J. For. Res. (2016) 27(4):821–836
DOI 10.1007/s11676-015-0173-2

ORIGINAL PAPER

Thinning and in-stream wood recruitment in riparian second growth forests in coastal Oregon and the use of buffers and tree tipping as mitigation

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Received: 5 June 2015 / Accepted: 14 October 2015 / Published online: 30 November 2015

Abstract Many aquatic habitats in coastal Oregon have been impacted by historic land use practices that led to losses of in-stream wood and associated degraded fish habitats. Many of these streams are now bordered by stands of dense second growth forests (30–80 years) that are incorporated into riparian buffer zones with low wood recruitment and storage. Thinning in riparian zones is one management option to increase the rate of large tree growth and eventually larger in-stream wood, however, it raises concern about impacts on current wood recruitment, among other issues. Using a forest growth simulation model coupled to a model of in-stream wood recruitment, we explore riparian management alternatives in a Douglas-fir plantation in coastal Oregon. Alternatives included: (1) no treatment, (2) single and double entry thinning, without and with a 10-m buffer, and (3) thinning combined with mechanical introduction of some portion of the thinned trees into the stream (tree tipping). Compared to no treatment, single and double entry thinning on one side of a channel, without a 10-m buffer, reduce cumulative in-stream wood volume by 33 and 42 %, respectively, after 100 years (includes decay). Maintaining a 10-m buffer reduces the in-stream wood loss to 7 % (single entry thin) and 11 % (double entry). To completely offset the losses of in-stream wood in a single entry thin (on one or both sides of the stream), in the absence or presence of a 10-m buffer, requires a 12–14 % rate of tree tipping. Relative to the no-treatment alternative, cumulative in-stream wood storage can be increased up to 24 % in a double-entry thin with no buffer by tipping 15–20 % of the thinned trees (increased to 48 % if thinning and tipping simultaneously on both sides of the stream). The predicted increases in in-stream wood that can occur during a thin with tree tipping may be effective for restoring fish habitat, particularly in aquatic systems that have poor habitat conditions and low levels of in-stream wood due to historic land use activities.

Keywords Forest management · Thinning · Riparian · Woody debris · Forestry · Watersheds · Fish habitat

Introduction

Riparian environments strongly influence the condition of adjacent aquatic ecosystems (Naiman et al. 1998). In particular, large in-stream wood is considered critical for healthy aquatic habitats (Bisson et al. 1987). However, many aquatic ecosystems are still recovering from past impacts, including loss of in-stream wood associated with riparian forest harvest and splash dams (log drives) in rivers (Sedell and Froggatt 1984). In addition, dense, single-species stands of relatively young trees (30–80 years) dominate in riparian areas, because logging was allowed

Project funding: This research was supported by the U.S. Forest Service, Pacific Northwest Research Station and Earth Systems Institute, Seattle Washington.

The online version is available at http://www.springerlink.com

Corresponding editor: Yu Lei

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adjacent to channel banks prior to establishment of streamside protection strategies starting in the 1980s.

During the past 25 years, streamside protection in the form of uniform-width buffers, with minimal to no activity allowed within them, has been the dominant paradigm in riparian management on federal (FEMAT 1993) and on state and private lands (Ice 2005). The dominance of young, small trees in riparian zones results in low recruitment of large wood to channels and perpetuates impacted conditions of streams and rivers. Full recovery of riparian forests to mixed-species stands of large-diameter trees, with recruitment of large wood to streams, could take another one to two centuries.

Debate continues on the ecological effectiveness of creating fixed-width streamside buffers to protect riparian areas and associated stream environments, particularly in second growth forests (Everest and Reeves 2007; OSAF 2009; Dodson et al. 2012; Richardson et al. 2012; Spies et al. 2013; Pollock and Beechie 2014). Alternative approaches are being proposed that focus on the spatially variable nature of watershed environments and on how riparian-stream protection and management practices can be tailored to achieve the best ecological outcomes (Pickard 2013; Benda and Bigelow 2014; Reeves et al. in press). One approach is thinning in riparian second-growth forests to encourage more rapid growth of larger trees (Spies et al. 2013). Fewer, larger trees may benefit certain types of riparian terrestrial habitats and increase the recruitment rate of large in-stream wood, thereby benefiting aquatic habitats (Reeves et al. in press). Thinning within riparian zones, however, raises concerns about impacts to aquatic systems, including short-term reduction in recruitment of wood to streams, heightened erosion leading to increased sedimentation in channels, and reduced shade, thereby increasing stream temperatures (Beechie et al. 2000; Groom et al. 2011; Pollock and Beechie 2014).

Wood is recruited to streams by a variety of processes including tree mortality (e.g., blowdown), bank erosion, landsliding and post-wildfire toppling (Murphy and Koski 1989; King et al. 2013). Bank erosion that undercuts tree roots can be an important in-stream wood recruitment agent and can dominate wood loading where channels are laterally dynamic (Murphy and Koski 1989; Martin and Benda 2001; Benda and Bigelow 2014). Wildfire related tree death can be a large source of woody material to channels over the long term, particularly in semi-arid environments where post-fire toppling can account for up to 50 % of the long term in-stream wood supply (Benda and Sias 2003).

Considerable progress has been made in modeling wood recruitment to streams, primarily motivated by forest management. Van Sickle and Gregory (1990) pioneered modeling of tree mortality and the effect of random fall on rates of wood recruitment to streams. Welty et al. (2002) examined the effect of varying riparian buffer dimensions on both wood recruitment rates and shade, again focusing on tree mortality. Meleason et al. (2003, 2007) developed a model to simulate riparian forest growth, tree entry into streams, and in-channel processes, including breakage, movement, and decomposition. In addition to mortality recruitment, Benda and Sias (2003) evaluated the effects of bank erosion, landsliding, and wildfire in their theoretical treatment of the wood budget over century time scales, including effects of piece breakage, decomposition, and fluvial transport.

Here we develop a model to examine in-stream wood recruitment in the context of thinning in second-growth forests, including only forest mortality and streamside no-harvest buffers as an option. In addition, we add the mechanical introduction of trees into streams during thinning as a form of mitigation and restoration. Our goal is to build a user-friendly model to explore thinning and mitigation options that can be applied by forest managers and others.

Materials and methods

Study site

Our study site is located within the Alsea watershed in central coastal Oregon, a mountainous terrain that includes steep uplands that have a high landslide and debris flow risk, low gradient channels that form the habitats of threatened and endangered coho salmon (*Oncorhynchus kisutch*), and wider floodplain channels in the lowlands (Fig. 1). The mild humid climate is characterized by wet winters and a summer drought with annual precipitation ranging between 1500 and 2000 mm (PRISM Climate Group 2014). Dominant lithology is sandstone and siltstone of the Tyee Formation.

Forest vegetation in central coastal Oregon is dominated by conifers comprised of Douglas fir (*Pseudotsuga menziesii*) and western Hemlock (*Tsuga heterophylla*). Deciduous species include Big Leaf Maple (*Acer macrophyllum*) and alder (*Alnus rubra*), particularly in streamside areas. Conifers trees are intermixed with deciduous trees near stream margins. Extensive timber harvest that began in the 1940s–1950s has left a patchwork of young second growth forests intermixed with older conifer forests. Mature conifer forests on both sides of the 10 m wide study reach were clear cut logged before 1975 with no stream protection (e.g., no buffers).

Reach scale wood recruitment model

We developed a reach scale wood model (RSWM) for project scale silvicultural applications (e.g., for relatively small segments of riparian forests and associated channels)

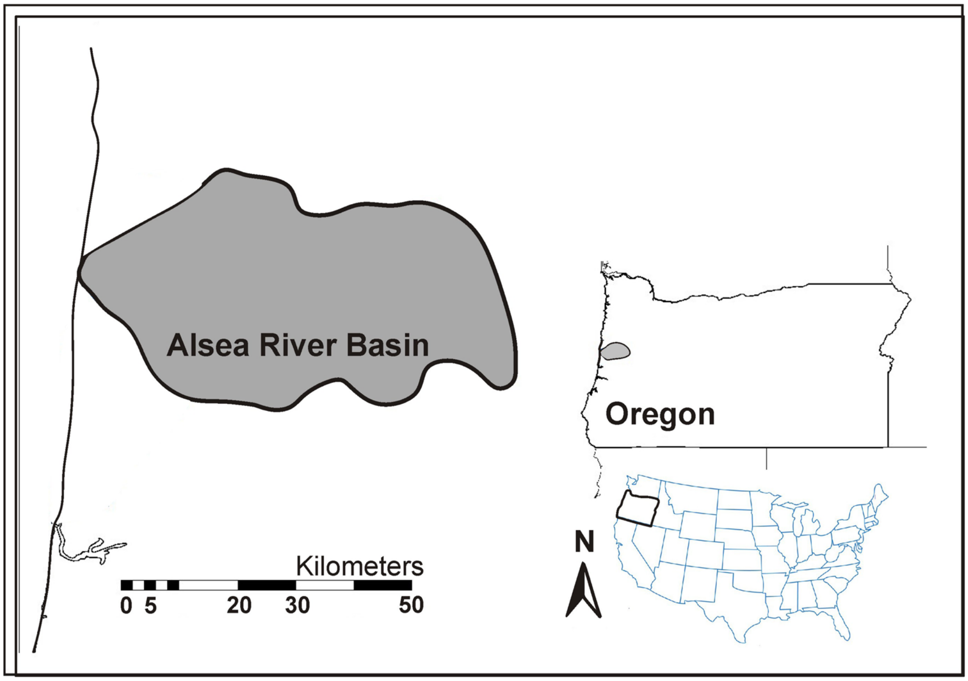

Fig. 1 Study location in the Alsea watershed in the Oregon Coast Range

to address how thinning in riparian zones can impact the recruitment of wood into streams and how no harvest buffers and manual introduction of trees into streams by directional felling can offset those impacts. The RSWM requires: (1) forest growth predictions (stand tables), (2) forest stand dimensions, and (3) channel width and hillslope gradient. RSWM divides the riparian forest area to be modeled (on one or both sides of the channel) into parallel zones, each of which can have unique stand characteristics (Fig. 2).

The RSWM follows a wood budget approach (sensu Benda and Sias 2003) where the quantity of in-stream wood in a unit length of channel is the result of differences in input, output and decay:

$$\Delta S = (Li - Lo + Qi - Qo - D)\Delta x \Delta t \tag{1}$$

where ΔS is the change in wood quantity within a reach of length Δx over time Δt, specified in terms of number of pieces or total volume, and may also be grouped by piece size, e.g., number or volume of pieces of different diameter classes. Change in in-stream wood quantity is a consequence of terrestrial sources of wood (tree mortality, bank erosion, landsliding) (Li), loss of wood due to overbank deposition in flood events and abandonment of jams (Lo), fluvial transport of wood into (Qi) and out of (Qo) the reach, and in situ decay (D) (Benda and Sias 2003). Fluvial transport and overbank deposition are not considered in the RSWM because our focus is on recruitment only and thus Eq. 1 is reduced to:

$$\Delta S = (Li - D)\Delta x \Delta t \tag{2}$$

Li in the RSWM encompasses only the recruitment process of tree mortality and hence tree fall following death (Li_m) and excludes bank erosion and landsliding:

$$Li_{\mathrm{m}} = f(B_L, M, P, N) \tag{3}$$

where, B_L is the amount or density of trees adjacent to the stream of specific diameters and heights, M is the mortality rate (tree death per year), P is the probability that trees that fall will intersect the stream, and N is the number of banks (1–2).

The probability that a tree located at any point in a riparian forest will intersect the channel segment, given that the distance to the stream is less than H, is calculated as:

$$P = \int_{a1}^{a2-a1} f(a)da \tag{4}$$

where a is the fall angle referenced to the orthogonal of the nearest channel edge (Fig. 2), $f(a)$ is the probability density of all fall angles, and a_1 and a_2 are the fall angles of a tree to the endpoints of the channel segment.

Estimating P in the RSWM follows the approach of Sobota et al. (2006) in which fall-angle data were well characterized using a normal distribution having zero mean (directly towards the stream) and slope-dependent standard deviation σ, for which P is calculated as:

$$P = \mathrm{erf}\left(\frac{\theta/2}{\sigma\sqrt{2}}\right) \tag{5}$$

and where

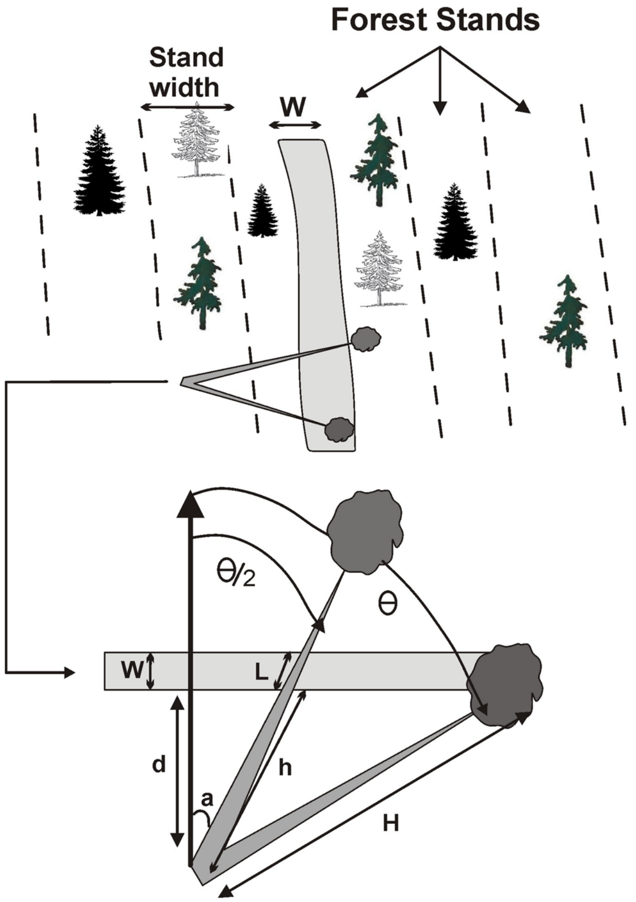

Fig. 2 The reach scale wood model creates three distinct forest stands on either side of the stream. The geometry of tree fall with respect to the channel is shown in the *lower panel*: *W* equals bankfull channel width; *H* is tree height; *L* is length of the tree that intersects the channel; *h* is the distance of the tree to the channel edge; *a* is the tree fall angle referenced to the orthogonal (*d*) of the nearest channel edge; θ is the angle between the tree fall orthogonal to the channel and all other fall trajectories

$$\theta/2 = \cos^{-1}(d/h), \tag{6}$$

where erf is the error function, θ is the angle between the tree fall orthogonal to the channel (e.g., nearest to the channel edge) and all other tree fall orientations, d is the distance to the reach, h is the height of the tree as it intersects the reach, and σ is the empirically derived standard deviation of the fall direction in degrees for the valley side slope gradient (Fig. 2). When the valley side slope is less than or equal to 40°, $\sigma = 76$; when the valley side slope is greater than 40°, $\sigma = 41$ (Sobota et al. 2006).

The RSWM divides the forest stands to be simulated (e.g., Fig. 2) into one meter increments from the stream. In each distance increment, the probability of a tree intersecting the stream is calculated for each angular arc (1°) increment (e.g., a_1 to a_2, Eq. 4); the angle of the full arc and the number of angular increments is determined by tree height and distance away from the stream. The calculation is applied to a density of trees within specific heights, diameters and species classes. All angular increment probabilities, across all diameter, height and species classes, are summed across all one meter increments from the stream until the tree height (H) exceeds distance to the stream (h), orthogonal to the channel. This yields the number of in-stream pieces of wood of varying diameters per 100 m channel segment.

Piece breakage is not included in the RSWM and in-stream wood is only that portion of a tree that is contained within the bankfull channel width (L in Fig. 2); piece breakage and wood extending outside of channel banks are details that could be incorporated in the future.

In addition to predicting pieces of in-stream wood per length of channel, the RSWM predicts wood volume in streams. This requires, in addition to the length of trees that intersect a channel (L in Fig. 2), the diameter of intersecting pieces. Tree taper equations are used to predict the diameters of trees that intersect streams for both conifers (Waddell et al. 1987; Kozak 1988) and hardwoods (Hibbs et al. 2007).

Volume of wood pieces intersecting streams is calculated using:

$$Vp = L \times \pi \times \frac{(d1^2 + d2^2)}{4} \tag{7}$$

where Vp is the piece volume, L is piece length and d_1 and d_2 are diameters at each end of the piece intersecting the channel. A volume is assigned to each piece of wood and all volumes are summed along the 100 m modeled reach for each time step.

RSWM can be run for multiple decades or centuries depending on the output from forest growth models, and hence decay of wood is included to calculate the cumulative change in in-stream wood over time. Decay limits the volume of wood that accumulates in streams and is influenced by temperature, humidity, precipitation, piece size, and wood species (Means et al. 1985).

In the RSWM, wood decay is calculated using an exponential decay function (Harmon et al. 1986):

$$\mathrm{S_t} = \mathrm{S_o} e^{-\mathrm{kt}}, \tag{8}$$

where S_t is the volume at time t, S_o is initial wood volume (year 1) and k is the decay coefficient. Rates of decay (k) range from 1 to 6 % (Murphy and Koski 1989) with conifers decaying more slowly than hardwoods (Bilby et al. 1999). In the RSWM, wood decay and accumulation are calculated for hardwoods and conifers separately and we use a decay coefficient of 1.5 % for conifers (Murphy and Koski 1989) and 3 % for hardwoods (Bilby et al. 1999). The volume of decayed wood is subtracted from the predicted wood recruitment at each time step and from accumulated wood from previous years.

Thinning trees in second-growth forests reduces suppression mortality and thus the recruitment of in-stream wood. To mitigate the predicted loss of in-stream wood from thinning, either a no harvest buffer is applied or some portion of the thinned trees is mechanically introduced into the stream, referred to as "tree tipping", an innovation we added to the RSWM. A percentage of thinned trees is chosen to be "tipped" for each stand, each year, and each diameter class (tree tipping rate). Introduction of tipped trees (from the thinned tree population), with a probability of one for intersecting the stream (e.g., felled orthogonal to the stream edge), begins with those closest to the stream edge. If a buffer exists, tree tipping begins in the stand adjacent to the buffer. Tree tipping modifies Eq. 2 to:

$$\Delta S = (Li_m + Li_{tt}) - D)\Delta x \Delta t, \tag{9}$$

where Li_{tt} is the wood recruitment associated with tree tipping.

Forest growth modeling

The size and quantity of wood pieces recruited to streams are primarily dependent on the size and quantity of trees available to fall into the channel. Hence, wood recruitment rates depend on forest stand characteristics. The RSWM requires inputs of predicted forest growth and death over time from a simulation model. In this study we used ORGANON (Northwest Oregon version 9.13, 2013), because it was developed using data from even age, second growth stands in northwest Oregon (Hann 2006). Thus, it is well-suited to modeling second-growth, mixed species forests in our study site. ORGANON simulates individual tree growth, density-dependent mortality, and other density-independent mortality agents (e.g., windthrow, pathogens, and insects) that can kill trees across a stand's diameter distribution (although it does not simulate tree regeneration). Density-dependent mortality generally targets the smaller end of a stand's diameter distribution. In addition, trees that die in ORGANON are assumed to die standing as snags and they are made to topple the year following death in the RSWM.

ORGANON produces output in the form of stand tables or tree lists, e.g., the density of live and dead trees per unit time and unit area across a range of species and diameter classes (e.g., 10–30, 30–50 cm etc.). ORGANON's predicted density of dead trees (with uniform spacing) represents the B_L and M components (Eq. 3) of Li_m (Eq. 3). ORGANON requires initial stand conditions (species, density, diameter and heights of all trees) and the modeled time series generally encompass a century or less. We do not describe forest growth modeling and the reader is encouraged to research the details of individual models.

ORGANON was applied to a second growth forest adjacent to our 100-m stream reach (10 m wide) in the Alsea watershed (Fig. 1) located in the Siuslaw National Forest in coastal Oregon. ORGANON was initialized with data from the Forest Inventory Analysis (FIA) Program via the Gradient Nearest Neighbor (GNN) database (Ohmann and Gregory 2002). Three inventory plots (FCID's 21335, 25245, 25466, http://lemma.forestry.oregonstate.edu/) were used to represent the plantation. Each tree list was dominated by Douglas-fir with small numbers of maple and alder.

Silvicultural treatments

The RSWM was run for 100 years (5-year time steps) using three different silvicultural treatments that reflect current management approaches in second growth forest plantations in the Siuslaw National Forest: (1) no treatment on both sides of the channel which is used as the reference; (2) a single-entry thin from below (thinning from below removes the smallest trees to simulate suppression mortality); and (3) a double-entry thin from below with the second one occurring 25 years after the first. Both single and double entry thins were simulated with and without a 10-m buffer. Thinning was applied to one and both sides of the channel (e.g., encompassing two scenarios). Tree tipping was applied to single and double entry thins and encompassed a range between 5 and 20 % of the thinned trees, in 5 % increments, and also applied to one and both sides of the stream. The 10-m buffer encompassed the forest closest to the channel with the thinning occurring beyond. σ is 76 (e.g., side slope less than 40°, Eq. 5) and the in-stream wood volume is zero at the beginning of the simulation.

Simulation results

Change in forest stand density and diameter

In the no treatment alternative, the density of live trees declines from 687 trees-per-hectare (tph) in 2015 to 266 tph in 2110 due to natural suppression mortality (−61 % from initial conditions); live trees in 2110 include 100 tph in 0–50 cm and 166 tph in 51–100 cm diameter-breast-height (dbh) classes (Fig. 3). The single-entry thin reduces stand density to 225 tph in 2015 (−67 %) and declines further to 160 tph by 2110 (−77 %); at 2110 it includes 6 tph in 0–50 cm and 154 tph in 51–100 cm dbh classes (Fig. 3). A double-entry thin begins with the single entry thin and with the second thin (25 years later) leading to a further reduction in tree density to 123 tph in 2040 (−82 %) and remains approximately constant thereafter

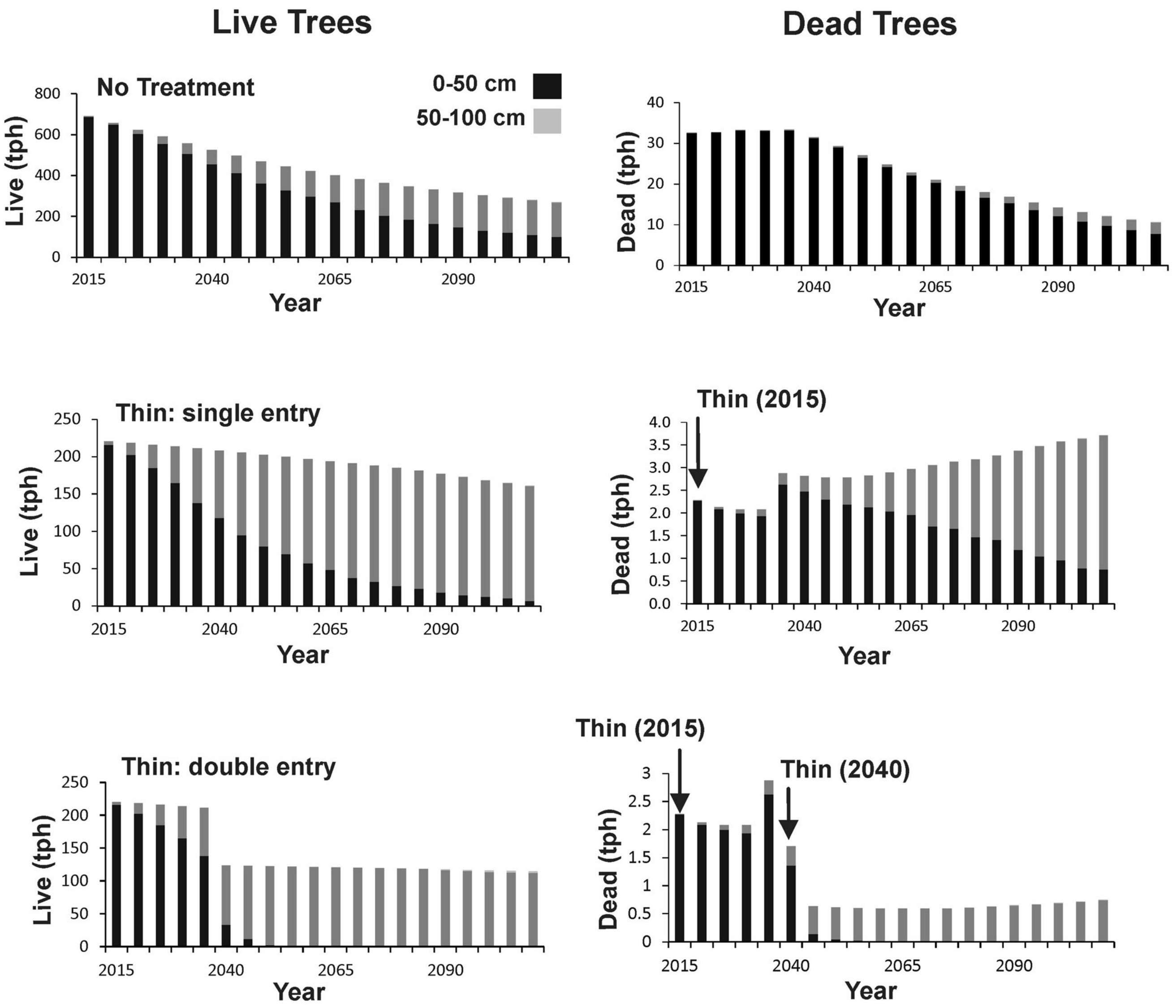

Fig. 3 Model output using ORGANON forest growth simulation for live and dead trees using three scenarios: no treatment, single entry thin and double entry thin

(Fig. 3). From 2050 onward all live trees in the double-entry thin are in the 50–100 cm dbh class (Fig. 3).

The dbh of live trees are predicted to vary with thinning. In the no treatment alternative, 24 % of trees are in the larger 50–100 cm diameter class. That percentage in the single and double entry thins increases to 57 and 62 %, respectively (Fig. 3).

Thinning also results in a substantial reduction in the number of dead trees over time (the trees that contribute to in-stream wood). In the no treatment alternative there are 32 dead tph (0–50 cm) in 2015; by 2110 there are 8 dead (0–50 cm) and 3 dead tph (51–100 cm) (Fig. 3). In the single-entry thin in 2015 there are 2 dead tph (0–50 cm) and by 2110 there is one dead (0–50 cm) and 3 dead tph (51–100 cm). In the double-entry thin in 2015 there is the same dead tph as in the single-entry thin, but by 2110 there is 1 dead tph in the 51–100 cm diameter class (Fig. 3).

Changes in wood recruitment in single and double entry thinning

RSWM simulations reveal reductions in in-stream wood due to the heavy, single entry thinning (corresponding to a reduction from 687 TPH into 225 TPH in 2015) with no buffer or tree tipping. All reported decreases and increases in in-stream wood storage represents wood volume integrated over a century, including the effect of decay. There is a cumulative loss of the predicted volume in-stream wood of 33 % integrated over a century with thinning on one stream side (Fig. 4; Table 1). The reduction is 66 % if thinning treatment occurs simultaneously on both sides of the stream. Adding a 10-m wide no treatment buffer reduces the cumulative loss of wood storage to 7 % (or 14 % if stands on both sides of the channel were thinned simultaneously).

Mechanical tipping of 5, 10, 15, and 20 % of the volume of thinned trees into the stream on one side of the channel in the absence of a buffer, yielded changes to in-stream wood storage, compared to the no treatment alternative, of −15, −6, +1 and +6 %, respectively (Fig. 4; Table 1); negative values refer to less in-stream wood compared to no treatment and positive values refer to wood volume that is greater than no treatment. Mechanical tipping the same percent of the volume of thinned trees on one side of the channel, with a 10-m wide buffer, lowered the predicted reductions and the increases (Fig. 4; Table 1). To completely offset the predicted losses of in-stream wood due to thinning on one side of the stream requires tipping of 14 and 12 % of the thinned trees into the stream, without and with a 10-m buffer, respectively (Fig. 5). Thinning and tipping on both sides of the channel double the predicted decreases and increases (Fig. 6); e.g., thinning leads to a 66 % reduction in in-stream wood and a 20 % rate of tree tipping leads to a 12 % increase in in-stream wood. A no treatment buffer dampens the effect of tree tipping as indicated in the slope of the 10-m buffer lines in Fig. 5.

Effects of a double entry thin on in-stream wood recruitment are more pronounced both in reductions and in gains across the different management alternatives. With treatment on one side of the channel, the double entry thin is predicted to result in a cumulative 42 % decrease of in-stream wood, over the simulated century (Fig. 7; Table 1). If forest stands on both sides of the stream were thinned simultaneously in the absence of a buffer, in-stream wood reductions would equal 84 %. Tree tipping of 5, 10, 15 and 20 % of the thinned volume, without a 10-m buffer, yields changes to in-stream wood volume, compared to the no treatment alternative, of −15, +1, +16 and +24 %, respectively, when thinning on one side of the channel (Fig. 7; Table 1). Tree tipping across the range of 5–20 %, in the presence of a 10-m buffer, dampens both the reductions and increases (Fig. 7; Table 1). Double entry thinning and tipping on both sides of the stream of 5–20 %, without a buffer, would double the predicted changes in cumulative in-stream wood (e.g., −30, +2, +32, +48 %). To completely offset predicted reductions of in-stream wood due to double entry thinning on one side of the stream (cumulatively over a century) would require tipping

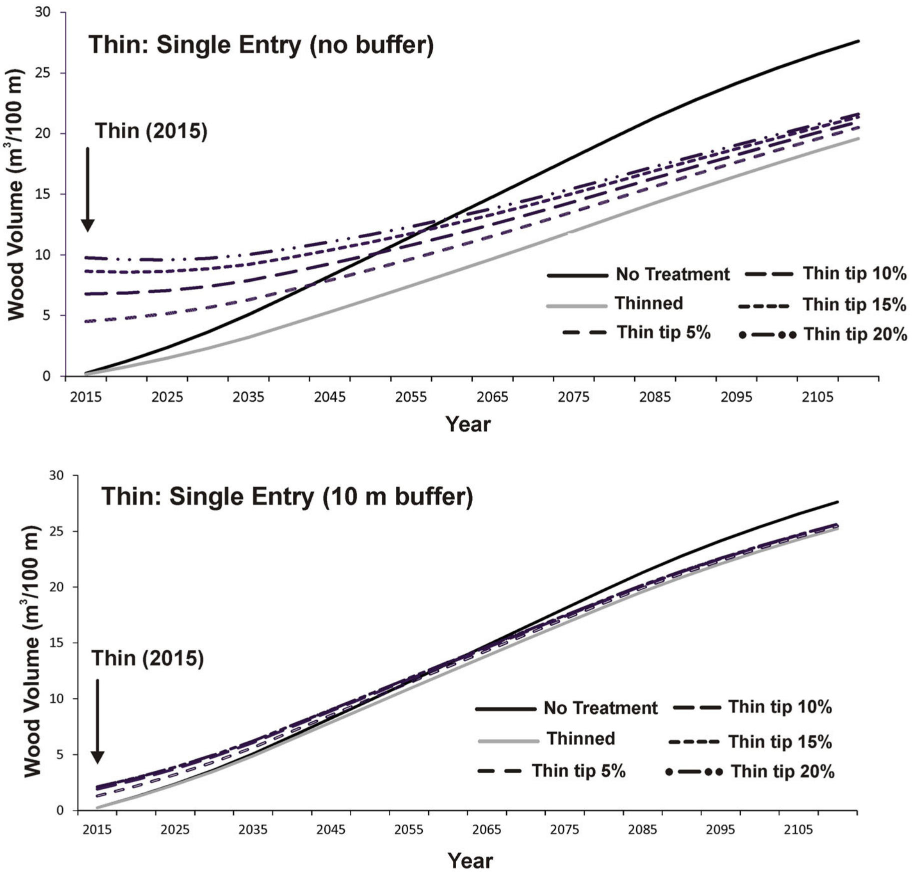

Fig. 4 Predictions from the reach scale wood model showing cumulative wood volume over time (included decay) for a single entry thinning, without and with a 10 m no harvest buffer, only on one side of the channel (with no treatment on the opposite side of the channel). Also shown are the results from tree tipping from 5 to 20 % of the thinned trees into the stream

Table 1 Predicted cumulative wood volume (m^3/100 m) over the simulated century

Scenario	Single entry thin (m^3/100 m)	Percent change from no treatment	Double entry thin (m^3/100 m)	Percent change from no treatment
No treatment (reference)	279	0	279	0
Thin	187	−33	163	−42
Thin, buffer	258	−7	249	−11
Thin, tip 5 %	236	−15	237	−15
Thin, tip 10 %	261	−6	283	+1
Thin, tip 15 %	282	+1	323	+16
Thin, tip 20 %	295	+6	347	+24
Thin, buffer, tip 5 %	270	−3	274	−2
Thin, buffer, tip 10 %	277	−1	292	+5
Thin, buffer, tip 15 %	280	+0.28	303	+9
Thin, buffer, tip 20 %	280	+0.30	310	+11

Negative values refer to less in-stream wood compared to no treatment and positive values refer to wood volume that is greater than the no treatment alternative. Thinning, buffer, and tree tipping occur only on one side of the channel with no treatment on the other side; the no treatment alternative occurs on both sides of the channel. For thinning and tipping simultaneously on both sides of the channel, the losses and gains reported in the table are doubled

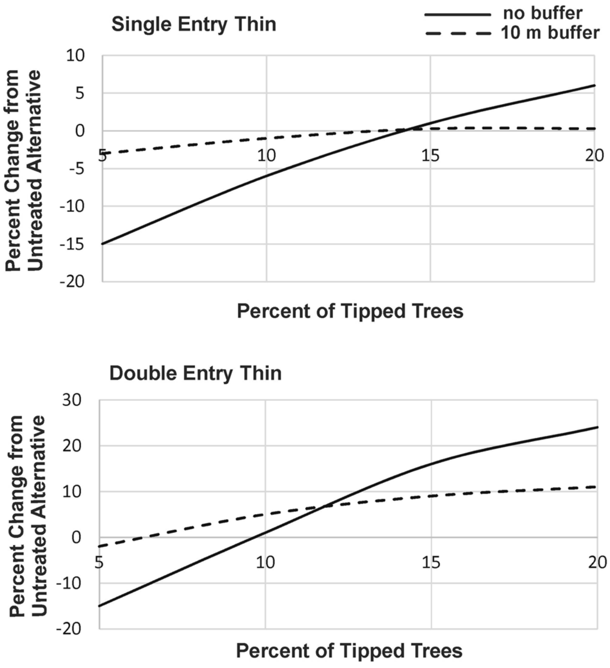

Fig. 5 Negative values refer to wood volume that is less than the no treatment and positive values refer to wood volumes greater than the no treatment. To completely offset the loss of in-stream wood due to thinning (single entry) would require a 14 % rate of tree tipping; adding a buffer reduces the effectiveness of tree tipping. In the double entry thin, a 6 and 10 % rate of tree tipping would be necessary to completely offset the loss of in-stream wood due to thinning with and without a buffer respectively

of 10 and 7 % of the volume of thinned trees into the stream, without and with a 10-m no treatment buffer, respectively (Fig. 5).

The single entry thin-tipping treatment on one side of the channel increases in-stream wood volume over the non-treatment alternative that extends 25 to 50 years following tipping (in 2015), depending on the proportion tipped (Fig. 4). Wood volumes then decline below the no-treatment alternative (after year 2040–2055), with volume at any time following equivalent to the no treatment amount but at an earlier time. Thus, wood storage in the latter half of the simulated century associated with tree tipping (single entry) lags behind the no treatment storage on average about 10–30 years and becomes less than the no treatment approximately 75 years after the start of the simulation (Fig. 4). Thinning and tipping simultaneously on both sides of the stream results in in-stream wood volume that is always above the no treatment alternative over the simulated century (Fig. 6).

The double entry thin-tipping treatment on one side of the channel results in a large increase in in-stream wood storage (above the no treatment) that extends between 35 and 60 years following tipping (Fig. 7). Similar to the single entry thin, the in-stream wood volume corresponds to the no treatment wood volume, but at an earlier time. However, the thinning with tipping instream wood volume falls below the no treatment for approximately the last 40 % of the century. A double entry thinning and tipping simultaneously on both sides of the channel results in larger gains in in-stream wood volume that extends beyond the no treatment for the entire century (Fig. 6).

Variable buffer widths, tree diameters, heights and in-stream piece sizes

The analysis of thinning applied a 10-m buffer (approximately one third of a tree height in year 2015). However,

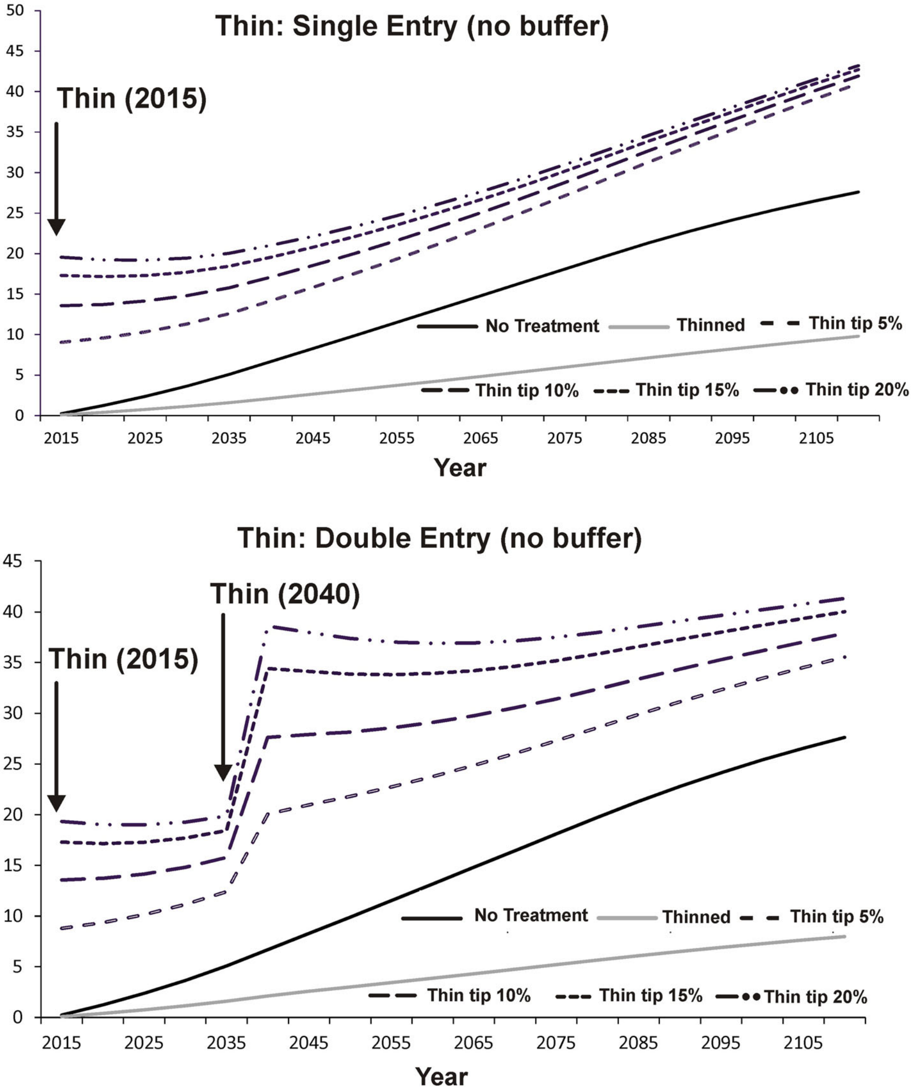

Fig. 6 Predictions from the reach scale wood model showing cumulative wood volume over time (included decay) for a single and double entry thinning, without a 10 m buffer, simultaneously on both sides of the channel. Also shown are results from tree tipping from 5 to 20 % of the thinned trees into the stream

source distance curves can be used to estimate how varying the width of buffers changes the amount of in-stream wood that is protected. For example, with a single entry thin restricted to one side of the stream at the beginning of the simulation, a 10-m buffer maintains 93 % of in-stream wood and 89 % in a double entry thin (Fig. 8; Table 1); this includes the no treatment condition on the other channel bank that is also contributing wood to the stream. Single and double entry thinning on both sides of the stream with a 10 m buffer would maintain 86 and 78 % of in-stream wood volume, respectively (Fig. 8). Varying buffer width produces varying levels of protection of in-stream wood. For example, increasing buffer width to 20 m (approximately 2/3 of an average tree height in 2015) would protect more than 95 % of the no treatment in-stream wood in single and double entry thins on one or both sides of the stream (Fig. 8). A full tree height is required to ensure no losses of wood due to thinning, although the last one third of tree height will only yield 5–15 % of additional in-stream wood volume (Fig. 8).

In the first 30 years of the simulation there is little difference in wood storage between the no treatment and the thinning with a 10-m buffer (Fig. 8). Following 2040, however, there is an increasing disparity in in-stream wood between the two scenarios. This results partly from increasing tree heights over time that reduces the proportion of in-stream wood that is protected with the fixed 10-m wide buffer; e.g., tree heights increase over time from 28 to 36 m at 2015 to between 55 and 65 m at 2110 (Fig. 8).

In the no treatment and thinning without buffer alternatives, the majority of in-stream wood originates from within the first 6 m of the stream but at a much lower volume compared to thinning and tipping alternatives (Fig. 9). The distance to sources of wood in the single entry thin with tipping across the range of 5–20 % (in 5 % increments) of the thinned volume without a buffer is 4, 7, 11, and 14 m, respectively (Fig. 9). Thus, the most efficient

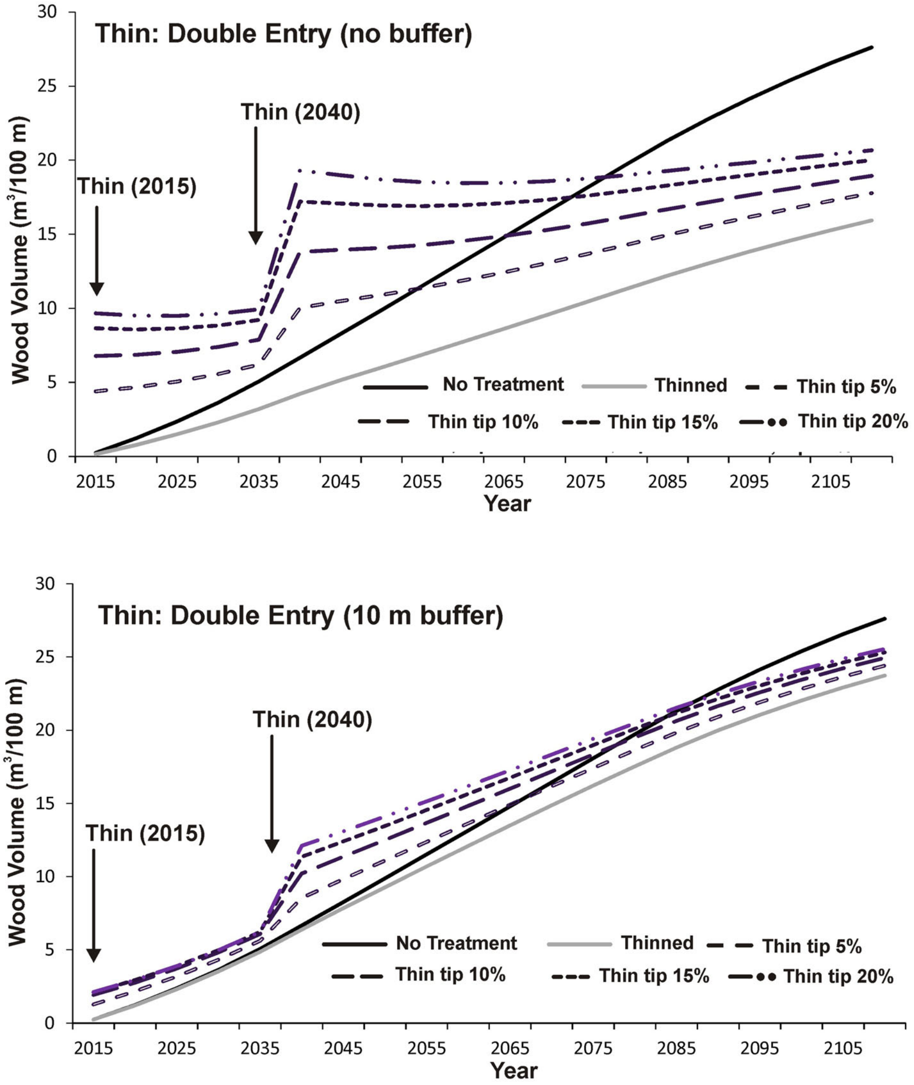

Fig. 7 Predictions from the reach scale wood model showing cumulative wood volume over time (included decay) for a double entry thinning, without and with a 10 m buffer, only on one side of the channel (with no treatment on the opposite side of the channel). Also shown are results from tree tipping from 5 to 20 % of the thinned trees into the stream

tree tipping, in terms of contributing volume of wood in streams, is the 5 and 10 % rates because tipping begins at the stream margin (in the absence of a buffer) and progresses away from the stream at higher tipping rates, where the portion of the tree reaching the stream is smaller in diameter (and thus of smaller volume) than for trees nearer to the stream (due to tree taper).

Piece sizes of in-stream wood across all management alternatives are dominated by the 10- to 35-cm diameter class, as measured at the midpoint of wood pieces in channels. There is a 6 % increase in in-stream volume in the 35- to 60-cm size class in the single and double entry thins without the 10-m buffer, aggregated over all years (Table 2). This is due to the larger trees that remain following the first thinning and increased growth rates that result as predicted by ORGANON (Fig. 3). Using a 10-m buffer eliminates that increase. There is minor (2 %) increase in wood volume in the larger piece sizes (35–60 cm) in the single entry thin with tipping (10 % tip rate) because the tipped trees are part of the thinned tree population, which have smaller diameters (e.g., thinning from below) and because tree taper limits the diameter of the tree intersecting the stream. There is no change in the proportion of wood volume in the larger piece diameters in the double entry thin because even though there was a second tipping (year 2040), the tipped trees were comprised of the smallest diameters at that time period (Table 2).

Concurrently with a reduction in dead tree density, there is a marked increase in the diameter of those trees. For example, only 4 % of dead trees in the no treatment are in the 50–100 cm diameter class. In contrast, there are 39 and 43 % of dead trees in that class in the single and double entry thins (Table 3). However, this does not translate into notably larger diameter in-stream wood because of the large reduction in dead tree density and the selection of the tipping trees from the smaller trees in a thin (thinning from below). One

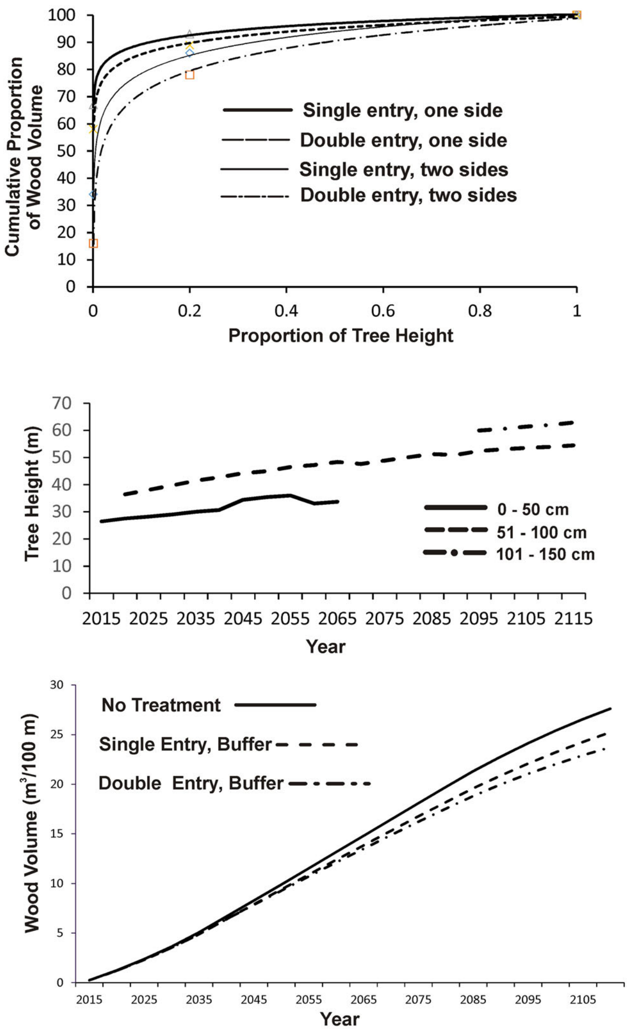

Fig. 8 *Upper* Source distance curves showing varying cumulative proportion of in-stream wood volume with distance from stream for single and double entry thinning, on one and both sides of the stream. *Middle* Predicted tree heights varying over time for different diameter classes of trees. *Bottom* Increasing disparity of accumulated wood volume over time for single and double entry thinning (with 10-m buffer) compared to no treatment, in part due to the effects of increasing tree height over time and the incremental reduction in buffer effectiveness

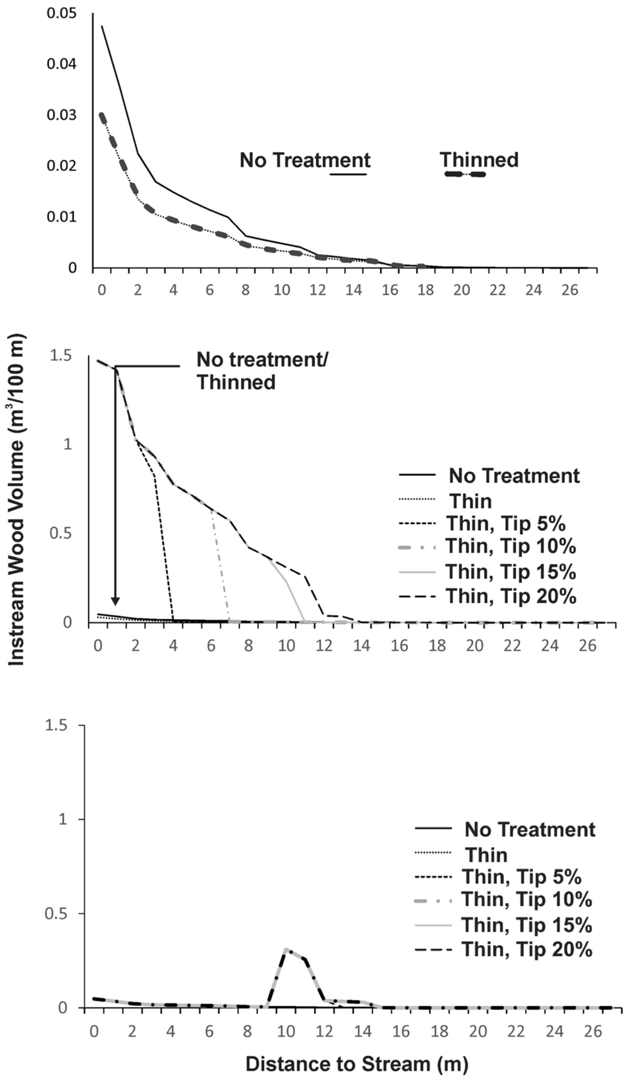

Fig. 9 *Upper* Thinning reduces the wood volume entering the stream at distances less than about 16 m from the channel edge. *Middle* The large effects of thinning and tipping on in-stream wood recruitment, compared to the no treatment, are most pronounced nearest the channel edge. *Note* The change in the vertical axis of wood volume values between the *upper* and *middle graphs*. *Bottom* Adding a 10-m buffer greatly reduces the effectiveness of tipping mitigation

option to increase the diameter of in-stream wood is to select the trees to be tipped from the larger tree diameters.

Discussion

Thinning in riparian areas, buffers and tree tipping as mitigation

ORGANON in our study site in coastal Oregon predicts that thinning results in large changes to forest structure over the 100-year simulation. There are large reductions in the densities of live trees and a corresponding increase in diameters, a prediction similar to others (Dodson et al. 2012; Spies et al. 2013). The ecological effects of such changes will vary among organisms, with some responding positively to the increase in size of trees while other may be affected negatively by the reduction in the number of trees live and dead (Pollock and Beechie 2014). Predicted live and dead tree density is sensitive to the forest growth model that is applied; Zelig (Urban 1990) and Vegetation Simulator (FVS, Crookston and Dixon 2005) are models that may produce different results (Pabst et al. 2008; Spies et al. 2013) but they are not included here.

Table 2 Percentage (cumulative) of in-stream wood piece volumes in three size categories (10–35, 35–60, and >60 cm)

Treatments	Percentage of in-stream wood piece volumes (%)		
	10–35 cm	35–60 cm	>60 cm
No treatment	91	9	0
Single entry, no buffer	85	15	0
Single entry, with buffer	91	9	0
Double entry, no buffer	86	14	0
Double entry, with buffer	90	10	0
Single entry, no buffer, tip 10 %	89	11	0
Single entry, with buffer, tip 10 %	91	9	0
Double entry, no buffer, tip 10 %	92	8	0
Double entry, with buffer, tip 10 %	91	9	0

Table 3 The cumulative proportion, over the century simulation, of live and dead trees per treatment in different diameter (dbh) classes

Tree type	dbh (cm)	No treatment (%)	Single entry thin (%)	Double entry thin (%)
Live trees	0–50	76	43	38
	50–100	23	56	61
	100–150	1	1	1
Dead trees	0–50	95	60	56
	50–100	4	39	43
	100–150	1	1	1

Our analysis explored two different mitigation strategies to offset losses of in-stream wood due to thinning: a 10 m no harvest buffer, and mechanical introduction of some portion of the thinned trees. The width of the buffer controls the proportion of in-stream wood that is maintained during the thinning alternatives. A 10 m buffer maintains 93 % of in-stream wood in a single entry thin and 89 % in a double entry thin (thinning on one side of the stream with no treatment on the opposite bank), a width approximately equivalent to one third of a tree height in 2015 (Fig. 8). Doubling the buffer width to 20 m, or approximately 2/3 of a tree height, increases the maintenance of in-stream wood beyond 95 % in single and double entry thinning on one or both sides of the channel.

The mechanical introduction of some portion of the thinned trees into streams (tree tipping rate) is another effective form of mitigation and can be used to either completely offset any losses of in-stream wood due to thinning or to increase in-stream wood compared to the no treatment or thinning with buffers. The extent of the change varied with the proportion of the trees placed in the channel, whether this contribution was from one bank or both, and the presence of 10-m no harvest zone (Fig. 5). The double entry thin with tipping, particularly without a buffer, is the most effective at increasing wood storage in magnitude and duration over the no treatment alternative. Moreover, thinning and tipping on both sides of the stream simultaneously leads to the largest increases in in-stream wood (2–12 % in a single entry thin without a buffer and 2–48 % in a double entry thin without a buffer) (e.g., doubling the values in Fig. 6; Table 1).

Thinning and tipping in the context of fish habitat restoration

Pools and cover, which are often directly related to the abundance of wood, are important for certain species of fish, such as coho salmon (*Oncorhynchus kisutch*) in coastal Oregon (Roni and Quinn 2001; Anlauf et al. 2011). Thus, predicted reductions in in-stream wood in the simulation due to thinning without and with buffers (no tree tipping) could lead to reductions in fish habitats, throughout the century period. However, thinning with tipping can produce more in-stream wood, cumulatively over a century, compared to the no treatment. Tree tipping could be considered an in-stream restoration activity (Jones et al. 2014; Carah et al. 2014). However, with thinning and tipping only on one side of the stream most of the increases occur in the first half of the simulated century, which is then followed by a period during which wood volumes drop below the no treatment alternative. However, with thinning and tipping simultaneously on both sides of the stream, the increase above the no treatment continues for the entire century.

The predicted increases in the volume of in-stream wood due to tipping could offset concerns about reductions of in-stream wood and loss of fish habitat (Beechie et al. 2000). Additionally, in tipping, the amount of wood increases immediately rather than being delayed for 25–50 years in the no treatment, unmanaged stand. This could be particularly important for improving habitat conditions for U.S. Endangered Species Act-listed species, such as the coho salmon in the near term, rather than waiting an additional half century or more for higher levels of wood recruitment and storage. The increase in the size of the trees in the riparian zone over time that results from thinning is also important ecologically because they will be more effective in forming pools than smaller sized pieces, although the in-stream piece size effect might not occur until after the first century. To increase the size (diameter) component of in-stream wood earlier in the century, the tipped trees could be selected from the larger diameter classes within the riparian forest.

The presence of a no harvest buffer reduces the effectiveness of tipping, a consideration in the context of aquatic restoration. For example, with a buffer very little increase in in-stream wood volume occur with tree tipping because tree recruitment occurs away from the channel (e.g., greater than 10 m) and only the thinner, upper sections of trees are recruited, providing very little in-stream wood because of tree taper.

Thinning and tipping in conjunction with in-stream structures

Thinning operations could be integrated with other in-stream restoration efforts. For example, the magnitude and duration of predicted in-stream wood storage in any management scenario in the RSWM does not account for fluvial transport in and out of channel reaches and thus wood redistribution (e.g., Qi and Qo in Eq. 1). Wood recruitment, including by tree tipping, does not include the roots of trees, thus leading to less stable, in-stream pieces. In addition, the diameter of many pieces are predicted to be of smaller diameters (Table 2), another factor leading to lower stability and higher wood transport (unless the tipped trees are selected from the larger diameter classes). Hence, fluvial export of wood could lead to reductions in in-stream wood in any particular stream reach, below the amounts predicted. One approach to maintaining increased storage of in-stream wood due to tipping is to interrupt or reduce fluvial wood transport by the placement of in-stream structures, such as engineered log jams and or boulder deposits. Such structures could be strategically placed in the context of thinning and tipping to ensure that increases in wood storage are maintained over time.

Another approach to offset losses of in-stream wood due to fluvial transport is to conduct thinning and tipping activities along long and contiguous reaches of stream, so that Qi and Qo remain approximately balanced over long sections of streams. Estimates of in-stream wood transport, using a combination of modeling and field data in northern California, suggest that wood transport (over the lifetime of wood pieces) in small headwater streams can range from 50 m to 250 m while transport distances in larger third through fifth order streams might attain multi-kilometers (Benda and Bigelow 2014). Transport distances may even exceed those, considering that transport impeding jams may be breached by large floods (Lassetter and Kondolf 2003).

Thinning and its design conditioned by different environmental conditions

The alternatives considered in this paper could be applied in different areas and to different extents, depending on varying physical and ecological conditions. Environmental conditions could encompass: (1) riparian forest condition (e.g., ages, heights, diameters, densities etc.), (2) condition of terrestrial and avian habitats, particularly those dependent on riparian environments for some part of their life cycles, (3) current fish habitat conditions for different species (such as coho salmon), including in-stream wood recruitment, (4) shade, thermal loading and stream temperature concerns, (5) headwater and upslope (debris flow) supply of wood, and (6) erosion potential and sediment delivery to streams (Reeves et al. in press). Watershed scale analyses that provide information on these, and other physical and biological settings, would be important components in developing watershed to landscape scale strategies for implementing thinning and other forest and stream management and restoration plans.

For example, in second growth forests (occurring on both sides of the stream) where both terrestrial and aquatic habitats are of poor quality, and where sensitivity to increases in thermal energy is low, thinning and tipping, in the absence of a buffer, could be applied to both channel sides as a form of fish habitat restoration. In areas where a decrease in shade can lead to large increases in thermal loading due to thinning, a buffer can be applied, with a width and vegetation density designed to eliminate or reduce predicted increases in thermal loading; tree tipping may or may not be applied, depending on objectives for stream restoration. Along non-fish bearing headwater streams where large in-stream wood is lacking and where vegetation controls on thermal loading are considered low, aggressive thinning without tipping could occur, with the objective of creating larger pieces of in-stream wood over century time scales. This tactic might be particularly relevant in small headwater streams that are predicted to be important upslope sources of large wood to downstream habitats, via the process of debris flows (Reeves et al. 2003; Burnett and Miller 2007; Bigelow et al. 2007).

The potential for surface erosion and mass wasting in and near riparian areas is an important concern that should be addressed when designing watershed scale thinning treatments (Litschert and MacDonald 2009). Models, coupled with field observations and measurements, could be used to estimate the potential for erosion. Thinning could be replaced with a no treatment alternative or the use of buffers in areas where erosion risk and potential for sediment delivery to streams is high.

Model limitations, field validation and adaptive management

Forest growth models contain approximations that influence the predicted wood storage in streams. In our analysis, use of FIA data spatially extrapolated by the GNN method, provides only an approximation of actual riparian forest conditions in any location; the majority of FIA plots lie outside of riparian areas. It is recommended that forest stand inventories occur in the riparian second growth forests targeted for thinning, at least in a subset of proposed project areas. Assessing effects of thinning on wood recruitment and tree growth is partially dependent on the forest growth model (Pabst et al. 2008; Spies et al. 2013). ORGANON has lower growth rates and low competition mortality rates compared to the other models such as FVS (Crookston and Dixon 2005) and ZELIG (Garman et al. 1992). Resource managers could examine results from more than one model especially for projections that extend out 50–100 years. Sources of variability can include mortality from non-density dependent factors (e.g. wind throw, bank erosion) that become more important over time.

The RSWM contains several approximations in its predictions of century-scale in-stream wood budgets. Tree spacing is assumed to be uniform, although trees in actual forest stands might be clumped. There may be higher concentration of deciduous species nearest to the stream although this could be incorporated into stand divisions in the RSWM. Tree taper equations are approximations of actual tree shape. The amount of in-stream wood is limited to what is circumscribed by both stream banks (e.g., modeled pieces of wood do not extend beyond the channel banks in the RSWM). However, piece breakage and pieces extending outside of channel banks can be added in the future. In the no treatment scenario, high density stands of smaller trees may inhibit the probability of tree fall (in any direction). Thus, recruitment from dense untreated stands could be over-predicted in the RSWM. This issue may also complicate tree tipping effectiveness.

Conclusion

We found that single and double entry thinning, with no mitigation (buffers or mechanical tipping of trees into the stream) can lead to large losses of in-stream wood over a century time scale; single and double entry thins on one side of the stream leads to reductions of 33–42 % of instream wood with simultaneous thinning on both sides of the stream doubling those losses. No cut buffers are effective at protecting in-stream wood recruitment. However, tree tipping can lead to large increases in in-stream wood that could be considered a form of fish habitat restoration.

The need for thinning, including its design, will vary spatially depending on variable site conditions including existing terrestrial and aquatic habitat needs (Pollock and Beechie 2014), in-stream wood recruitment potential, thermal sensitivity, floodplains and erosion potential. Applications of thinning without and width buffers or without and with tree tipping offers a framework to consider the design and implementation of thinning, including as a form of channel restoration.

Acknowledgements Funding for this research and manuscript preparation originated from the U.S. Forest Service, Pacific Northwest Research Station and Earth Systems Institute, Seattle Washington. We would like to thank Stuart Johnston for consultations involving silvicultural practices in the Siulsaw National Forest and his forest growth modeling. We also thank Jack Sleeper for his help in understanding the existing conditions of stream side riparian forests in the Alsea watershed. Author S.E. Litschert was a scientist at Earth Systems Institute at the time of this work.

References

Anlauf KJ, Jensen DW, Burnett KM, Steel EA, Christiansen K, Firman JC, Feist BE, Larsen DP (2011) Explaining spatial variability in stream habitats using both natural and management-influenced landscape predictors. Aquat Conserv 21:704–714

Beechie T, Pess GR, Kennard P, Bilby PR, Bolton S (2000) Modeling recovery rates and pathways for woody debris recruitment in northwestern Washington streams. N Am J Fish Manag 20:436–452

Benda L, Bigelow P (2014) Recruitment, storage transport and function of wood in northern California streams. Geomorphology 209:79–97

Benda L, Sias J (2003) A quantitative framework for evaluating the mass balance of wood in streams. J For Ecol Manag 172:1–16

Benda L, Miller DJ, Andras K, Bigelow P, Reeves G, Michael D (2007) NetMap: a new tool in support of watershed science and resource management. For Sci 52:206–219

Bigelow P, Benda L, Miller DJ, Burnett KM (2007) On debris flows, river networks, and the spatial structure of channel morphology. For Sci 52:220–238

Bilby R, Heffner J, Fransen B, Ward J, Bisson P (1999) Effects of immersion in water on deterioration of wood from five species of trees used for habitat enhancement projects. North Am J Fish Manag 19:687–695

Bisson PA, Bilby RE, Bryant MD, Dolloff CA, Grette GB, House RA, Murphy ML, Koski KV, Sedell JR (1987) Large woody debris in forested streams in the Pacific Northwest past, present, and future. In: Salo EO, Cundy TW (eds) Streamside management, forestry and fishery interactions. University of Washington Press, Seattle, pp 143–190

Braudrick CA, Grant GE, Ishikawa Y, Ideda H (1997) Dynamics of wood transport in streams: a flume experiment. Earth Surf Proc Land 22:669–683

Burnett KM, Miller DJ (2007) Streamside policies for headwater channels: an example considering debris flows in the Oregon Coastal Province. For Sci 53:239–253

Burnett KM, Reeves GH, Miller DJ, Clarke S, Vance-Borland K, Christiansen K (2007) Distribution of salmon-habitat potential relative to landscape characteristics and implications for conservation. Ecol Appl 17:66–80

Carah JK, Blencowe CC, Wright DW, Bolton LA (2014) Low-cost restoration techniques for rapidly increasing wood cover in coastal coho salmon streams. N Am J Fish Manag 34:1003–1013. doi:10.1080/02755947.2014.943861

Crookston NL, Dixon GE (2005) The forest vegetation simulator: a review of its structure, content, and applications. Comput Electron Agric 49:60–80

Dodson EK, Ares A, Puettmann KJ (2012) Early responses to thinning treatments designed to accelerate late successional forest structure in young coniferous stands of western Oregon, USA. Can J For Res 42:345–355

Everest FH, Reeves GH (2007) Riparian and aquatic habitats of the Pacific Northwest and Southeast Alaska: ecology, management history and potential management strategies. Gen. Tech. Rep., PNW-GTR-692 Pacific Northwest Research Station

Forest Ecosystem Management Assessment Team (FEMAT) (1993–2003) Forest ecosystem management: an ecological, economic, and social assessment. Report of the Forest Ecosystem Management Assessment Team, U.S. Government Printing Office 1993-793-071

Garman SL, Hansen AJ, Urban DL, Lee PF (1992) 1992. Alternative silvicultural practices and diversity of animal habitat in western Oregon: a computer simulation approach. In: Luker P (ed) Proceedings of Summer Computer Simulation Conference. Society for Computer Simulation, Reno, pp 777–781

Groom JD, Dent L, Madsen LJ, Fleuret J (2011) Response of western Oregon (USA) stream temperatures to contemporary forest management. For Ecol Manag 262:1618–1629

Hann DW (2006) ORGANON user's manual: Edition 8.0. Department of Forest Resources, Oregon State University, Corvallis

Harmon ME, Franklin JF, Swanson FJ, Sollins P, Gregory SV, Lattin JD, Sedell JR, Lienkaemper GW, Cromack K, Cummins KW (1986) Ecology of coarse woody debris in temperate ecosystems. Adv Ecol Res 15:133–302

Hibbs DE, Bluhm AA, Garber SM (2007) Stem taper and volume of managed red alder. West J Appl For 22(1):61–66

Ice G (2005) Forest riparian protection in the Pacific Northwest. West For 50(2):8–10

Jones KK, Anlauf-Dunn K, Jacobsen PS, Strickland M, Tennant L, Tippery SE (2014) Effectiveness of in-stream wood treatments to restore stream complexity and winter rearing habitat for juvenile coho salmon. Trans Am Fish Soc 143:334–345

King L, Hassan MA, Wei X, Burge L, Chen X (2013) Wood dynamics in upland streams under different disturbance regimes. Earth Surf Proc Land 38(11):1197–1209

Kozak A (1988) A variable-exponent taper equation. Can J For Res 18:1363–1368

Lassetter NS, Kondolf GM (2003) Process based management of large woody debris at the basin scale, Soquel Creek, California. Final Report prepared for the California Department of Forestry and Fire Protection and Soquel Demonstration State Forest. Department of Landscape Architecture and Environmental Planning, University of California, Berkeley. http://www.demoforests.net/Warehouse/Docs/Soquel/Reports/LWDinSoquelCreek.pdf

Litschert S, MacDonald L (2009) Frequency and characteristics of sediment delivery pathways from forest harvest units to streams. For Ecol Manag 259:143–150

Martin DJ, Benda L (2001) Patterns of instream wood recruitment and transport at the watershed scale. Trans Am Fish Soc 130:940–958

Means JE, Cromack K, MacMillan PC (1985) Comparison of decomposition models using wood density of Douglas-fir logs. Can J For Res 15:1092–1098

Meleason MA, Gregory SV, Bolte JP (2003) Implications of riparian management strategies on wood in streams of the Pacific Northwest. Ecol Appl 13:1212–1221

Meleason MA, Davies-Colley RJ, Hall GMJ (2007) Characterizing the variability of wood in streams: simulation modeling compared to multiple reach surveys. Earth Surf Proc Land 32:1164–1173

Miller DJ, Burnett KM (2008) A probabilistic model of debris-flow delivery to stream channels, demonstrated for the Coast Range of Oregon, USA. Geomorphology 94:184–205

Murphy ML, Koski KV (1989) Input and depletion of woody debris in Alaska streams and implications for streamside management. N Am J Fish Manag 9:427–436

Naiman RJ, Bisson PA, Lee RG, Turner MJ (1998) Watershed management. In: Naiman RJ, Bilby RE (eds) River ecology and management: lessons from the Pacific coastal ecoregion. Springer, New York, pp 642–661

Ohmann JL, Gregory MJ (2002) Predictive mapping of forest composition and structure with direct gradient analysis and nearest-neighbor imputation in coastal Oregon, USA. Can J For Res 32(4):725–741

Pabst RJ, Goslin MN, Garman SL, Spies TA (2008) Calibrating and testing a gap model for simulating forest management in the Oregon Coast Range. For Ecol Manag 256:958–972

Pickard B (2013) Keying forest stream protection to aquatic ecosystem values in multi-owner watersheds. Masters Thesis, Oregon State University, Corvallis

Pollock MM, Beechie TJ (2014) Does riparian forest restoration thinning enhance biodiversity? The ecological importance of large wood. J Am Water Resour Assoc 50(3):543–559

PRISM Climate Group (2014) Oregon State University, June 2014. http://prism.oregonstate.edu

Reeves GH, Burnett KM, McGarry EV (2003) Sources of large wood in the main stem of a fourth-order watershed in coastal Oregon. Can J For Res 33(8):1352–1362

Reeves GH, Pickard BR, Johnson KN (in press) Options for managing riparian ecosystems on federal lands in the area of the northwest forest plan. Pacific Northwest Research Station GTR PNWXXX, PNW Research Station, USDA Forest Service, Portland

Richardson JS, Naiman RJ, Bisson PA (2012) How did fixed-width buffers become standard practice for protecting freshwaters and their riparian areas from forest harvest practices? Freshw Sci 31(1):232–238

Roni P, Quinn TP (2001) Density and size of juvenile salmonids in response to placement of large woody debris in western Oregon and Washington streams. Can J Fish Aquat Sci 58(2):282–292

Sedell JR, Froggatt JL (1984) Importance of streamside forests to large rivers: the isolation of the Willamette River, Oregon, U.S.A., from its floodplain by snagging and streamside forest removal. Verh Int Verein Limnol 22:1828–1834

Sobota DJ, Gregory SV, Van Sickle J (2006) Riparian tree fall directionality and modeling large wood recruitment to streams. Can J For Res 36:1243–1254

Society of American Foresters (Oregon Society, OSAF) (2009) Position statement: Riparian Forest Management and Fish. Online. http://www.oregon.gov/odf/BOARD/docs/April_2009/A_Att_2.pdf

Spies T, Pollock M, Reeves G, Beechie T (2013) Effects of riparian thinning on wood recruitment: a scientific synthesis. Science Review Team Wood Recruitment Subgroup, USDA Forest Service, PNW Research Station, Portland

Urban DL, Bonan GB, Smith TM, Shugart HH (1991) Spatial applications of gap models. For Ecol Manag 42:95–110

Van Sickle J, Gregory SV (1990) Modeling inputs of large woody debris to streams from falling trees. Can J For Res 20:1593–1601

Waddell DR, Weyermann DL, Lambert MB (1987) Estimating the weight of Douglas-Fir tree boles and logs with an iterative computer model. USDA, Forest Service, Pacific Northwest Research Station, PNW-RP-374

Welty JJ, Beechie T, Sullivan K, Hyink DM, Bilby RE, Andrus C, Pess G (2002) Riparian aquatic interaction simulator (RAIS): a model of riparian forest dynamics for the generation of large woody debris and shade. For Ecol Manag 162:299–318