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Direct and Indirect Effects of Forest Harvesting on Sediment Yield in Forested Watersheds of the United States

Zachary P. McEachran, Diana L. Karwan, and Robert A. Slesak

Research Impact Statement: Stream sediment comes from terrestrial landscapes *and/or* within streams, but it is unclear which dominates after forest harvest; our conceptual model identifies drivers of these sediment sources.

ABSTRACT: Managed forests generally produce high water quality, but degradation is possible via sedimentation if proper management is not implemented during forest harvesting. To mitigate harvesting effects on total watershed *sediment yield*, it is necessary to understand all processes that contribute to these effects. Forest harvesting best management practices (BMPs) focus almost exclusively on overland sediment sources, whereas in-and-near stream sources go unaddressed although they can contribute substantially to sediment yield. Thus, we propose a new framework to classify forest harvesting effects on stream sediment yield according to their direct and indirect processes. *Direct effects* are those caused by erosion and sediment delivery to surface water from overland sources (e.g., forest roads). *Indirect effects* are those caused by a shift in hydrologic processes due to tree removal that accounts for increases in subsurface and surface flows to the stream such that alterations in water quality are not predicated upon overland sediment delivery to the stream, but rather in-stream processes. Although the direct/indirect distinction is often implicit in forest hydrology studies, we have formalized it as a conceptual model to help identify primary drivers of sediment yield after forest harvesting in different landscapes. Based on a literature review, we identify drivers of these effects in five regions of the United States, discuss current forest management BMPs, and identify research needs.

(KEYWORDS: forestry; water quality; watershed management; forest roads; timber harvest; best management practices; erosion; sediment delivery; instream erosion; connectivity; geomorphology.)

INTRODUCTION

Managed forests generally produce high-quality surface water (Neary et al. 2009), providing nearly two-thirds of the drinking water supply in the United States (U.S.) (NRC 2008). Because of this, forest harvesting effects on water quality have been an area of concern for decades (Megahan 1972; Binkley and Brown 1993; Cristan et al. 2016), with sedimentation often identified as the greatest water quality threat (Binkley and Brown 1993). There has been a tremendous amount of work developing and evaluating water quality best management practices (BMPs) to address this concern, and it is generally concluded that BMPs are very effective at reducing overland sediment delivery when properly implemented (Binkley and Brown 1993; Aust and Blinn 2004; Cristan et al. 2016). However, overland sources of sediment delivery forms only a portion of the watershed's sediment yield over a given time interval. Sediment yield, the mass of sediment flowing from a watershed outlet per year,

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Department of Forest Resources (McEachran, Karwan), University of Minnesota St. Paul, Minnesota, USA; and USDA Forest Service, Pacific Northwest Research Station (Slesak), Olympia, WA, USA (Correspondence to McEachran: mceac015@umn.edu).

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incorporates sediment delivery from the entire watershed above the outlet as well as fluvial transport processes and (re)mobilization of sediments within and connected to the channel network. In-and-near-stream sources of sediment yield (e.g., bank erosion, remobilization of stored or "legacy" sediments) are often not considered in forestry water quality assessments, but have been identified as important contributors to sediment yield that can change in response to forest harvest and disturbance (Hewlett and Doss 1984; Beasley and Granillo 1988; Gomi et al. 2005; Moore and Wondzell 2005; Hassan et al. 2006; Karwan et al. 2007; McBroom et al. 2008; Terrell et al. 2011; Fraser et al. 2012; Klein et al. 2012). For example, Fraser et al. (2012) attributed the majority of sediment yield after forest harvesting to instream sources eroding due to altered hydrology in the Georgia (USA) Piedmont.

Here, we propose a new framework to holistically classify forest harvesting effects on surface water variables according to their direct and indirect processes and contribution to watershed sediment yield. We demonstrate its utility in the context of sediment yield with a review of the existing literature for several regions containing managed temperate forests in the contiguous U.S. (and adjacent ecoregions in Canada) grouped by physiographic and management conditions (Figure 1) to explore drivers of direct and indirect effects in different landscape settings. We also identify future research directions on the effects of forest harvesting on surface water sediment yield. We then discuss implications of the direct/indirect framework for forest management, spatial and temporal scaling considerations and how these are modulated by management intensity and extent, and harvesting interactions with nonharvest disturbances.

Direct/Indirect Framework

Forest harvesting can have both direct and indirect effects on water quality variables, including sediment and nutrient yields. We define direct effects as those caused by overland hydrologic delivery of sediments or nutrients to surface water (i.e., connected by overland flow), including those sourced from site infrastructure such as the forest road network, log decks,

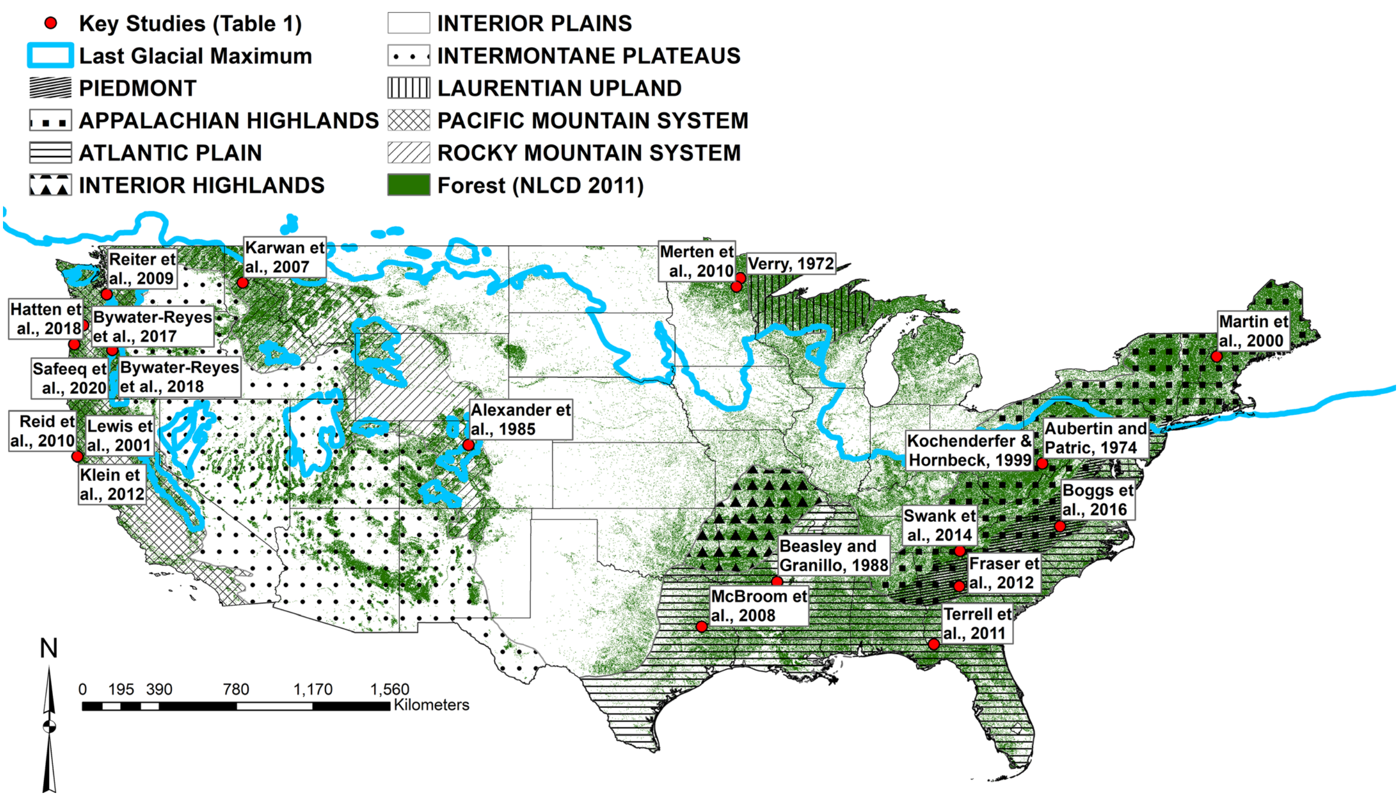

FIGURE 1. Contiguous United States with physiographic divisions (Fenneman and Johnson 1946) and U.S. states. The regional review is based on landscape and management characteristics: Northeast (Appalachian Highlands, Piedmont, and Coastal Plain north of Maryland), western Lake States (Laurentian Highlands and surrounding areas in Minnesota, Wisconsin, and Michigan), Southeast (Appalachian Highlands, Piedmont, and Coastal Plain south of Maryland), intermountain West (Rocky Mountain System), and Pacific Mountain System (Pacific Mountain System). State boundaries modified from National Weather Service 1999. Forest cover is shown from the NLCD 2011 (Homer et al. 2015), and the last glacial maximum is shown in light blue (Ehlers et al. 2011).

and general harvesting area. In certain terrain, surface erosion may be an issue even within protected riparian zones (Puntenney-Desmond et al. 2020: southwest Alberta/northern Rocky Mountains). Such sediments are rapidly delivered and exported from the channel due to high hydrologic connectivity that carries recent surface erosion with it — that is, sediment and hydrologic connectivity occur along the same pathways and on the same time scale (Figure 2). Indirect effects result from a postharvest shift in hydrologic processes, due to a reduction in watershed evapotranspiration (ET), that delivers more water to the stream via subsurface and surface pathways. This increase in streamflow leads to an increase in sediment yield from river corridor sources that are not predicated upon overland sediment delivery to the stream. Indirect effects encompass increases in subsurface and surface hydrologic connectivity that do not precisely overlap in space and time with sediment connectivity (Figure 2). In these cases, the hydrologic connectivity extends well into the upslope contributing areas, but the sediment connectivity to the channel remains in and very near the fluvial network. Indirect effects are invariant to the path by which water arrives at the stream, relying only on the shear stress of flowing water against the channel and cohesion of streambanks (including effects of altered pore pressure in streambanks due to altered water table levels). Thus, the hydrologic connectivity causing increased flows via surface and subsurface pathways throughout a watershed is not spatially and temporally aligned with the sediment connectivity, which occurs in the channel area only. Direct effects, in contrast, occur such that sediment and water are delivered along the same paths (i.e., overland flow), so can be traced via the contemporaneity of sediment influxes to the stream with overland flow influxes to the stream in time and space.

Both direct and indirect mechanisms could cause a change in sediment yield following forest harvest; however, most BMPs only address the former (Fraser et al. 2012) with some exceptions (e.g., green up rules). The distinction between “direct” vs. “indirect” effects may be applied to many different water quality variables, but we focus exclusively on sediment because it is the water quality variable of the highest concern related to forest harvesting (Binkley and Brown 1993). The distinction between direct and

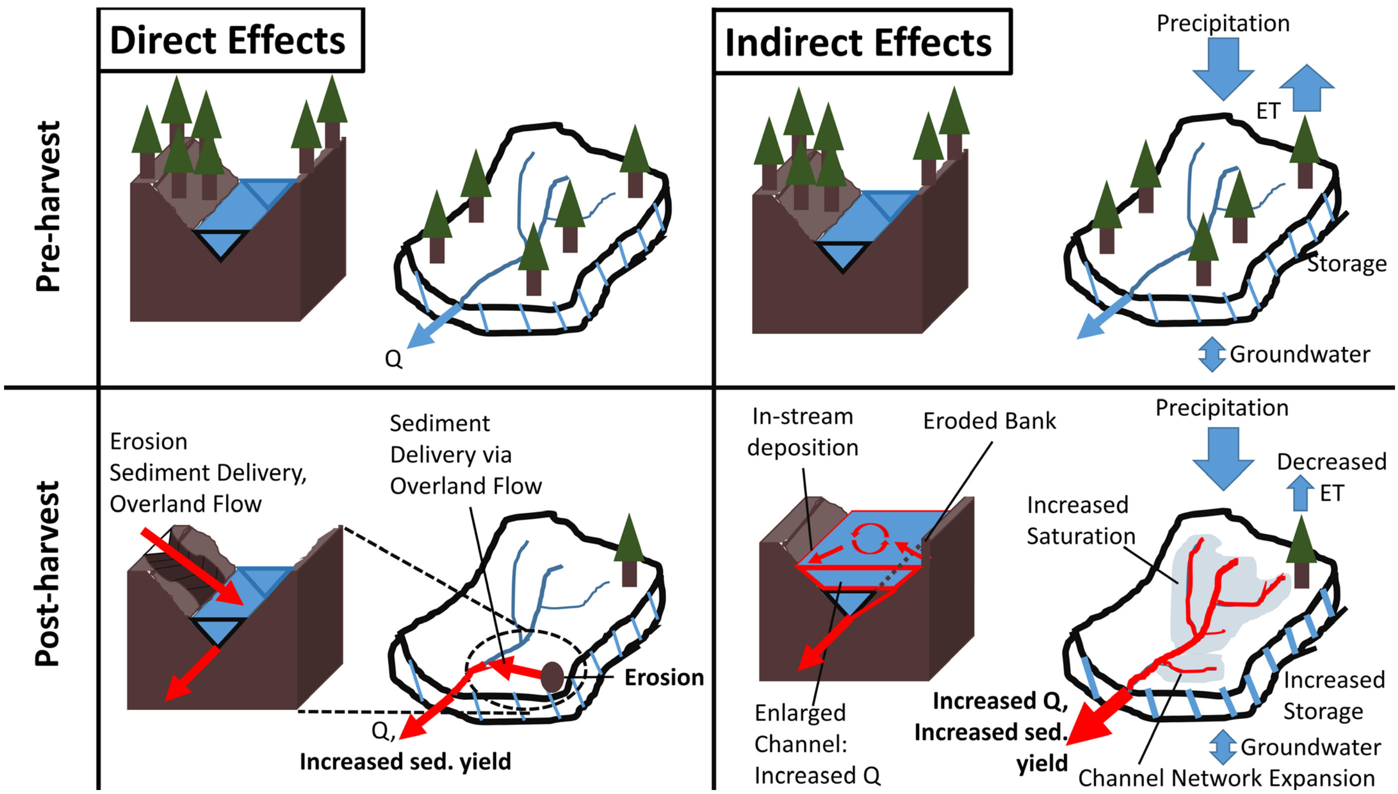

FIGURE 2. Conceptual model of direct and indirect effects of forest harvesting on sediment yield in temperate forested watersheds. Sediment movement and transport are illustrated in red. Note that for direct effects, sediment connectivity (red) is congruous with overland hydrologic connectivity (represented by red sediment delivery arrow). For indirect effects, hydrologic connectivity (light blue) is large throughout the watershed but sediment connectivity (red) is primarily within and near the fluvial network. Q represents streamflow, and ET, evapotranspiration.

indirect effects has been alluded to previously (Hassan et al. 2006; Anderson and Lockaby 2011; Varanka et al. 2015), and even termed as such (Hassan et al. 2006), but these effects have not been formally defined, nor have the drivers of these effects and their relative importance been identified. Sediment yield increases after forest harvesting derived from paired-catchment studies integrate direct and indirect effects. Some paired watershed studies have indicated that contemporary harvest practices can have little effect on stream sediment yield (Hatten et al. 2018); others, however, have shown sediment yield increases (Fraser et al. 2012). It is critical to define the direct and indirect processes by which sediment yield increases may occur to gain physical insight into sediment yield and water quality management. Drivers of direct and indirect effects include management intensity and extent, basin geology and physiography, disturbance history and disturbance interactions with management, legacy effects, cover type, geomorphic variables and stream stability, and hydrologic regime. The most important variables and relative importance of direct vs. indirect effects depend on the unique local combination of these factors.

DIRECT AND INDIRECT EFFECTS

Direct Effects

Direct effects of forest harvesting on sediment yield are dependent on the hillslope-scale processes of erosion (i.e., sediment detachment) and sediment delivery via overland pathways (Croke and Hairsine 2006). For direct effects, recent surface erosion is transported quickly through overland flow by infiltration-excess and/or saturation-excess flow pathways. Erosion on forest harvest sites in temperate regions is generally hydrologically controlled through sheet, rill, and gully processes, or through landslide events induced by altered hillslope hydrology (Rice and Lewis 1991); detached sediment is then transported to streams through pathways of hydrologic connectivity (Croke and Hairsine 2006; Bracken et al. 2015). Factors influencing sheet and rill water erosion and delivery are widely studied, and include slope grade, length, and roughness, vegetative ground coverage and root structure, soil texture, compaction, and erodibility, and rainfall amount and intensity (Wischmeier and Smith 1978; Luce and Black 1999). Hydrologically induced landslide events, a primary detachment process in steep terrain, occur naturally but are exacerbated by forest harvesting — by the interruption and concentration of road runoff, oversteepening of slopes by side-cast roads, valley fill failures, high subsurface water levels often caused by increased soil saturation of bare hillslopes, noncohesive slope materials, and loss of soil strength due to decay of roots (Beschta 1978; O'Loughlin 1985; Roberts and Church 1986; Durgin et al. 1988; Rice and Lewis 1991; Montgomery 1994; Wemple et al. 1996, 2001; Madej 2001; Gomi et al. 2005; Johnson et al. 2007; Collins 2008; Neary et al. 2009). Which erosion factors are dominant depends on local biophysical and management factors.

High-intensity management is associated with increased risk for both erosion and delivery aspects of direct effects due to increased soil disturbance and altered vegetation growth due to competition release, for example, compared to low-intensity managed sites (Grigal 2000; Hayes et al. 2005; McBroom et al. 2008). Intensive silvicultural practices and management include slash removal and utilization, site preparation, and vegetation control, in contrast to low-intensity practices, as discussed by Grigal (2000). BMPs are designed to address the direct effects of intensive management and are highly effective when utilized, and properly installed and employed (Aust and Blinn 2004; Cristan et al. 2016). Thus, although actual direct effects on intensively managed sites are low where BMPs are (properly) implemented, the risk of direct effect occurrence via erosion and sediment delivery is higher on these sites if BMPs are not (properly) implemented.

The road and skid trail network on any harvest site disproportionately influences both erosion and sediment delivery, especially where this network is near or intersects stream channels (Rivenbark and Jackson 2004; Croke and Hairsine 2006; Lang et al. 2015). Forest roads influence sediment detachment via landslide processes, as discussed earlier, but also can serve as a significant source of sediment themselves (Megahan and Kidd 1972; Luce and Black 1999; Megahan et al. 2001). This varies greatly by soil texture and road material (Luce and Black 1999). In steep terrain, forest roads intercept subsurface flow in hillslopes and redirect this flow to ditches, delivering water to streams more quickly; the hydrologic effects of forest roads are dependent on hillslope length, soil depth, and cutbank depth (Wemple and Jones 2003). Sediment production from roads also depends on how frequently the road is used (Reid and Dunne 1984). Gully initiation can occur where overland flow from forest roads is discharged onto hillslopes, particularly where slopes are steep and road contributing area is high (Croke and Mockler 2001; Madej 2001). Connection of forest road drainage directly to streams via gullies is a high-risk scenario for direct effects, as a sediment source (forest road) becomes connected via overland flow directly to the stream (Croke and Hairsine 2006). Many of the BMPs developed for reducing sediment yield effects of forest harvesting thus focus on reducing risks from forest roads, such as constructing water bars to slow overland flow, drainage control, and road removal (Madej 2001; Reid et al. 2010). In summary, direct effects occur in temperate watersheds via sediment sources eroding by water, delivered to the stream channel via pathways of overland hydrologic connectivity, and subsequently exit the watershed as suspended sediment. In undisturbed temperate forests, the primary mechanism for overland flow is saturation excess flow, but infiltration excess flow is common on forest roads and can become common after forest harvesting due to soil compaction and exposure in the general harvesting area (Chanasyk et al. 2003; Buttle 2011).

Indirect Effects

Indirect effects of forest harvesting on sediment yield are those caused by increased in-and-near-stream erosion due to increased flows. Such changes are predicted based on channel evolution models in alluvial rivers (e.g., Simon and Hupp 1987), but are an effect of channel processes propagating from an increase in streamflow rather than an increase in surface erosion delivered to the stream network. Hydrologic alterations themselves are directly related to decreases in ET after forest harvesting and changes in catchment flowpaths associated with disturbance (Buttle 2011). Although these hydrologic changes directly result from forest harvesting, the subsequent sediment yield response of streams is associated with increased flow, thus being a mediated process and an indirect result of the harvest. In connectivity parlance, the hydrologic and sediment connectivity are not coincident in both space and time (Figure 2). Hydrological effects of forest harvesting on streamflow vary widely due to regional and watershed conditions, but postharvest increases in streamflow are well-established (Bosch and Hewlett 1982; Sahin and Hall 1996; Stednick 1996; Brown et al. 2005; Zhang et al. 2017). Forest harvesting can affect the entire spectrum of flow regimes from baseflow (Price 2011) to peak flows (Guillemette et al. 2005). Although indirect effects have been alluded to and discussed in many studies, they are often not quantified and compared to direct effects (Table 1). For example, Table 1 references key studies relating hydrologic change to sediment yield change for the regions reviewed, including primary paired-watershed studies and reviews focused on paired-watershed results that could causally attribute the effects of forest harvesting on stream sediment.

Indirect effects depend on catchment-and-reach-scale variables such as watershed size, climate characteristics (e.g., hydrologic regime, energy regime: Zhang et al. 2017), watershed geologic and physiographic characteristics, cover type, and stream geomorphic characteristics (e.g., stability, bank material, floodplain storage, etc.). Furthermore, forest management may influence indirect effects via changing catchment flowpaths through road construction and altering vegetation composition postharvest (e.g., through control of competing vegetation or other actions that reduce total leaf area). For this review of indirect effects processes, we will focus on the small spatial (<10 km^2) watershed scale because the majority of the forest hydrology literature occurs at this scale (Andréassian 2004).

Changes in high and peak flows are particularly important for channel form and instream erosional dynamics, changing channel dimensions and mobilizing bank and floodplain sediments (Wolman and Miller 1960; Phillips and Jerolmack 2016). It is generally agreed upon that forest harvesting affects *at least* small, frequently occurring, peak flows important for channel formation and erosional dynamics in many streams (Beschta et al. 2000; Andréassian 2004; Guillemette et al. 2005; Buttle 2011). Infrequent high-discharge events can be important for channel form and structure in certain regions (e.g., where large materials form parts of important channel units: Grant et al. 1990), highlighting the importance of understanding how forest harvesting affects flows across a range of high flow regimes. In addition to peak discharge increases, streams can spend a longer time of the year at elevated discharge, thereby mobilizing more sediment within the channel compared to the preharvest condition. Furthermore, increases in baseflow can be important for indirect effects: for example, for headwater catchments where active channel length can be highly variable (Godsey and Kirchner 2014), channels may expand and activate new sources of instream erosion, and for longer periods of time during the year (Gomi et al. 2005).

Sediment yield generated within the fluvial network is based on complex feedbacks including discharge, channel geomorphic characteristics and history, sediment storage reservoirs, and sediment grain sizes and their distribution (Pizzuto et al. 2014). Channel characteristics and stability antecedent to disturbance can influence the sensitivity of streams to indirect effects, with "unstable" streams more sensitive to changes (Heede 1991; Harvey 2007; Mukundan et al. 2011). Furthermore, alterations to the flow regime can force streams across geomorphic thresholds and induce instability, dependent on

TABLE 1. Key paired-watershed studies relating forest harvesting to streamflow and stream sediment response in the reviewed regions. Rubric for "Discussion of indirect effects" — Yes = explicitly distinguished indirect vs. direct effects and discussed both; No = all increases in stream sediment attributed to direct effects without explicitly quantifying indirect effects; Mentioned in discussion = indirect effects were mentioned somewhere in the paper as a potential driver of increased stream sediment, but without further quantification; Unclear = indirect effects were alluded to but not discussed.

Study	Region	Physiographic section	Paper type	Sediment response variable to forest harvesting (+, −, inconclusive)	Discharge response to forest harvesting (+, −, inconclusive)	Discussion of indirect effects?	Comments
Lewis et al. (2001)	Pacific Mountain System	California Coast Ranges	Paired-watershed analysis	Storm suspended sediment loads (+)	Storm peaks (+); storm runoff volume (+)	Yes	Caspar Creek: Increases in storm sediment loads attributed to increased volume of streamflow
Gomi et al. (2005)	Pacific Mountain System	Entire Pacific Mountain System	Literature Review	Dependent on studies reviewed	Dependent on studies reviewed	Yes	"...an issue that cannot be definitively answered based on existing studies relates to the relative roles of hydrologic changes vs. changes in sediment supply from external sources after harvesting." (p. 893)
Moore and Wondzell (2005)	Pacific Mountain System	Entire Pacific Mountain System	Literature Review	Dependent on studies reviewed	Dependent on studies reviewed	Mentioned in discussion	Some reviewed studies related peak flow increases to increases in sediment yield, but drivers of sediment response not discussed in detail
Hassan et al. (2006)	Pacific Mountain System	Entire Pacific Mountain System	Literature Review	Dependent on studies reviewed	Dependent on studies reviewed	Yes	Dominant drivers of harvest-related direct vs. indirect effects importance not discussed in detail
Reiter et al. (2009)	Pacific Mountain System	Middle Cascade Mtns/Puget Trough	Time-series analysis	Turbidity (+)	Not quantified	Unclear	Flow-adjusted turbidity decreases are attributed to improvements in road construction and maintenance
Reid et al. (2010)	Pacific Mountain System	California Coast Ranges	Paired-watershed analysis	Suspended sediment yield based on Lewis et al. (2001) (+); Gully incidence and erosion rates (+)	See Lewis et al. (2001)	Yes: explicitly investigated	Caspar Creek: 28% increase in drainage density after logging; in-channel sources within logged area and downstream, and increased hillslope-channel connectivity, implicated in elevated sediment yields
Klein et al. (2012)	Pacific Mountain System	Klamath Mountains, California Coast Ranges	Multiple-basin analysis	Turbidity	Not quantified	Unclear	Legacy effects indicated but in-stream sediment sources not discussed
Bywater-Reyes et al. (2017)	Pacific Mountain System	Oregon Coast Range	Paired-watershed analysis	Suspended sediment yield (+)	Not quantified	Mentioned in discussion	Changes in sediment rating curves in given years encapsulate both direct and indirect effects
Bywater-Reyes et al. (2018)	Pacific Mountain System	Middle Cascade Mountains	Paired-watershed analysis	Suspended sediment yield (inconclusive)	Not quantified	Mentioned in discussion	H.J. Andrews Experimental Forest: Results could indicate increasing in-stream sourced sediment with drainage area

(continued)

TABLE 1. (continued)

Study	Region	Physiographic section	Paper type	Sediment response variable to forest harvesting (+, −, inconclusive)	Discharge response to forest harvesting (+, −, inconclusive)	Discussion of indirect effects?	Comments
Hatten et al. (2018)	Pacific Mountain System	Oregon Coast Range	Paired-Watershed Analysis	Suspended sediment yield (no effect)	Not quantified	No effect on sediment yield	Alsea Watershed Study: Revisited
Safeeq et al. (2020)	Pacific Mountain System	Middle Cascade Mountains	Paired-watershed analysis	Total sediment yield (+): suspended (+) and bedload (+)	Water yield (+); small peaks (+); large peaks (unchanged)	Yes: explicitly investigated	H.J. Andrews Experimental Forest: Both direct and indirect effects were found and attributed using modeling of sediment rating curves; direct effects substantially more important (20 times more)
Alexander et al. (1985)	Intermountain West	Southern Rocky Mtns	Paired-watershed analysis	Sediment yield (+)	Water yield (+); Peak flows (+ or unchanged)	No	Multiple paired-watershed experiments at Fraser Experimental Forest reviewed
Karwan et al. (2007)	Intermountain West	Northern Rocky Mtns	Paired-watershed analysis	Total suspended solids (+)	Not quantified	Mentioned in discussion	Mica Creek Experimental Watershed: Increase in suspended load not attributable only to hillslope or road erosion due to only marginal increases in concentration
Swank et al. (2014)	Southeast	Southern Blue Ridge	Paired-watershed analysis	Sediment yield (+) (based on weir pond collection)	Water yield (+); baseflow (+); peaks (small +)	Mentioned in discussion	Coweeta Hydrologic Laboratory: Only minor instances of streambank erosion derived from cross-section measurements (Swank et al. 2001; unpublished data). Sediment yield measured above and below road crossings found much of the sediment yield was sourced from forest roads. One large storm caused a large influx of sediment that continues to serve as an in-stream sediment source
Beasley and Granillo (1988)	Southeast	Mississippi Alluvial Plain	Paired-watershed analysis	Stormflow total suspended sediment (+)	Water yield (+)	Mentioned in discussion	Water yield discussed as a driver of sediment yield but not separated from increases in sediment concentration
McBroom et al. (2008)	Southeast	West Gulf Coastal Plain	Paired-watershed analysis	Sediment yield (+ on watersheds <10 ha; no effect or + on watersheds >50 ha)	Stormflow (+ on watersheds <10 ha, no difference on large watersheds >50 ha)	Mentioned in discussion	Only marginal increases in sediment concentration interpreted as supporting in-channel vs. upland supply source for sediment
Terrell et al. (2011)	Southeast	East Gulf Coastal Plain	Paired-watershed analysis	Total suspended solids yield (+)	Water yield (+); peaks (no change)	Mentioned in discussion	Bank erosion and failures observed in both treatment and control watersheds

(continued)

TABLE 1. (continued)

Study	Region	Physiographic section	Paper type	Sediment response variable to forest harvesting (+, −, inconclusive)	Discharge response to forest harvesting (+, −, inconclusive)	Discussion of indirect effects?	Comments
Fraser et al. (2012)	Southeast	Piedmont Upland	Paired-watershed analysis	Total suspended solids: concentration (no effect), yield (+)	Water yield (+); peak flows (+)	Yes: explicitly investigated	Assessed bed composition and streambank condition to attribute increased sediment yield to increased flows
Boggs et al. (2016)	Southeast	Piedmont	Paired-watershed analysis	Total suspended sediment (+)	Water yield (+); peak flows (+); stormflow (+)	Mentioned in discussion	Postharvest increases in sediment yields attributed to in-stream sources and mobilization of legacy sediment
Aubertin and Patric (1974)	Southeast/ Northeast	Allegheny Mtns.	Paired-watershed analysis	Turbidity (+)	Water yield (+); most increases in the growing season	Mentioned in discussion	Fernow: "…It is quite probable that most of the increased turbidity observed during storm periods resulted from channel extension or channel scour, or both…" (pg. 248)
Kochenderfer and Hornbeck (1999)	Southeast/ Northeast	Allegheny Mtns.	Paired-watershed analysis	Sediment yield (+), turbidity (+)	Water yield (+); Some peak flows (+)	Mentioned in discussion	Fernow Experimental Forest
Martin et al. (2000)	Northeast	White Mtns.	Paired-watershed analysis	Annual sediment yield (+); note this was sediment collected in weir pond	Water yield (+, mostly during growing season); Peaks (+ moderately)	Mentioned in discussion	Hubbard Brook: Small impacts on peak flows interpreted as having minimal effect on stream and channel scour
Verry (1972)	Western Lake States	Central Lowland: Western Lake	Paired-watershed analysis	Not collected	Water yield (+); small to moderate peak flows (+)	No	Marcell Experimental Forest: "Sediment losses were not measured because they were expected to be small due to the low relief and rapid regrowth of herbaceous plants, shrubs, and trees." (pg. 283)
Merten et al. (2010)	Western Lake States	Central Lowland: Western Lake	Paired-plot analysis on the stream-reach scale	Geomorphic assessment of reaches: streambed surficial fine sediments (+), residual pool depth (−), embeddedness (+), depth of refusal (+), and proportion unstable banks (+)	Not collected	Mentioned in discussion	Increases in streamflow discussed and implicated as a potential driver, but discharge was not measured

predisturbance stream conditions (Church 2002). Consideration of both the preharvest conditions of the stream as well as its disturbance history is important where streams are unstable or include large sources of erodible sediment. Some examples include where legacy sediments have dramatically altered stream morphology and comprise large sediment storage reservoirs (Jackson et al. 2005; James 2013), streams are incising due to crustal rebound after glaciation (Riedel et al. 2005), or where streams are adjusting to a sudden base-level change (Gran et al. 2011). Legacy sediment deposited as a result of anthropogenic land use (such as clearcutting or grazing), and channel alterations due to historic anthropogenic activities (e.g., log drives, beaver trapping, and placer mining) will also influence the potential for indirect effects to occur (Wohl and Merritts 2007; Noe et al. 2020). For example, where legacy sediments are pervasive in the mid-Atlantic Chesapeake Bay watershed, implementation of traditional agricultural and upland BMPs is expected to decrease sediment yields eventually, but reworking of legacy sediments within the channel may confound and mask the effect of these BMPs for years to come (Noe et al. 2020).

Undisturbed streams have historically been modeled in a state of quasi-equilibrium, wherein sediment transport rate equals sediment supply rate. When a disturbance in this equilibrium condition occurs, either in transport capacity (i.e., increased streamflow), or increased sediment supply, then streams adjust their grade and/or width depending on bank and bed grain size and cohesion, and catchment characteristics such as the presence of bedrock controls (Simon 1992). Thus, indirect effects of forest harvesting on sediment yield of streams follow directly from these energy and adjustment considerations from fluvial geomorphology (Langbein and Leopold 1964; Simon and Rinaldi 2006; Phillips and Jerolmack 2019). Perturbations to this equilibrium will tend to re-approach equilibrium through processes of degradation, channel widening, and aggradation, with channel incision an archetypal behavior of a stream in disequilibrium (Simon and Hupp 1987; Phillips 1992a; Simon and Rinaldi 2006). However, there has been widespread debate about the validity and exact definition of equilibrium concepts, and the need for conceptual frameworks that can support disequilibrium, nonlinear processes, and multiple equilibria (Trimble 1977; Phillips 1992b; Bracken and Wainwright 2006). Furthermore, there continues to be debate about the primary drivers of channel form even in well-studied gravel bed systems (Phillips and Jerolmack 2016; Pfeiffer et al. 2017; Pfeiffer and Finnegan 2018). Streams are hypothesized to be in a state of disequilibrium in large areas of the U.S., such as areas of the Southeast Piedmont that store large amounts of legacy sediment in floodplains (Trimble 1977). Furthermore, it remains unclear how equilibrium concepts, developed for application to alluvial rivers with relatively coarse-grained sediment, apply in regions with ubiquitous wetland rivers and/or regions recently glaciated, which have patterns of channel evolution considerably different from alluvial or bedrock rivers (Jurmu and Andrle 1997; Watters and Stanley 2007). Thus, when considering indirect effects, local geomorphic variables and fluvial characteristics need to be considered, such as possible nonequilibrium conditions, to understand the full geomorphic ramifications of altered discharge regimes after forest harvesting.

Cover type also determines hydrologic response to harvesting and potential for indirect effects, as cover type exerts a strong influence on the ET of the regenerating forest. For example, harvesting conifers often increases streamflow more than harvesting deciduous trees because of the higher water use of conifer species (Brown et al. 2005; Mao and Cherkauer 2009; Sebestyen, Verry, et al. 2011). A conversion from deciduous to coniferous species at the Coweeta Hydrologic Laboratory in North Carolina (Southern Blue Ridge section) caused water yield decreases 10 years after conifer planting, with marked differences during the dormant season (Swank and Miner 1968; Swank and Douglass 1974). Evergreen conifer species have higher leaf area and maintain an evaporative flux throughout the year through transpiration longer into the deciduous dormant season and by maintaining their leaf area as an interception surface even while dormant (Hornbeck et al. 1993; Pomeroy and Granger 1997; Sun et al. 2008; Sebestyen, Verry, et al. 2011). Bosch and Hewlett (1982) found water yield increases were highest from pine and eucalypt species, followed by deciduous, and finally brush/scrub cover. They also note that yield increases depended on annual precipitation of the study basin with wetter catchments experiencing greater yield increases after forest harvesting. Drier catchments typically have more persistent increases in water yield, probably due to slower regeneration of the vegetation. This is presumably true for all watershed conditions (infertile site, short growing season, etc.) where regeneration is slow. Annual water yield is only one metric of how forest cover and species assemblage affects streamflow; species assemblage can affect the whole range of flows, including geomorphically significant flows. For example, conversion from deciduous hardwood to evergreen conifer species reduces the incidence of extreme wet years because of increased soil storage, potentially reducing peak flows in these years, but may exacerbate dry years and drought (Ford et al. 2011).

The hydrologic effects of species selection and assemblages depend not only on conifer vs. deciduous, but rather on the particular species being compared and under consideration for unique regional conditions. For example, deciduous sweetgum (*Liquidambar styraciflua*) plantations in the Southeast U.S. have nearly 70% less water yield than evergreen loblolly pine (*Pinus taeda*): although ET was higher for loblolly pine in the dormant season, growing season ET was ~90% higher for sweetgum (Caldwell et al. 2018). Furthermore, understory vegetation can significantly impact catchment wetness and water yield, including offsetting ET losses from forest canopies lost through disease or drought through increased growth of understory shrub species (Guardiola-Claramonte et al. 2011; Ford et al. 2012; Bladon et al. 2019). Furthermore, partial catchment harvesting can cause remaining trees to increase transpiration rates and partially offset increases in streamflow after forest harvesting (Boggs et al. 2015). Finally, long-term effects of climate change can alter species assemblages even in reference conditions, in turn causing changes in water yield (Caldwell et al. 2016). In this case, altered sediment yield regimes may prevail in the absence of any watershed harvesting because of gradual changes in forest composition and their respective resulting hydrologic regimes.

Forest management and silvicultural system used can influence indirect effects by introducing changes in vegetation composition, either via cover type conversion or through the use of practices that further reduce postharvest leaf area and ET such as competing vegetation control. Thus, similar to intensively managed sites posing a greater risk of direct effects, certain intensive management practices such as competing vegetation control also may increase the risk of indirect effects by altering the recovery time of ET to preharvest levels. In addition to the type and intensity of silvicultural practices, the spatial extent of harvesting is critically important via its influence on overall change in ET at the catchment scale.

We discuss multiple implications — for short- and long-term management — of direct and indirect effects in an “Implications” section to flesh out management intensity and extent in the context of spatial and temporal scaling effects for both direct and indirect effects. We also discuss how forest management can influence disturbance regimes a site may eventually experience in the long run. Direct and indirect effects are not always clear and distinct — there are some cases for which it remains unclear whether elevated sediment yield should be attributed to direct or indirect effects, or both. Some uncertainty will persist in partitioning direct and indirect effects, along with background sediment yield expected in the absence of harvesting. However, it is important to recognize both direct and indirect effects as potential contributors to sediment yields. These two types of effects act through different processes and can be distinguished by how indirect effects result from alterations of the hydrologic cycle and the different patterns for how sediment and hydrologic connectivity overlap in space and time.

REGIONAL REVIEW

To facilitate management of direct and indirect effects specific to local and regional conditions and explore their drivers, we have structured our review by region to highlight how differences in physical hydrology and geomorphic variables, different cover types, and management affect direct and indirect effects. The regions highlighted are those in the U.S. where temperate working forests are common and include the Pacific Mountain System, Intermountain West, Southeast, Northeast, and Western Lake States (Figure 1; Fenneman and Johnson 1946). Regions are broad and contain much internal variation. Rather than serve as a comprehensive review, the regional review highlights pertinent literature and explores how sensitive different biophysical systems may be to direct or indirect affects based on their characteristics, and are not necessarily applicable within each subset of the regions reviewed. We stress how broad differences between regions can affect direct and indirect effects drivers, such as the presence of mountains, glacially deposited material, precipitation trends, and anthropogenic landscape history to further elucidate and explore direct and indirect effects.

Pacific Mountain System

The Pacific Mountain System, defined by the northern portion of the eponymous physiographic division (Fenneman and Johnson 1946), includes areas west of the Cascade range in the U.S. states of Washington and Oregon, areas of northern coastal California, and extends north to western British Columbia in Canada. This region has a complex geologic history influenced by tectonic, volcanic, and glacial activity, but glacial effects were generally localized to the effects of mountain glaciers not physically connected to the Laurentide Ice Sheet in the U.S. (Orr and Orr 2002). Landscape variables such as slope, soils, and geomorphology are strongly dependent on the recency of tectonic activity and bedrock geology (Swanson et al. 1987). Precipitation amount is high compared to other regions in the U.S. The rainfall erosivity variable associated with the

Universal Soil Loss Equation (USLE), average annual rainfall erosivity factor R, ranges from 1% of the coterminous U.S. maximum value east of the Cascades, to nearly 50% of the maximum value for the U.S. in the Cascades and Olympic Peninsula (Renard 1997; Wieczorek and LaMotte 2010). Generally, this region experiences wet winters and dry summers. Hydrologic regime varies widely in space depending on altitude (Dettinger and Cayan 1995). Many lower-altitude catchments are rainfall-dominated, higher-altitude catchments snowmelt-dominated, and a mixed regime at mid-altitudes. However, the altitude at which these changes occur may increase due to climate warming (Klos et al. 2014). Intensive silvicultural practices (e.g., vegetation control, fertilization) are commonly used in the Pacific Mountain System, with coniferous Douglas-Fir (*Pseudotsuga menziesii*) being the primary commercial species (Moores et al. 2007). Areas of the Pacific Mountain System have relatively large harvest extent compared to other regions reviewed, including areas where 2%–3% of the regional land area is clearcut each year compared to an annual coterminous U.S. average of 0.9% (Masek et al. 2008). However, recent work on the Alsea watershed study has indicated that when contemporary BMPs are used, suspended sediment can be unaffected by forest harvesting, indicating low potential for direct and indirect effects (Hatten et al. 2018: Oregon Coast Range).

Direct Effects. In the Pacific Mountain System region, many of the direct effects after forest harvesting are the result of hydrologically induced landslides and mass failures on a small minority of forest harvest sites (Grant and Wolff 1991; Rice and Lewis 1991). Attributes in the Pacific Mountain System that influence direct effects are high slope grades and hillslope position (Luce and Black 1999; Madej 2001; Litschert and MacDonald 2009), mountain and coastal driven precipitation patterns (Madej 2001; Rashin et al. 2006; Bywater-Reyes et al. 2017), catchment geology and sediment supply (Bywater-Reyes et al. 2017), and intensive management (Hayes et al. 2005).

Bedrock type is highly correlated with slope and soil characteristics, influencing areas in which landslide risk factors are present such as cohesiveness of slope materials. Furthermore, precipitation patterns in mountainous catchments are highly heterogeneous, especially during the wet winters in the Pacific Northwest (Beschta 1999), influencing patterns of rainfall erosivity. Although landslide risk is comparatively high in this region, sheet and rill erosion remain uncommon due to low precipitation intensity and high infiltration rate of hillslopes (Swanson et al. 1987). The connectivity of landslide-eroded sediment to streams, however, is determined by basin morphology; sediment eroded via landslide processes is more likely to be delivered in steep-sloped basins with narrow stream valleys in contrast to basins with broad valley floors formed via glaciation and less strong hillslope-stream connectivity (Swanson et al. 1987). Furthermore, although silvicultural management is generally intensive in the region, skyline logging is common in steep terrain, which in general can limit soil disturbance and risks for direct effects (Worrell et al. 2011). When roads are used, their interruption of hillslope drainage creates increased risk for landslide events, in addition to gullying where road runoff drains onto hillslopes through concentrated pathways (e.g., culverts) (Madej 2001; Wemple et al. 2001).

Indirect Effects. The Pacific Mountain System includes two of the only identified key studies that have directly quantified indirect effects (Table 1), where one study found that both direct and indirect effects contribute to sediment yield, but direct effects were substantially more important (Safeeq et al. 2020: Middle Cascade Mountains). However, studies in the California Coast Ranges have attributed increases in storm sediment loads to increased streamflow volume and drainage network expansion (Lewis et al. 2001; Reid et al. 2010). In the Oregon Coast Range, forest harvesting was shown to have little effect on suspended sediment concentration or yields (Hatten et al. 2018). Another study in the Oregon Coast range found that >90% of the suspended sediment in both reference and treatment (via partial clear cut) basins was sourced from within the stream channel, but did not specifically attribute how instream sediment mobilization may have changed in response to altered hydrology after harvesting through comparison with preharvest conditions (Rachels et al. 2020). These varied responses between physiographic sections within the Pacific Mountain System illustrate the high diversity of hydrologic and sediment response within a region, and the difficulty with generalizing without accounting for local landscape factors. However, the importance of instream sediment for suspended sediment yield is clear across landscape regions.

The risk for indirect effects in the Pacific Mountain System varies with basin geology and hydrologic regime. Basin geology exerts a primary control on sediment dynamics, and possibly the potential for indirect effects, for Pacific Mountain System streams by determining sediment supply in forested headwater catchments (Gomi et al. 2005; Bywater-Reyes et al. 2017). In this region, suspended sediment depends on sediment source, with friable bedrock and/or presence of unconsolidated glacial material providing a greater source of sediment than erosion-resistant bedrock; this has been supported both in the Cascades and the Oregon Coast Range (Gomi et al. 2005; Reiter et al. 2009; Bywater-Reyes et al. 2017). It is not overall catchment sediment supply *per se* that controls indirect effects, but rather how sediment is connected to and suspended within streams throughout time and space (Rachels et al. 2020). In steep headwaters, streams will have high unit stream power and high transport/flushing capacity, vs. gradual streams with depositional floodplains further downstream (Hassan et al. 2006). Increased discharge increases shear stress, but indirect effects require the increased discharge to overcome the mobilization threshold which varies based on sediment grain size, channel material, bed substrate, etc. Bedrock geology and presence of glaciation, altitude, and stream order may serve as an initial indication of hillslope-floodplain-channel connectivity of streams, stream power, and sediment characteristics such as grain size (i.e., steep bedrock headwaters vs. alluvial downstream valleys). The pathways of (sub)-surface hydrologic connectivity after forest harvesting, dependent on the structure of the critical zone — that is, the layer of earth from the bottom of groundwater to the top of the tree canopy (Banwart et al. 2013) — and how the flow pathways align with sources of sediment in time and space, will indicate whether direct or indirect effects will be dominant.

Debris jams can be important drivers of stream sediment in all regions, but are especially important for indirect effects in small to mesoscale, steep forested Pacific Mountain System catchments where hillslopes and streams are highly connected, and steep high-energy streams have the energy to export even large debris from channels. This is in contrast to small low-gradient streams such as lowland tributaries, and some at high elevations such as low-gradient mountain meadows or very small headwater reaches, where there is less transport energy and/or volume of water to dislodge woody debris (Hassan et al. 2006). Sediment supply and abundance of woody debris are the primary drivers of sediment travel distance for small to mesoscale, steep Pacific Mountain System streams, and woody debris tends to control the amount of sediment stored in the channel and impact stream stability (Hassan et al. 2006). Changes in large woody debris recruitment to streams after harvest for these catchments (i.e., decreases with the harvest of large trees), may cause large changes to stream and reach morphology over time as well as change the pulse dynamics of sediment impoundment and release associated with the downstream movement of debris jams and debris flows (Jakob et al. 2005; Moore and Wondzell 2005; Hassan et al. 2006).

Recent work in the Pacific Northwest (Middle Cascade Mountains), intermountain West (Lower Rocky Mountains), and British Columbia (Okanagan Highlands and Columbia Mountains: Church and Ryder 2010) indicate that forest harvesting may have a large effect on high flow and channel-forming events, particularly in snowmelt-dominated catchments (Alila et al. 2009; Green and Alila 2012; Kuraś et al. 2012; Schnorbus and Alila 2013; Yu and Alila 2019). After harvesting in snowmelt-dominated catchments, large changes in snowmelt peaks are possible due to increased soil moisture caused by decreases in ET, increased snow accumulation due to the absence of long-wave radiation and sublimation from tree canopies, and more uniform snowmelt due to lack of heterogeneities in shading (Pomeroy et al. 1994; Murray and Buttle 2003; Green and Alila 2012; Kuraś et al. 2012; Schnorbus and Alila 2013). Rain-on-snow events cause some of the largest peak flow events (Marks et al. 1998; Jones and Perkins 2010), and are expected to increase in some mid-to-high elevation basins currently dominated by snowmelt as climate warms (Surfleet and Tullos 2013). Thus, basins in the mid-to-upper-elevation range that experience rain-on-snow and widespread harvesting may be most susceptible to increases in large peak discharge events that influence channel morphology and evolution in the region. However, the results of these recent studies contrast with other work in the region that has shown a diminishing effect of forest harvesting for large discharge events (e.g., Thomas and Megahan 1998: Middle Cascade Mountains). Thus, more research is needed on how forest harvesting affects peak flows across the whole range of occurrence probabilities.

Intermountain West

The intermountain West, defined as the Rocky Mountain System physiographic division (Figure 1), is defined by heterogeneous geologic characteristics created by tectonic activity (Thompson and Burke 1974; Kluth and Coney 1981) and climate regimes heavily influenced by elevation gradient (Cowie et al. 2017; Seyfried et al. 2018). Although slope steepness and stream power are similar compared to the Pacific Mountain System, slope characteristics such as erodibility, vegetative communities, and climate are significantly different. The climate varies across the region, but generally has wet winters in which much of the precipitation for the year falls as snow, but also includes erosive, high-intensity summer storms (Clayton and Megahan 1997: Idaho Batholith). Forests dominate at higher elevations where there is sufficient water, but lower elevations are generally too dry to support forest cover (Wondzell and King 2003: Northern Rocky Mountains). Fire is an important driver of intermountain West ecosystems, and is more common in water-limited regions of the western U.S. compared to the eastern U.S. (Southeast, Northeast, and western Lake States) (Finney et al. 2011). However, fire is an important ecosystem driver in nearly all ecosystems. The interactions between forest harvesting and large-scale disturbance such as fire are discussed in the "Implications: Non-Harvest Disturbances" section. Fire suppression in the intermountain West has changed the composition of fire-dependent forests (Arno et al. 1995; Gavin et al. 2007), and promoted the spread of woody species into areas once dominated by shrub and grass species (Pierson et al. 2007). Forest management in the intermountain West, primarily for conifer species, can be intensive in areas, but intensive practices and harvest extent are less widespread than in the Pacific Mountain System or Southeast.

Direct Effects. Direct effects in the intermountain West are influenced by hillslope and geologic factors, including basin parent material (Northern Rocky Mountains: Sugden and Woods 2007; Megahan *et al.*, and precipitation characteristics. Slopes tend to be high and soils thin in headwater reaches, and level out to drier alluvial valleys (Northern Rocky Mountains: Seyfried et al. 2018; Southern Rocky Mountains: Wicherski et al. 2017). Overland flow in arid to semiarid lower elevation catchments can be common following high-intensity summer storms (Wondzell and King 2003), but rainfall erosivity is on average generally lower than the rest of the U.S., with the highest R-factor for the Rocky Mountain System division 7% of the national maximum for the coterminous U.S. (Renard 1997; Wieczorek and LaMotte 2010). However, it should be noted that this is an expression of average rainfall erosivity in the long run, applied to low-precipitation intermountain West watersheds, and it is important to account for the fact that some convective summer storms may be much more erosive than the mean conditions (Fletcher et al. 1981). Furthermore, mass slope failure is an important process in high-slope areas and can detach large amounts of sediment (Megahan et al. 2001: Idaho Batholith). Unlike the Pacific Mountain System where mass slope failure is almost always initiated as debris flows due to loss of slope stability, etc., mass slope failure can be initiated via overland flow in the intermountain West region (Wondzell and King 2003). Furthermore, wind erosion can be a major driver of erosion in semiarid to arid regions (Whicker et al. 2006).

Similar to the Pacific Mountain System, unconsolidated glaciated basins produce a higher sediment supply to streams than unglaciated basins (Sugden and Woods 2007). Compared to the Pacific Mountain System where forested slopes are relatively more wet and often have high infiltration capacity, the relatively drier slopes combined with intense summer storms in the intermountain West facilitate different erosional processes (i.e., overland-flow induced mass failure vs. loss of hillslope stability due to increased saturation: Wondzell and King 2003). Compared to the coast ranges of California, Oregon, and Washington in the Pacific Mountain System, there is generally a lower risk of mass failure in the more arid Northern Rocky Mountains, with localized areas of high landslide risk still occurring (Megahan and King 2004). Surface erosion by sheet, rill, and gully processes is also important, especially for dry slopes that support less vegetation (Clayton and Megahan 1997). As with other regions, forest roads tend to be the primary source of direct effects in the intermountain West (Schnackenberg and MacDonald 1998; Megahan and King 2004).

Indirect Effects. Drivers of indirect effects in the intermountain West include basin geology and hydrologic/climatic regime. Travel time for fine sediments in mountain streams tends to be fairly quick, with single-event transport distances for fine particles in high flow events on the order of tens of kilometers (Northern Rocky Mountains/Idaho Batholith: Bonniwell et al. 1999). However, landscape position influences exchange with the banks and floodplains (and thus indirect effects), as lower-gradient alluvial reaches at lower elevations tend to have more exchange than high-energy mountain headwaters (Bonniwell et al. 1999). This indicates that, like the Pacific Mountain System, basin sediment supply, geology, and stream characteristics such as stream order and channel material (alluvial vs. bedrock) will explain subregional differences and drive indirect effect response. Elevation and geology are highly correlated with surface and subsurface hydrologic behavior and regimes, and conditions are heterogeneous in western basins (Seyfried et al. 2018). Woody debris can be an important sediment driver, but wood supply to streams in the interior West has been hypothesized to be generally lower than in the Pacific Mountain System based on results seen in Colorado (Wohl and Goode 2008). This relatively lower wood supply to streams in Colorado may be a legacy effect of late 19th Century forest harvesting and relatively slow forest regeneration (Wohl and Goode 2008). Relatively slow forest regeneration in water-limited environments has been associated with more persistent hydrological changes following forest cover change than humid or water-rich areas (Bosch and Hewlett 1982).

Indirect effects have been identified as potentially important in the intermountain West region (Karwan et al. 2007), but have not been directly quantified (e.g., Alexander et al. 1985). Despite proximity to the Pacific Mountain System region and many similarities (e.g., bedrock close to the soil surface, recent tectonic activity), there are important landscape and climate differences that influence indirect effects response and variation throughout the intermountain West. In particular, the intermountain West includes many catchments that are water-limited at lower elevations. Because of this, streamflow responses to forest harvesting are more sensitive to changes in forest cover (Zhang et al. 2017), including a lower threshold of basin area cut that will induce a change in annual water yield (Stednick 1996). Forest harvesting also increases the geomorphic adjustment rate of ephemeral streams, which are common in water-limited environments, but particularly in the southern portion of the intermountain West and Great Basin (Heede 1991; Bull 1997). Similar to the Pacific Mountain System, the rain-snow transition is increasing in elevation as a result of climate change (Klos et al. 2014; Seyfried et al. 2018). This is important for forested catchments at mixed-regime elevations: rain-on-snow is often the driver of the annual maximum discharge in the region at mixed hydrologic regimes (MacDonald and Hoffman 1995). As discussed in the Pacific Mountain System section, recent findings have indicated that even high flow events in snowmelt-dominated basins may increase due to forest harvesting, but the effect of forest harvesting on the highest flows remains contentious (Green and Alila 2012; Bathurst 2014; Birkinshaw 2014).

Legacy sediment deposits from widespread mining activity, many of which are highly erodible, are common in floodplains in some areas such as the Colorado Mineral Belt (Wicherski et al. 2017). Other legacy impacts include channel clearing for log and tie drives that have increased flow erosivity, but also decreased the presence of woody debris and sediment storage (southeastern Wyoming: Young et al. 1994). These are two examples where legacy effects on stream geomorphology may affect indirect effects — the former by offering an ample supply of erodible mining legacy sediment, and the latter by increasing the erosivity of streamflow but not necessarily the supply of sediment. This illustrates that local knowledge of the anthropogenic history and geomorphic condition of streams is necessary to adequately characterize the risk of indirect effects in a catchment. Furthermore, episodic events that produce large amounts of sediment such as wildfire and debris flows dominate long-term sediment yields, and can produce influxes of sediment mobilized for indirect effects for up to centuries (Kirchner et al. 2001; Moody and Martin 2001). Thus, in previously burned catchments, geomorphic assessments and consideration of increased near-stream sediment supply for increased streamflows to erode may be a dominant legacy affect.

Southeast

The Southeast is defined by several distinct physiographic zones, including the Appalachians (mountainous, bedrock close to the soil surface), Piedmont (foothills, rolling and sometimes steep hills with erodible soils), and Coastal Plain (very low relief, erodible soils), south of Maryland (Figure 1). The hydrologic regime is rainfall-dominated, with large peak discharges possible due to extreme events such as tropical cyclones (Villarini and Smith 2010). Compared to other regions, the Southeast has high precipitation amount and intensity, most prominently in the Coastal Plain (Hershfield 1961), which includes the highest R-values in the coterminous U.S. (Renard 1997; Wieczorek and LaMotte 2010). Intensive silvicultural management and relatively large harvest extent of conifer forests and plantation forestry are common in the Southeast (Grace 2005; Masek et al. 2008; Eisenbies et al. 2009). Compared to the rest of the U.S., the Southeast (and Northeast) have relatively long land-use and forest management history, with many forests second growth or more and in abandoned agricultural areas (Rivenbark and Jackson 2004).

Direct Effects. In the Southeast, direct effects are affected by the legacy of agricultural land use (Rivenbark and Jackson 2004; Jefferson and Mcgee 2013; Lang et al. 2015), geologic and hillslope factors (Rivenbark and Jackson 2004; Aust et al. 2015; Vinson et al. 2017a, b; Lang et al. 2018), relatively high precipitation amount and intensity compared to the rest of the U.S. (Hershfield 1961; Beasley and Granillo 1988; Terrell et al. 2011), and intensive management (Grace 2005). Flat areas of the Coastal Plain exhibit very little direct effects due to the combination of low slope (McBroom et al. 2008; Terrell et al. 2011) and rapid revegetation which helps to reduce the risk of erosion and direct effects soon after harvest (Beasley and Granillo 1988; Ensign and Mallin 2001). However, where slopes are higher in the Piedmont and Appalachian regions, direct effects are more likely to occur compared to the Coastal Plain (Rivenbark and Jackson 2004; Vinson et al. 2017a).

Historical land use influences direct effects, particularly sediment delivery, in the Southeast Piedmont (Rivenbark and Jackson 2004; Lang et al. 2015). In that area, the most important of these legacy effects for direct effects are gullies that formed during post-

European settlement agriculture that are a major delivery pathway for eroded sediment, bypassing riparian areas and directly connecting uplands and streams (Rivenbark and Jackson 2004; Jefferson and Mcgee 2013; Lang et al. 2015). Direct effects occur, where sediment sources and delivery pathways are connected spatially and temporally (i.e., sediment eroding and being flushed down an abandoned gully within the timeframe of a single storm). Thus, it is not surprising that direct effects have been found to be most common where harvest operations occur within streamside management zones, and/or are connected to abandoned agricultural gullies that drain directly to streams and bypass riparian buffers (Lang et al. 2015).

Intensive silvicultural practices in the Southeast are associated with increased potential for water quality effects (Grace 2005). The areas with the highest potential for direct effects in the Southeast are those with high slope and erodible soils. In many of these areas, bladed skid trails are often used to extract timber, increasing the likelihood of erosion compared to overland skid trails (Vinson et al. 2017a, b; Lang et al. 2018) or skyline systems used in the Pacific Mountain System. Implementation of BMPs, however, is proven to mitigate direct effect impacts of intensive practices (Griffiths et al. 2017).

Indirect Effects. In much of the Southeast, a key driver of indirect effects is the widespread distribution of legacy sediments in banks and floodplains. Legacy sediments are deposited primarily in Piedmont and Coastal Plain streams as a result of historical landscape erosion and subsequent deposition in river valleys in the post-European settlement agricultural era, and constitute a large source of in-and-near-stream erosion (Trimble, 1977, 2008; Hupp 2000; Rivenbark and Jackson 2004; Walter and Merritts 2008; Pizzuto and O'Neal 2009; Mckinley et al. 2013; Lang et al. 2015; McCarney-Castle et al. 2017; Balascio et al. 2019). Stored legacy sediments in the banks and floodplains of streams cause channel instability, and may cause sediment yield to be particularly sensitive to flow increases (Jackson et al. 2005; Mukundan et al. 2011; Donovan et al. 2015). Many Piedmont streams in particular commonly have unstable banks, mobile streambeds, and are high in turbidity (Jackson et al. 2005).

In the Piedmont and Appalachian regions, flow increases are associated with increases in sediment and nutrients, contributing sediment through channel extension and/or channel scour (Aubertin and Patric 1974; Hewlett et al. 1984; Kochenderfer and Hornbeck 1999). Studies in the Appalachians have found increases in peak flows due to forest harvesting that varies with basin responsiveness to precipitation as well as the magnitude of logging and road disturbance (Hewlett and Helvey 1970; Swank et al. 2001). In one Appalachian study, most of the increased sediment yield in the harvested catchment was sourced from forest roads (i.e., direct effects), but indirect effects were not quantified (Swank et al. 2001). Further, Appalachian streams tend to have higher water quality than those in the Piedmont region (Price and Leigh 2006). As land use changes from forest to agriculture downstream from the Appalachians, however, water quality can degrade especially during stormflow, highlighting the importance of peak flows in determining sediment and nutrient yields (Bolstad and Swank 1997).

In the Coastal Plain, indirect effects can be important contributors to observed increases in sediment yield after forest harvesting, with deeply incised channels in erodible parent material (McBroom et al. 2008; Terrell et al. 2011). Flat, wet watersheds in the Coastal Plain can experience high saturation excess flow due to channel expansion during wet conditions (Beasley and Granillo 1988), and many streams in the Coastal Plain exhibit a majority of their runoff due to infrequent storm events (McBroom et al. 2003, 2008). Because direct effects are often limited on Coastal Plain sites due to low slope and rapid revegetation, indirect effects may be more important in that region. For example, high precipitation and low slope can increase the spatial area of hydrologic connectivity rapidly throughout a watershed, and can connect new sources of sediment through channel expansion. The importance of indirect effects in flat, wet watersheds in the Coastal Plain follows from the increased and spatially pervasive hydrologic connectivity, much of which is subsurface, that cause increased flows and erosion of ample sediment supply of legacy sediments in many streambanks. Furthermore, surface flowpaths and channel network expansion that are caused by increased catchment connectivity and saturation create new sources of sediment to contribute to sediment yield. Instream impacts of altered hydrological regimes in the Coastal Plain depend on wetland characteristics as well. In areas of the Coastal Plain where in-channel wetland streams are common, vegetation on streambanks, groundwater discharge patterns, and wetland type all influence channel form (Jurmu and Andrle 1997; Gurnell 2014). Furthermore, site preparation and silvicultural prescription that include wetland drainage directly alters flowpaths in addition to any changes in hydrology induced by decreased ET (Shepard 1994).

Northeast

The Northeast, grouped roughly by physiographic characteristics and silvicultural management, includes the northern reaches of the Appalachian, Piedmont, and Coastal Plain physiographic provinces north of Maryland, and New England (Figure 1). With average forestland ownership dispersed among a large number of small land owners, forest management is generally not intensive and with small harvest extent (Butler et al. 2016). Further, the hydroclimatic regime transitions from rainfall-dominated to snowmelt-dominated on a northward gradient, as does the importance of freeze-thaw for streambank erosion (Inamdar et al. 2018). The average annual R-factor varies from about 5%–25% of the coterminous U.S. maximum, the highest on the coast and lowest in inland New England (Renard 1997; Wieczorek and LaMotte 2010). Although nonintensive management is most common throughout the Northeast, it can be intensive in localized areas (e.g., areas of Maine: Czapowskyj and Safford 1993; Masek et al. 2008). Harvested species often consist of northern hardwoods dominated by deciduous species (Hornbeck and Leak 1992). Precipitation through the year is relatively evenly distributed, with large rainfall and snowmelt peaks possible (Hodgkins et al. 2003; Huntington et al. 2009); further, large peak flows are possible from extreme events such as tropical storms (Villarini and Smith 2010; Vidon et al. 2018).

Direct Effects. In general, adverse effects of forest harvesting on sediment yield in the Northeast are thought to be low (Patric 1976), and BMPs have been documented as highly effective in reducing direct effects (Hornbeck and Leak 1992; Briggs et al. 1998; Martin et al. 2000; Schuler and Briggs 2000; Wilkerson et al. 2010; Maine Forest Service 2013). The southern states of the Northeast include some of the same physiographic regions as the Southeast, (e.g., Appalachian and Piedmont provinces), but the New England states also include areas recently glaciated (Figure 1; Dyke et al. 2002). In areas of the Northeast that experience soil freezing in the winter, harvesting on frozen soils is recommended (e.g., Advisory Committee for Vermont FPR 2015), which reduces many of the risk factors for direct effects (Kolka et al. 2012).

Similar to other landscape regions, the potential for direct effects is expected to be high where slope grade is high, soils are erodible, erosion sources are connected to streams (e.g., where skid trails are located close to streams or cross streams), and soils are poorly drained (increased risk of rutting; associated with hillslope position) (Briggs et al. 1998; Schuler and Briggs 2000).

Indirect Effects. History of land use and glaciation influence indirect effects in the Northeast. In the Northeast, increases in water yield after harvesting are mostly augmentations to low flows, with some peak flows increased (Hornbeck et al. 1993, 1997; Bent 2001). Conversion of intermittent streams to perennial due to baseflow increases have been observed and may contribute to a longer period of connected flow that carries sediments (Lynch and Corbett 1990). However, peak flow increases are thought to be small and of only minor importance for stream and channel scour (Martin et al. 2000).

Legacy sediments deposited in-and-near-stream are pervasive in the mid-Atlantic region, where they constitute fine-grained erodible streambanks (Hupp 2000; Walter and Merritts 2008; Pizzuto and O'Neal 2009; Schenk and Hupp 2009; Pizzuto et al. 2014; Balascio et al. 2019). This has been attributed to post-European settlement land clearing and agricultural practices, as well as the widespread construction of milldams that altered channel morphology and caused accretion of sediments in floodplains throughout the eastern U.S., but especially in the mid-Atlantic region (Walter and Merritts 2008). Freeze–thaw dynamics, when followed by intense winter rainfall events, destabilize banks and cause high levels of bank erosion (Inamdar et al. 2018). We hypothesize that streams with these large legacy sediment deposits, such as in the mid-Atlantic Piedmont and Coastal Plain, are most susceptible to indirect effects. Farther north, in the glaciated region of New England, we hypothesize streams have less of a sediment source in the immediate channel area due to less sustained and widespread legacy effects. However, legacy sediments in floodplains have been documented in formerly glaciated New England catchments that had similar intensity of agricultural and milldam activity as the mid-Atlantic. These legacy deposits varied based on the presence of lake and wetland sinks, and the thickness of glacial deposit available for a sediment source, indicating legacy sediment presence and distribution is modulated by glacial history (Johnson et al. 2019).

The Northeast has both glaciated and unglaciated areas with respect to the last glaciation (Figure 1; Dyke et al. 2002). Glacial deposits, and their interaction with bedrock forms, are first-order controls on flowpaths in glaciated catchments of the Northeast (Shanley et al. 2015). Thus, the distinction between recently glaciated areas vs. those that did not serves as a boundary between different drivers of hydrologic response and indirect effects. In glaciated regions, where landscape features are highly heterogeneous, glacial landforms and sediment deposits will determine the critical zone development that influence sensitivity to indirect effects, such as dominant soils and runoff flowpaths. For example, streams in glacial outwash areas will have a higher baseflow component and sustained flows, as well as have more moderate stormflow peaks due to high infiltration in coarse sands compared to till or lacustrine areas (Urie 1977; Winter 2001).

Western Lake States

The western Lake States, including primarily the Laurentian Uplands physiographic division in the U.S. states of Minnesota, Wisconsin, and Michigan (Figure 1), is unique compared to the other regions because they were heavily glaciated during the last glaciation (Dyke et al. 2002; Jennings and Johnson 2011; Larson 2011; Syverson and Colgan 2011). Here, relief is low, and groundwater-surface water connection via wetlands widespread. Forest management is common, but generally not intensive, with practices such as site preparation, short rotations, and vegetation control uncommon; further, harvesting often occurs in the winter on frozen soils (D'Amato et al. 2009; Slesak et al. 2018). Mean rainfall erosivity (R-factor) ranges from about 0.10 to 0.20 of the coterminous U.S. maximum within the Laurentian Uplands (Renard 1997; Wieczorek and LaMotte 2010). Dominant species harvested include northern hardwoods, with some conifer harvesting, including wetland species such as black spruce (*Picea mariana*) during winter while the ground is frozen. The largest streamflow of the year is driven mostly by snowmelt or early-spring rain (on saturated catchments after snowmelt) dominated, but large summer rainfall peaks can occur (Sebestyen, Dorrance, et al. 2011; Villarini et al. 2011).

Direct Effects. Given the low relief and high amount of winter harvesting, direct effects in the western Lake States are generally very low (Verry 1972, 1986; McEachran et al. 2018). There are localized regions where mass slope failure is a risk, especially in the Glacial Lake Duluth clay plain and where slopes are >30% in river valleys (Radbruch-Hall et al. 1982; Riedel et al. 2005; Merten et al. 2010), but most erosion occurs via sheet or rill processes due to the low relief. Where direct effects do occur, vegetative cover is the dominant factor controlling erosion where slopes are slight; both erosion and vegetative cover levels are influenced heavily by surficial geology and glacial landform (McEachran et al. 2018). However, slope is an important driver where it is steep relative to within-region conditions. The importance of vegetation in low-relief areas is similar to the findings from the low-relief Coastal Plain in the Southeast, where rapid postharvest revegetation helps reduce the risk of direct effects soon after harvest (McBroom et al. 2008; Terrell et al. 2011). The risk of direct effects is also reduced by widespread winter harvesting on frozen soils (Kolka et al. 2012; Minnesota Forest Resources Council 2012; McEachran et al. 2018).

Indirect Effects. Indirect effects in the western Lake States are uniquely influenced by glacial geology and its influence on sediment deposits and wetland extent. Studies on peak flow effects of forest harvesting in the western Lake States have generally found small increases for low-discharge, frequently occurring peak flows, with potential increases in discharge response to large rainfall-caused events (Verry et al. 1983; Sebestyen, Verry, et al. 2011). After the loss of mature forest cover, there may be more variation between base and peak flows (Detenbeck et al. 2005), which can be an important geomorphic driver that varies with land use (Richards 1990). Increases in unstable banks and sedimentation have been observed in response to riparian thinning on glacial moraines, pointing to potential indirect effects (Merten et al. 2010). In other glaciated boreal regions similar to the western Lake States, there was little effect of clearcutting on watershed peak flows, but low flows were significantly increased, similar to findings from the Northeast U.S. (Sørensen et al. 2009).

Unlike the glaciated mountainous Northeast, where bedrock is still relatively close to the land surface, the western Lake States includes many areas with a greater depth of glacial deposits (commonly >100 m, Jennings and Johnson 2011), and thus catchment flowpaths are more strongly controlled by glacial landform. Studies in the western Lake States have shown that glacial geology is a dominant control on watershed hydrology, and influences the sensitivity of hydrologic and indirect effect response to changes in land use and land cover (Stoner et al. 1993; Schomberg et al. 2005; Belmont et al. 2011; Gran et al. 2011; Foufoula-Georgiou et al. 2015; Vaughan et al. 2017). Glacial deposits control geomorphic attributes and affect physical stream characteristics (Phillips and Desloges 2014, 2015), and influence partitioning of water and peak flow generation. For example, high-infiltration outwash and morainal watersheds have a higher groundwater component to flow than "flashier" low-infiltration lacustrine watersheds (Urie 1977; Richards 1990; Richards et al. 1996; Naylor et al. 2016). Where fine-grained lacustrine deposits occur in the repeatedly glaciated western Lake States, layering of heterogeneous deposits with abrupt changes in hydrologic conductivity between layers cause preferential flowpaths, bank slumping, and small mass wasting events (Magner and Brooks 2008), processes that may be exacerbated by increases in discharge (Riedel et al. 2005). Thus, streams developed in lacustrine sediments may be more sensitive to indirect effects than outwash, moraine, or coarse-grained till deposits.

Wetlands are common and relatively large in spatial extent compared to the other regions reviewed, and influence catchment response to forest harvesting. Wetlands have a “buffering” effect on hydrological response to harvesting (Verry et al. 1983; Detenbeck et al. 2005), and peak flows are smaller in watersheds with more storage (i.e., wetlands and lakes); however, when storage dips below ~10% of watershed area, peak flows can increase rapidly (Detenbeck et al. 2005). Wetlands are also hydrologically important areas for runoff generation (Verry and Kolka 2003), but it remains unclear how their spatial distribution and effects on stream geomorphic variables influence flow in mixed upland-wetland watersheds common in western Lake States conditions. The location of wetlands is often glacially determined, making this driver of indirect effects inextricable from the driver of glacial geology (Richards 1990; Verry and Janssens 2011).

Although there is much literature on alluvial and bedrock stream geomorphology response to flow alterations (e.g., Phillips and Jerolmack 2016), there is less understanding about wetland streams, which can exhibit significantly different geomorphic characteristics (Jurmu and Andrle 1997; Watters and Stanley 2007). Wetland stream morphology in peatlands, for example, is governed by biological processes such as peat decomposition and accumulation, as well as groundwater controls, compared to the alluvial channels that are primarily shaped by sediment load and discharge (Watters and Stanley 2007). Sediment loads in wetland streams tend to be low in general, and bank materials tend to be resistant to erosion (Watters and Stanley 2007). Furthermore, wetlands can act as a sink for sediments, removing them from flow and transport (Hupp et al. 1993; Zierholz et al. 2001). Because of this, indirect effects on sediment yield within wetland streams are likely low, but changes in wetland hydrology can affect sediment yield downstream because of their disproportionate influence on discharge to downstream alluvial reaches. This may cause indirect effects depending on local glacial geology and the properties of the wetland-alluvial stream reach interaction.

Future Directions

Although each region exhibits different biophysical and management characteristics, and exhibits vast diversity of landscape structure within each region, literature from all regions identifies basin geology as a critical driver of variables that influence both direct and indirect effects. Thus, basin geology may serve as a unifying framework to discuss direct and indirect effects. Basin geologic factors are important drivers of direct and indirect effects in diverse landscapes, from the mountainous western states to the low-relief western Lake States (Sugden and Woods 2007; Seibert and McDonnell 2010; Vinson et al. 2017a; McEachran et al. 2018). This is not surprising since basin geology is a predictor of many interrelated factors known to influence both direct and indirect effects including soil development and erodibility, native vegetation communities, sediment supply, dominant flowpaths and hydrology, and slope factors. Future regional-level studies could encapsulate subregional variability in landscape characteristics using proxies for basin geology and map out high-risk areas for direct and indirect effects. However, some process drivers of direct and indirect effects warrant further investigation.

Direct Effects. Although the drivers of erosion are relatively well understood, sediment delivery is often less understood (Croke and Hairsine 2006). Identifying primary delivery pathways through the identification of areas that are hydrologically connected via overland flow, the time over which the connection takes place, and an understanding of internal watershed sediment storage factors within regional conditions is critical for improving our knowledge of connections between erosion sources and sediment delivery in temperate working forests (Croke and Hairsine 2006; Bracken et al. 2015). The role of BMPs in preventing sediment delivery is a topic of ongoing investigation, especially how BMPs influence water quality and cumulative effects at the watershed outlet (Klein et al. 2012; Slesak et al. 2018).

Indirect Effects. Because many studies do not quantify indirect effects alongside direct effects (Table 1), their importance relative to direct effects remains unclear. Sediment fingerprinting techniques are a promising tool that can discriminate between sediment sourced from direct and indirect effects (Belmont et al. 2011) and have been utilized in the context of forest harvesting studies before (Motha et al. 2003). Pairing measurements of stream geomorphology with discharge, landscape erosion, and suspended sediment records from experimental catchments, and utilizing more methods based on the concepts from fluvial geomorphology such as the analysis of sediment rating curves, also could help determine the relative importance of direct and indirect effects (Reid et al. 2010; Fraser et al. 2012; Rachels et al. 2020; Safeeq et al. 2020).

Peak and high flows are critically important in shaping channels as well as mobilizing and transporting sediment (Wolman and Miller 1960; Blom et al. 2017). There is still much debate about how forest harvesting affects peak flows across the range of peak flow frequencies (Alila et al. 2009; Lewis et al. 2010; Green and Alila 2012; Alila and Green 2014; Bathurst 2014; Birkinshaw 2014), and more research is needed to understand the full behavior of peak flow response to forest harvesting for large magnitude, infrequently occurring flows. This is important for basins where flows important for channel morphology and instream grade-control elements (e.g., large woody debris) are associated with large, infrequent discharge events.

Despite the importance of the peak and high flow regime, other portions of the flow duration curve such as low flow and mean flow are also important for in-channel sediment yield generation. For example, a change in the sediment supply to fluvial environments (such as introduction of legacy sediments into banks and floodplains) can change the effective discharge necessary to mobilize sediments, causing instream erosion even in the absence of a change in discharge. Variable channel length and increases in connectivity of sediment sources due to increased baseflow after forest harvesting are also necessary to consider, particularly for headwater catchments (Godsey and Kirchner 2014). Thus, consideration of changes in peak flows only (despite their importance) does not encapsulate the full range of indirect effects drivers, pointing to the necessity of quantifying indirect effects instead of utilizing peak flows as a proxy for changes in sediment transport.

The role of cover type and species harvested on indirect effects also warrants further investigation. There are large inter-species differences between regions; for example, conifer regeneration in subalpine conditions in the intermountain West (Alila et al. 2009) will utilize water differently than short-rotation loblolly pine in the Southeast (McBroom et al. 2008). Of particular interest is the concept of hydrological recovery, that is the time after harvest it takes for the water and energy budget terms associated with vegetation cover to re-converge to an approximation of the preharvest time period (Stednick 2008). This will vary with the growth rate of the recovering species, management interventions (e.g., competition release), climate, and watershed physiographic conditions. Management designed to decrease recovery times may decrease the potential for indirect effects.

IMPLICATIONS

Forest Management

The direct/indirect effects framework expands the scope of the traditional forested watershed management paradigm, that usually seeks to protect water quality from direct effects at small spatial and temporal scales (Aust and Blinn 2004; Slesak et al. 2018). The direct/indirect framework holistically considers potential sediment yield effects of forest harvesting in a given region of practice. Contemporary forest harvesting BMPs focus almost exclusively on direct effects, either through preventing erosion (e.g., scattered slash, revegetating exposed soil), or preventing sediment delivery (e.g., riparian corridors, silt fences) (Aust and Blinn 2004). Often, these BMPs are implemented at the plot scale and have high effectiveness at that scale for at least several years after harvest (Cristan et al. 2016). However, some direct effects BMPs can also influence indirect effects such as BMPs related to road placement (Buttle 2011), watershed-scale harvest limits, and green-up adjacency rules that may limit cumulative impacts and indirect effects downstream (Azevedo et al. 2005). The impacts of these practices on indirect effects remain unclear and lack the widespread evaluation that direct effects BMPs have garnered in the forest hydrology literature (e.g., Edwards and Williard 2010). There is potential to further develop and optimize indirect effects BMPs at the watershed-scale to mitigate increased instream erosion. For example, harvest planning BMPs would allow managers to identify basins where indirect effects are likely to occur for their particular landscape situation, such as widespread legacy sediments and erosive channels, and plan tailored harvesting schedules that remain below a threshold level of harvest where indirect effects degrade water quality. Where forest harvesting is identified as a driver of indirect effects, more active measures to buffer increases in peak discharges may need to be explored, such as the construction of wetlands or retention basins, a strategy already used in agricultural watersheds (Mitchell et al. 2018). There are likely many opportunities to address indirect effects with management actions, but exploration of these are outside the scope of this paper.

In some regions, analysis of sediment rating curves and hysteresis during individual events may be helpful to determine sensitivity to indirect effects and provide management guidance where data are available. In particular, the presence of sediment hysteresis can indicate probable sediment supply, source, and/or depletion within an event or sequence of events (Smith and Dragovich 2009; Gellis 2013; Rose et al. 2018), offering managers more information about the hydrogeomorphic context of a particular watershed. However, information on sediment rating curves and sediment hysteresis in watersheds of various sizes relevant for forest management can have limited data availability. Sediment rating curve analysis is not uniquely diagnostic of underlying physical conditions (Warrick 2015). Sediment hysteresis has been found susceptible to dependencies that vary across watersheds and events (e.g. grain size, event sequence, hydrogeomorphic context) in their interpretation (Malutta et al. 2020). Thus, while analysis of sediment hysteresis and rating curves to determine sensitivity to indirect effects might be possible with sufficient data in a local or regional context, this technique requires further development.

Spatiotemporal Scaling of Direct and Indirect Effects

This review focused primarily on the literature from small, paired catchment studies. For basins at larger spatial scales and for long-term management, it remains unclear how or if the drivers of direct and indirect effects change. The fundamental processes for direct effects (i.e., erosion and delivery) can occur at the hillslope scale in the timespan of a single storm or season, and thus direct effects generally are studied at a localized (e.g., hillslope) scale (Figure 3). However, with increasing disturbance extent within watersheds, direct effects can become dominant drivers of sediment yield at larger spatial scales (i.e, cumulative effects; MacDonald 2000). Furthermore, with increasing disturbance severity and management intensity, direct effects can persist for a relatively longer amount of time (e.g., severely compacted soil can take many years to recover: Croke et al. 2001; Zenner et al. 2007).

Indirect effects are defined in relation to a watershed-level change in hydrologic flowpaths, and occur at larger spatial scales than direct effects (Figure 3). Forest harvesting can promote changes in forest species composition at large spatial scales (Wang et al. 2015), introducing the potential for long-term changes to watershed hydrology at multiple scales (Mao and Cherkauer 2009). The effect size of land use and land cover changes on hydrologic variables is widely hypothesized to decrease with increasing spatial scale (Blöschl et al. 2007; Viglione et al. 2016), as variation in climate becomes the dominant factor influencing hydrologic variables (Rogger et al. 2017). The point at which forest cover becomes insignificant has been generally hypothesized to occur at the level of 1 to 100 square kilometers, but remains unclear

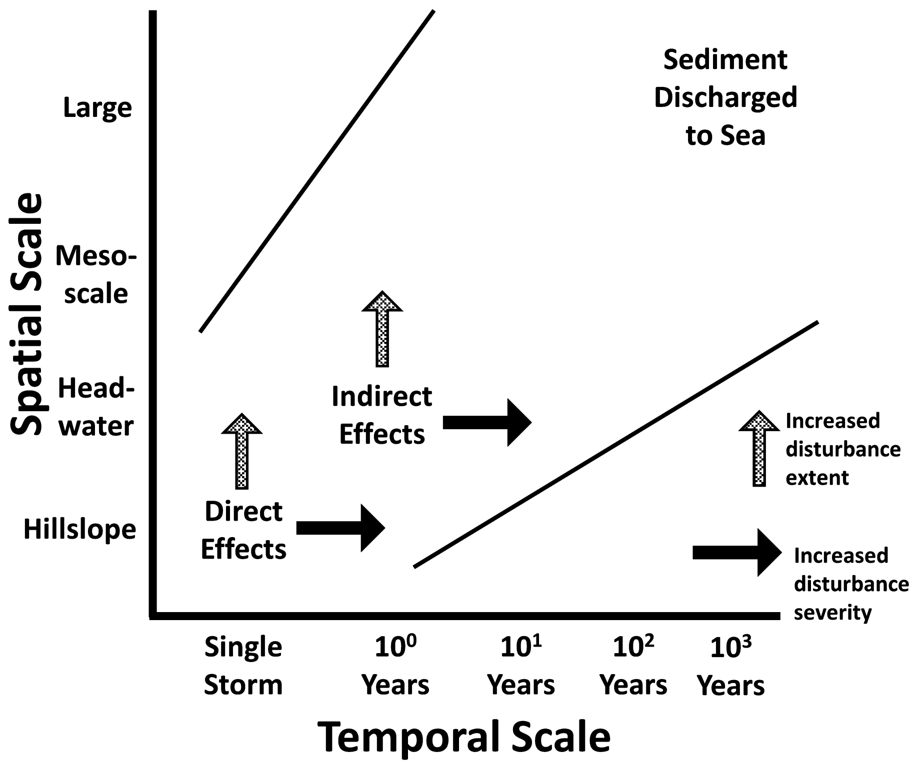

FIGURE 3. Space-time diagram for direct and indirect effects (based on figure 2.3 in National Research Council 1988). Direct effects are defined at the hillslope spatial scale and single storm temporal scale; indirect effects are defined in reference to catchment-scale changes in the water balance and thus occur at the scale of (generally small) catchments. Increased disturbance severity that limits soil and hydrologic recovery can cause direct and indirect effects to persist longer in time, and increased spatial extent of disturbance can cause direct and indirect effects to be significant at larger spatial scales. Discharge of sediment deposited in streams due to direct or indirect effects can take >1,000 years depending on local geomorphic and hydrologic conditions.

(Andréassian 2004; Blöschl et al. 2007; Bathurst et al. 2011; Viglione et al. 2016). If disturbance is widespread, indirect effects would likely occur at larger spatial scales than if it were limited in extent. Similarly, hydrological recovery and temporal persistence of indirect effects vary based on regrowing species, climate, and basin physiographic characteristics such as soil fertility.

Although this review has focused on postharvest sediment yield effects of incremental processes such as land surface denudation and instream erosion and deposition, episodic catastrophic events can dominate as long-term sediment sources, such as debris flows and landslides caused by fire (Goode et al. 2012; Wicherski et al. 2017). The small paired catchment studies that we have used to form the foundation of our review may greatly underestimate long-term erosion rates because they often do not capture catastrophic and rare events that dominate long-term sediment budgets (Kirchner et al. 2001).

Nonharvest Disturbance

Any sediment yield increases caused by forest harvesting via direct or indirect effects should be weighed against the potential long-term sediment yield risks and benefits that silvicultural and forest management, with BMPs, may offer, such as risk reduction for wildfire (Starrs et al. 2018). Wildfire is known to produce large amounts of sediment via exposure of the soil surface and connection of overland flow pathways to the stream over hydrophobic soils, and by altering stream geomorphology and the partitioning of water in catchments. Fire increases peak flows that change channel dimensions and sediment yield (Helvey 1980; Moody and Martin 2001), and can alter channel dimensions through loss of bank stability associated with riparian forests (Eaton et al. 2010). In addition to fire, pest outbreaks such as mountain pine beetle (*Dendroctonus ponderosae*) in the intermountain West have caused large-scale tree die-offs that increase the risk of wildfire (Negron et al. 2012). Such outbreaks can be further exacerbated by climate change (Kurz et al. 2008). In Colorado, salvage logging can change the species composition of regenerating forests compared to beetle-killed stands that are unharvested, promoting lower fire-risk species that are more tolerant to drought die-off and with a canopy structure that decreases the risk of ground fires to transfer to the canopy. This tree species change after salvage logging could alter fire risk for more than a century (Collins et al. 2012).

In addition to "fast" nonharvest disturbances such as wildfire, long-term incremental alterations in forest species composition, watershed hydrology, and forest harvesting should also be considered. For example, Swiss needle cast in the Oregon Coast Range, a chronic canopy disturbance, has been found to gradually increase water yields (Bladon et al. 2019), which could cause increased sediment yields through time. Long-term incremental disturbances such as canopy disease, and very rare but catastrophic changes such as debris slides, illustrate the importance of assessing what the "baseline" conditions in a watershed are — in particular, geomorphic and near-stream variables that may be gradually changing through time, or change rapidly in "stepwise" form in response to sudden nonharvest disturbance events. Nonharvest disturbances have the potential to alter hydrologic flowpaths as well as sediment sources and connectivity. Future efforts could place them into the direct/indirect framework.

CONCLUSION

Our conceptual model of direct and indirect effects, and our exploration of these effects in various hydrogeomorphic contexts based on a review of regional literature where temperate working forests are common in the U.S. provides a foundation for managers and for further research to determine the relative importance of different regional drivers of sediment yield. This includes information to facilitate the identification of harvest sites and watersheds within regions where increased sediment yield is most likely to occur due to direct and indirect processes that is critical for targeted and optimized management of water quality. To identify these "high risk" areas, it is necessary to account for potential direct and indirect effects, including distinguishing which process is most likely to cause increased sediment yield given the unique local situation. Research directed towards increasing process-based knowledge and the scope of water quality management in forested watersheds to account for spatial and temporal changes in direct and indirect effects, quantification of indirect effects, and the development of more specifically indirect effect BMPs will create a more holistic paradigm in which to account for sediment yield effects of forest harvesting. This review forms the foundation for identifying basins where direct and indirect effects are likely to occur; however, there are few studies that quantify indirect effects alongside direct effects

(Table 1). Thus, the development and efficacy of indirect effects BMPs will depend also on further research.

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AUTHORS' CONTRIBUTIONS

Zachary P. McEachran: Conceptualization; formal analysis; investigation; methodology; project administration; software; visualization; writing-original draft; writing-review & editing. **Diana L. Karwan:** Conceptualization; funding acquisition; investigation; project administration; resources; supervision; validation; visualization; writing-review & editing. **Robert A. Slesak:** Conceptualization; funding acquisition; project administration; resources; supervision; validation; writing-review & editing.

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