, K.A. Lohse, S.E. Godsey, B.T. Crosby, L.G. Larsen, P.D. Brooks, Van R.W. Kirk, and N.F. Glenn. 2017. Regional sensitivities of seasonal snowpack to elevation, aspect, and vegetation cover in western North America. *Water Resour. Res.* 53(8):6908–6926.

Tonina, D., C.H. Luce, B. Rieman, J.M. Buffington, P. Goodwin, S.R. Clayton, S.M. Alì, J.J. Barry, and C. Berenbrock. 2008. Hydrological response to timber harvest in northern Idaho: Implications for channel scour and persistence of salmonids. *Hydrol. Process.* 22:3223–3235.

Troendle, C. 1983. The potential for water yield augmentation from forest management in the Rocky Mountain region. *J. Am. Water Resour. Assoc.* 19:359–373.

Troendle, C., and R. King. 1985. The effect of timber harvest on the Fool Creek watershed, 30 years later. *Water Resour. Res.* 21:1915–1922.

Troendle, C., and R. King. 1987. The effect of partial and clearcutting on streamflow at Deadhorse Creek, Colorado. *J. Hydrol.* 90:145–157.

USDA Forest Service. 2017. *Forest inventory and analysis national core field guide, version 7.2*. Available online at https://www.fia.fs.fed.us/library/field-guides-methods-proc/docs/2017/core_ver7-2_10_2017_final.pdf; last accessed December 28. 2018.

Van Mantgem, P.J., N.L. Stephenson, J.C. Byrne, L.D. Daniels, J.F. Franklin, P.Z. Fulé, M.E. Harmon, et al. 2009. Widespread increase of tree mortality rates in the western United States. *Science* 323:521–524.

Vanderhoof, M., and C. Williams. 2015. Persistence of MODIS evapotranspiration impacts from mountain pine beetle outbreaks in lodgepole pine forests, south-central Rocky Mountains. *Agr. Forest Meteorol.* 200:78–91.

Varhola, A., N.C. Coops, C.W. Bater, P. Teti, S. Boon, and M. Weiler. 2010. The influence of ground- and lidar-derived forest structure metrics on snow accumulation and ablation in disturbed forests. *Can. J. For. Res.* 40(4):812–821.

Wei, X., and M. Zhang. 2010. Quantifying streamflow change caused by forest disturbance at a large spatial scale: A single watershed study. *Water Resour. Res.* 46(12):W12525.

Wigmosta, M., L. Vail, and D. Lettenmaier. 1994. A distributed hydrology-vegetation model for complex terrain. *Water Resour. Res.* 30:1665–1679.

Williams, A.P., C.D. Allen, A.K. Macalady, D. Griffin, C.A. Woodhouse, D.M. Meko, T.W. Swetnam, et al. 2013. Temperature as a potent driver of regional forest drought stress and tree mortality. *Nat. Clim. Change* 3:292.

Wilm, H. 1948. The influence of forest cover on snow-melt. *Trans. Am. Geophys. Union* 29(4):547–557.

Wine, M., and D. Cadol. 2016. Hydrologic effects of large southwestern USA wildfires significantly increase regional water supply: Fact or fiction? *Environ. Res. Lett.* 11:014010.

Wine, M., D. Cadol, and O. Makhnin. 2018. In ecoregions across western USA streamflow increases during post-wildfire recovery. *Environ. Res. Lett.* 13:014010.

Winkler, R., S. Boon, B. Zimonick, and D. Spittlehouse. 2014. Snow accumulation and ablation response to changes in forest structure and snow surface albedo after attack by mountain pine beetle. *Hydrol. Process.* 28(2):197–209.

Winkler, R., D. Spittlehouse, and S. Boon. 2017. Streamflow response to clear-cut logging on British Columbia's Okanagan Plateau. *Ecohydrology* 10:e1836.

Winkler, R., D. Spittlehouse, S. Boon, and B. Zimonick. 2015. Forest disturbance effects on snow and water yield in interior British Columbia. *Hydrol. Res.* 46(4):521–532.

Winkler, R., D. Spittlehouse, and D. Golding. 2005. Measured differences in snow accumulation and melt among clearcut, juvenile, and mature forests in southern British Columbia. *Hydrol. Process.* 19(1):51–62.

Yazzie, K., and H. Chang. 2017. Watershed response to climate change and fire-burns in the upper Umatilla River Basin, USA. *Climate* 5(1):7.

Zhang, M., and X. Wei. 2012. The effects of cumulative forest disturbance on streamflow in a large watershed in the central interior of British Columbia, Canada. *Hydrol. Earth Syst. Sci.* 16(7):2021–2034.

Ziemer, R. 1964. Summer evapotranspiration trends as related to time after logging of forests in Sierra Nevada. *J. Geophys. Res.* 69:615–620.