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Riparian forest management synthesis

Effects of stream buffer width on stream temperature and ecosystem health

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High-level points

- The literature reviewed did not provide clear scientific justification for no-cut buffers wider than 100 ft to protect stream temperature.
- The literature reviewed showed that most sediment problems come from a minority of poorly engineered and maintained roads, especially those with frequent use.
- Most buffer studies examine effects of clear cuts on streams. Therefore, smaller buffers may suffice when less intense harvest is used.
- The studies show that even after clearcut logging, stream temperatures generally return to baseline levels quickly following harvest and within a relatively short distance after flowing into shaded areas from a harvested area.
- Most dead wood contributed to steams comes from forests closer than 100' from the stream
- Riparian areas are ecosystems in and of themselves, and large no-touch buffers could limit our ability to restore natural qualities of these ecosystems in previous conifer plantations.

Executive summary

Large planning areas have a diverse range of environmental conditions that warrant flexible management strategies. However, efficient policy and operational implementation requires simplified rules that do not respect the nuances within a particular planning area. Examples are fixed-width stream buffers. However, to achieve the best ecological and economic results, buffers should be implemented to respect some of the ecological context of the areas around them.

Geophysical context is an important moderator of the effects of forest harvest on stream temperature. This can often be a first-order effect that completely masks the effects of harvest on stream temperature. Smaller buffers will be effective for moderating stream temperature any time stream water mixes with ground water while larger buffers are needed where ground water inputs are low.

Contemporary buffers of up to 100 ft (30 m) and often smaller (40 ft) are successful at moderating the effects of the most intense harvest practices (clear cuts) on stream sediment, temperature, and wood input. Most studies of in-stream responses to buffers are within clear-cut treatments. Most harvests on Federal land are not clear cuts, so the buffers will likely be more effective at moderating adverse effects of harvest than these studies show.

Stream temperature is naturally variable and heat does not accumulate downstream at a steady rate. Streams have inputs from ground water to offer refuges to cold water species. Stream temperature can cool quickly after passing through a harvested area, normally to baseline temperature within 330-ft of an area with rapid warming. Cooling distance can increase when groundwater mixing is reduced. Riparian vegetation can also rebound quickly following harvest, and re-shade streams, subsequently reducing temperature increases due to increased sun after harvest.

The riparian forest is an ecosystem in and of itself and treating it simply as a buffer to moderate the effects of upland harvests on stream temperature and wood input neglects other important ecosystem functions. For example, fish abundance and size can be higher near harvests due to better insect production and prey visibility. Natural forested riparian ecosystems contain gaps and complex species assemblages that are not necessarily present in plantation Douglas-fir regions within stream buffer areas.

Synthesis

This synthesis reviews several aspects of the effects of near-stream vegetation on stream water quality and structure. In forests that are logged, near stream vegetation is generally left intact as buffers to moderate the effect of the harvest on the stream. Here we review current literature on the effectiveness of buffers to moderate impacts to water temperature and sediment input from roads which affect water quality, as well as the effects on the input of dead wood which is important for creating favorable stream structure. This review covers the following topics: 1) the moderating effect of larger hydro-geological processes on stream temperature, 2) spatial and temporal patterns of stream warming following harvest, 3) the ability of different width buffers to moderate adverse effects of harvest on streams and 4) the view of riparian areas as ecosystems rather than as buffers and the ability of some harvest to restore higher functioning riparian areas.

Confounding effects on stream temperature

Before examining the effects of forested riparian buffer widths on stream temperature, it is important to acknowledge that buffers act on streams in a broader context. Stream temperature can increase, decrease, or stay the same after harvest (e.g. Gomi et al., 2006). One portion of this ambiguity is due to stream interactions with groundwater. Streams that are fed from colder groundwater, indicated by having more similar baseflow to mean flow, have less temperature sensitivity (Chang and Psaris, 2013). Factors that increase water exchange between streams and groundwater decrease the effects of forest harvest on water temperature (Janisch et al., 2012; Pollock et al., 2009; Story et al., 2011) and vice versa. Increased exchange occurs on steeper slopes (Kasahara and Wondzell, 2003), where there are abrupt changes in flow slope as in stepped pools (Harvey and Bencala, 1993), with more wood jams (Dent et al., 2008), when water passes through deep gravels or more porous geology (Johnson and Jones, 2000, Bladon et al., 2018), and where water flows intermittently above and below the surface (Janisch et al., 2012). If source water is from shallow wetlands (Janisch et al., 2012) or flows over significant portions of bedrock (Brown, 1969; Dent et al., 2008; Johnson, 2004) streams are more likely to warm significantly. In short, the context of geomorphic processes needs to be considered when designing riparian treatments to have minimal effects on stream temperature (Poole and Berman, 2001).

Another portion of the ambiguous relationships between stream temperature and forest harvest is that harvest simultaneously increases sunlight and reduces transpiration, which can have opposing effects. Reductions in transpiration following forest harvest generally increases stream flows, at least temporarily (Coble et al., 2020; Hicks et al., 1991; Keppeler, 1998; Perry and Jones, 2017; Surfleet and Skaugset, 2013, Segura et al., 2020). When soil water is increased following harvest, more can percolate to feed stream flows (Fan et al., 2017; Tashie et al., 2019), and more flow can moderate stream temperatures (Moore et al., 2023). At an extreme, plantations of rapidly growing conifers can reduce stream base flows by 50% relative to old forests (Perry and Jones, 2017). Reduced stream flow is not necessarily indicative of warmer summer stream temperatures, but it is a predisposing factor (Moore et al., 2023).

Transpiring riparian vegetation can also reduce stream flows in the summer when stream flow becomes decoupled from upslope soil moisture, especially during the hottest part of the day (Lundquist and Cayan, 2002; Tashie et al., 2019).

Much research documents how other factors not associated with forest management, including lithology, drainage area, elevation, and annual variation in climatic conditions, influence stream temperature (Bladon et al., 2018; Johnson and Jones, 2000; Johnson et al., 2020; Reiter et al., 2015). For example, Miralha et al., (2024) summarize explanations for how stream temperature in their study in Northern California is more strongly controlled by changes in elevation and precipitation than by riparian vegetation, stating:

> "there has been considerable variability in stream temperature responses to forest harvesting, which have been attributed to differences in groundwater discharge (Leach and Moore, 2011; Macdonald et al., 2014), steepness of channel slopes (Kasahara and Wondzell, 2003), bed conductive heat transfer (Story et al., 2003), hyporheic exchange (Magnusson et al., 2012; Moore et al., 2005b; Poole and Berman, 2001), or catchment physiography (Callahan et al., 2015; Ebersole et al., 2003)."

In another example, a study designed to test if the amount of harvested area contributes to increased water temperature finds that cumulative upslope harvested area between 25 and 100% raises daily maximum temperature ~2.4°C, but also finds that the dominant control over temperature is by geomorphology rather than harvested area (Pollock et al., 2009).

Riparian vegetation and patterns of stream warming.

Riparian shade is strongly associated with stream temperature regime (Brown, 1969; Groom et al., 2011; Johnson and Jones, 2000; Moore and Wondzell, 2005; Roon et al., 2021), especially in the western Pacific Northwest (Chang and Psaris, 2013). Narrower streams are more influenced by shade than wider ones simply because smaller statured plants can cast shade across their width and there is less water to heat. Shade in small streams can even be provided by logging debris, which can mitigate stream temperature rise (Jackson et al., 2001; Kibler et al., 2013). Their narrow width and low flow mean that forest practices have the most potential to increase temperature on small streams rather than larger ones.

Water temperatures increase after streams are exposed to more sunlight (all else being equal) but decrease again as vegetation recovers. Initial increases in daily maximum temperature with 50 to 100-ft buffers can be insignificant to as high as 5.3°C for a particular stream (Cole and Newton, 2013), but they recede quickly. In the western Pacific Northwest, rapid vegetation growth can re-shade streams and reduce temperature increases to baselines in as little as 2 years, normally within 3 to 5 years, and up to 10 years after riparian areas are thinned or cut (Gomi et al., 2006; McIntyre et al., 2018; Miralha et al., 2024; Moore et al., 2005; Roon et al., 2021).

Heat captured by streams can accumulate, however downstream heat transfer is rarely monotonic because of stream cooling and inherent temperature variability related to ground water inputs (Fullerton et al., 2015). Streams flowing from sunny to shaded reaches are able to cool (Bladon et al., 2018; Moore and Wondzell, 2005; Roon et al., 2021). Generally, average temperature increases downstream but maximum temperature does not (Cole and Newton, 2013). Temperature returns to preheating levels normally within 100 m but can also take up to 1400 m in extreme circumstances (Bladon et al., 2018; McIntyre et al., 2018; Roon et al., 2021). In large streams, temperature variability is high despite a warmer mean temperature because of refuges provided by seeping groundwater and more groundwater-to-stream-water (hyporheic) exchange (Dent et al., 2008; Ebersole et al., 2015; Fullerton et al., 2017).

Buffers and stream variables

Most buffer studies have been on small streams with buffers ≤ 100-ft wide within clear cut harvests (Brosofske et al., 1997; Cole and Newton, 2013; Groom et al., 2011; Janisch et al., 2012). While the buffers are largely representative of current buffers on federal land, the treatments are not. Less intense harvest outside of the buffer, as we expect on Federal land, will have less effect on the streams being buffered. Unfortunately, there has been little research of buffer widths beyond 100-ft in non-clearcut treatments. In one large study, streambed temperature was insensitive to buffer widths from 20 ft to > 330 ft or to variable upland thinning treatments (Anderson and Poage, 2014). Harvest without riparian buffers is no longer practiced in Washington, therefore the question becomes what width and composition of buffers are sufficient to control stream temperature increases due to harvest activities?

Microclimate gradients are steep < 32 ft from a stream and are typically less steep > 32 ft m from a stream (Anderson et al., 2007; Rykken et al., 2007). Curves depicting the relationship of distance from a core condition (e.g. forest interior, stream center) to variables like air temperature and solar radiation generally flatten by 100 ft (Brosofske et al., 1997) and within 65 ft if harvests are not clearcuts (Heithecker and Halpern, 2007). Stream temperature is at least one-step removed from microclimate effects. Accordingly, stream temperature is less responsive to harvest effects than terrestrial microclimate variables and the effect of harvest on stream temperature decreases rapidly with buffer width.

Buffers < 100-ft wide do not always mitigate the effects of harvest on stream temperatures, while those beyond 100-ft typically do. Buffers from 23- to 69-ft wide can allow temperature to exceed policy thresholds (0.3°C) up to 40% of the time (Groom et al., 2011; Herunter et al., 2004). For example, temperature (7 day mean maximum temperature) can increase 1 to 3°C in buffers < 50 ft (e.g. McIntyre et al., 2018). However, buffers common in intensive contemporary management (50 to 100 ft) mitigate most immediate problems (Bladon et al., 2016; Gomi et al., 2006; Groom et al., 2011; Reiter et al., 2020; Wilkerson et al., 2006). In 100-ft buffers, stream temperature changes can sometimes be detected if the area was clear cut, however, temperature changes are variable and generally small if positive (Gomi et al., 2006) even when all overstory trees are removed from the buffer (Macdonald et al., 2003).

Riparian buffers one-site-tree-height wide are sufficient to offset harvest effects on stream temperature (Moore et al., 2005; Reeves et al., 2018).

Chronic sediment input from harvest and logging roads can reduce water quality. A few notable impacts of excess sediment are reduced visibility for aquatic animals and infilling of gravel pores which reduces suitable invertebrate habitat, spaces for fish to lay their eggs, and restricts hyporheic exchange. If fine sediments clog river gravels, they restrict hyporheic exchange and cause larger increases in water temperature (Packman and MacKay, 2003; Schälchli, 1992). Up to 4.6 times as much sediment can be mobilized in clear cuts compared to reference slopes (Rachels et al., 2020) and if this reaches road networks, it can be moved to streams. Poor engineering during installation can increase stream connectivity 40% and roads create slope instability that leads to 10 to 300 fold increases in landslide rates in wet climates (MacDonald and Coe, 2008; Wemple et al., 2001). Sediment from slides and surface erosion is then conveyed long distances along roads and delivered to streams with up to an order of magnitude higher amounts (Sidle et al., 2006; Wemple et al., 2001). Thus, road density can be proportional to sediment input if practices are not included to curtail it (Luce et al., 2001).

Although road density is proportional to sediment input, a minority of roads create the most problems (Al-Chokhachy et al., 2016; MacDonald and Coe, 2008). Heavily trafficked roads can produce 130 times as much sediment as an unused road (Reid and Dunne, 1984). A majority of road sediment comes from regrading and ditching, practices that increase with more traffic (Luce and Black, 2001; Rachels et al., 2020). Ripping and mulching unused roads effectively mitigates sediment runoff (Sosa-Pérez and MacDonald, 2017). Redirecting ditch water onto slopes so that it percolates or is filtered by vegetation before entering streams as is now required (WAC 222-24-020) is probably also effective. Landslides originating from road cuts can be reduced by leaving dispersed trees on steeper slopes to maintain root strength (Roering et al., 2011), especially above and below problem roads located with a tool like NetMap (Benda et al., 2007). Sediment trends can be effectively reduced in actively logged areas by modern road construction practices (Reiter et al., 2009).

Contemporary riparian buffers (33 to 100 ft) are a proven strategy for reducing sediment into streams so should be maintained (Hatten et al., 2018; Rachels et al., 2020; Rashin et al., 2006). This does not mean buffers need to be dense conifers. Even relatively sparse forest buffers can filter sediment to healthy levels (Jackson et al., 2001), and there is little difference between forested versus herbaceous sediment filtration because it depends more on buffer width than composition (Yuan et al., 2009).

Other habitat factors

Riparian vegetation also augments streamflow through its interaction with streams. Both beaver dams and large wood from fallen trees forces water onto the floodplain during high flows thus reducing peak runoff (Keys et al., 2018). At the same time, impounding and slowing water helps recharge valley aquifers, which increases low flows later in the summer (Kasahara and

Wondzell, 2003). We now know that 95% of instream wood comes from forest within 60 to 70% of a site-tree maximum height (82 to 148 ft, Reeves et al. 2018).

Natural riparian areas have complex structure and composition including gaps, multi-layered canopies, and hardwoods (Nierenberg and Hibbs, 2000; Pabst and Spies, 1999, Table 1). Such conditions favor species like beaver that prefer hardwoods to conifers, and who's impoundments can decrease downstream temperatures 2.3 ℃, reduce flows by 20%, and increase salmon habitat (Dittbrenner, 2019; Pollock et al., 2004). Many riparian areas have been converted to conifer plantations over the course of the last century and show little resemblance to previous systems, thus provide fewer of the functions related to all species that reside there, not just Salmon.

Table 1. Ranges of variability of ecologically meaningful forest attributes in riparian Douglas-fir-western hemlock forests.

Attribute	Target range	Sources
Large trees	≥50 cm diameter for stream input, snags, and live trees	(Pollock and Beechie, 2014)
Wood in streams	12-25% coverage 0.2-0.8 pieces/meter >10 cm diameter	(Anderson and Sedell, 1979; Bilby and Ward, 1989)
Logs	6.5-18.5% cover	(Pabst and Spies, 1999)
Snags	>3/ha hardwood within 32m of stream >19/ha conifer within 32m of stream	(Pabst and Spies, 1999)
Hardwood composition	30-80% of basal area (higher in flood plain), 20-60% canopy cover	(Barker et al., 2002; Nierenberg and Hibbs, 2000)
Overstory canopy	70-87%	(Brosofske et al., 1997; Pabst and Spies, 1999)
Open patches	>20% ground area	(Nierenberg and Hibbs, 2000)
Environmental buffering	fish bearing, ≥30-60m non-fish bearing ≥15-30m	(Anderson et al., 2007; Brosofske et al., 1997; Rykken et al., 2007)

Wood recruitment into streams is often evaluated with relative increases or decreases in response to a treatment, however the absolute amount that is sufficient for a healthy stream system is rarely evaluated. In natural systems wood cover can range from 12 to 25% (Table 1) but will also go through periods of reduced wood just as a terrestrial system does as forests develop (Martens et al., 2020; Spies et al., 1988). Wood input to streams usually increases after harvest from logging activities and from subsequent blowdown (Anderson and Poage, 2014; Burton et al., 2016; Jackson et al., 2001). In riparian buffers composed of small trees, large wood input is a concern. Some argue that thinning in riparian areas with the goal of increasing growth of residual trees will reduce large dead wood (Pollock and Beechie, 2014). Simulations show that no buffers and thinning can reduce wood input 33 to 42%, but that this can be mitigated to only 7% with 33-ft m buffers, and can be increased 24% relative to controls by tipping 15 to 20% of thinned trees into the stream (Benda et al., 2016). Close to 80% of wood in streams is sourced within 50-ft of streams (Burton et al., 2016), so it is highly probable that 100-ft buffers also provide adequate supplies of dead wood (Reeves et al., 2018).

A myopic focus on a single variable such as stream temperature or dead wood can obscure equally important ecological relationships between riparian function and harvest practices. For example, few scientists or policy makers consider that fish abundance and size can be larger near harvests because of increased food abundance and foraging efficiency (Bateman et al., 2018; Bilby and Bisson, 2011; Wilzbach et al., 1986) despite warmer stream temperature. Variable light conditions, including areas of high light, are a feature of natural riparian ecosystems (Warren et al., 2013, Table 1). Riparian buffers should probably be viewed as complex ecosystems in and of themselves rather than simply as a buffer from the upland to in-stream ecosystems (Gregory et al., 1991; Richardson and Danehy, 2007). Many forested buffers exist with low species and structural diversity that would benefit from more variable forest structure and composition in terms of biodiversity and function.

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