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Streamside Policies for Headwater Channels: An Example Considering Debris Flows in the Oregon Coastal Province

Kelly M. Burnett and Daniel J. Miller

Abstract: Management policies are increasingly debated for headwater channels given their prevalence and ecological importance in many landscapes. Quantitative differences among headwater channels may offer an objective basis for prioritizing streamside protection. Here, we examine differences among headwater channels as potential transport corridors for debris flows. Specifically, we model differences among hill slopes and headwater channels in probabilities of initiating and being traversed by debris flows that deliver to fish-bearing channels. We develop an approach to rank these probabilities and apply the ranks in delineating alternative streamside management zones. Initiation and traversal probabilities are estimated from an empirically calibrated debris-flow model using regionally available 10-m digital elevation data. Alternatives are delineated by encompassing 25%, 50%, and 75% of debris-flow susceptible hill slopes and headwater channels. Highest initiation and traversal probabilities were contained in a relatively small percentage of the study area. Encompassing lower probabilities required disproportionately larger areas. Substituting delineated alternatives for currently prescribed headwater riparian management zones decreased the total area encompassed on federal lands but increased it on private and state lands. Our intent is not to advocate for any particular alternative but to demonstrate that knowledge about how headwater channels differ over large areas can help tailor riparian policies. FOR. SCI. 53(2):239–253.

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THE RECOGNITION THAT HEADWATER CHANNELS provide important habitats and influence conditions downstream is spurring discussions about management policies for these small streams. Science generally supports that riparian protection and restoration are effective ways to conserve stream ecosystem functions (National Research Council 2002). Thus, a potential management strategy for headwater channels is to afford streamside protection to each on the assumption that all are of equal conservation value. Protecting all headwater channels, however, can severely restrict land management options. This is particularly true in montane landscapes where headwater channels may comprise up to 90% of the stream-network length (Benda and Dunne 1997). Consequently, the ability to quantify ecologically relevant differences among headwater channels could aid in developing efficient and effective streamside management policies. Here, we examine headwater channels in light of their role as potential transport corridors for debris flows.

In mountainous terrain, debris flows can be a primary process by which headwater channels are connected to and influence larger rivers downstream. Debris flows commonly start as rainfall-initiated translational landslides of shallow soils (Iverson et al. 1997). These can transfer wood and sediment into and through headwater channels (Benda and Cundy 1990, Gomi et al. 2002). Over the decades to centuries between debris-flow events, headwater channels that are traversed by debris flows accumulate wood from blow down, chronic mortality, and landsliding in adjacent forests (May and Gresswell 2003a). High-gradient headwater channels can be scoured to bedrock and emptied of large wood by debris flows (Gomi et al. 2001). Accumulated wood and boulders can be carried out of headwater channels in debris flows and delivered downstream as potentially long-lasting deposits in larger, lower-gradient valleys and channels (Benda 1990, Wohl and Pearthree 1991, May and Gresswell 2004).

Debris flows can be a key disturbance mechanism, scouring or burying stream channels and riparian areas but also contribute to physical heterogeneity (Montgomery 1999, Benda et al. 2003). From an ecological perspective, this physical heterogeneity translates into habitat heterogeneity, which may influence the distribution and abundance of stream and riparian biota throughout a channel network (Pabst and Spies 2001, Rice et al. 2001, Bilby et al. 2003). Large wood delivered by debris flows can be a conspicuous component of habitat heterogeneity (May and Gresswell 2003b, Bigelow et al. 2007). Stream organisms are affected by large wood through its influence on numerous processes and structures, including sediment transport and channel morphology (for reviews see Bilby and Bisson 1998, Gregory et al. 2003).

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Because forest management may alter debris-flow characteristics and consequences, policies are debated for activities in areas that are susceptible to debris flows. Evidence that forest clearing may affect local susceptibility to debris-flow initiation (e.g., Montgomery et al. 2000, Schmidt et al. 2001, Sidle and Ochiai 2006) or distances debris flows travel (May 2002, Ishikawa et al. 2003, Lancaster et al. 2003) has sparked concern that timberland management can modify debris-flow regimes, including the frequency, magnitude, and synchronicity of events. Changes in such characteristics may negatively affect stream-dwelling organisms, such as Pacific salmonids (*Oncorhynchus* spp.), that are adapted to a particular disturbance regime (Reeves et al. 1995). Therefore, attempting to maintain or restore characteristics of debris-flow regimes and the sources of wood for debris-flow delivery to streams may be desirable policy goals. A realistic first step in the context of these goals is to identify probable debris-flow sources and traversal corridors and then to rank these based on the likelihood of initiating or being traversed by debris flows that deliver to a fish-bearing channel. The rankings can help when designing and evaluating policy alternatives aimed at source areas or headwater channels with different potentials to affect fish-bearing channels.

Debris-flow source areas and traversal corridors are identifiable based on understanding about the variety of factors influencing spatial variability in debris-flow initiation and runout (Dunne 1998). Such factors include topography (Benda and Cundy 1990, May 2002, Chen and Jan 2003), soil depth (Wu 1996), and geotechnical properties (Hammond et al. 1992). These can be assessed locally through field surveys over relatively small areas (of order 10^1 km^2). However, identifying the headwater channels that are debris-flow corridors is necessary over large areas (of order 10^5 km^2) to evaluate likely outcomes of policy alternatives at spatial extents that match affected social, economic, and ecological systems. Detailed field surveys are not feasible over these spatial extents. Most available modeling approaches address either the likely locations for shallow-rapid landslides (e.g., Guzzetti et al. 1999, Rollerson et al. 2002, van Westen et al. 2003, Brenning 2005) or the likely distances that debris flows travel (Benda and Cundy 1990, Fannin and Wise 2001). Any broad-scale identification of relevant source areas and traversal corridors requires a model that estimates probabilities of initiating and of delivering debris flows. And, this must be accomplished with widely available data, e.g., digital elevation models (DEMs).

In this study, we apply a model that identifies both the likely locations of debris-flow initiation and of traversal by relating mapped landslide initiation sites and debris-flow tracks to 10-m digital elevation data (Miller and Burnett 2007, Miller and Burnett in review). Essential to our efforts are three values that the empirical model generates for each DEM-pixel: the probability that a mapped debris flow initiated, the probability that an initiated debris flow traveled to a fish-bearing channel, and the probability of being traversed by a debris flow from upslope that continued on to a fish-bearing channel. We use these values to address four study objectives: 1) rank DEM pixels, differentiated into inferred hill slope and headwater channels, based on the separate probabilities of initiating and of being traversed by a debris flow that travels to a fish-bearing channel; 2) develop methods to delineate alternatives from these rankings that encompass specified percentages of the initiation and traversal pixels, starting with those having the highest probabilities; 3) demonstrate the methods in the central Oregon Coastal Province by delineating three alternatives to encompass 25%, 50%, and 75% of the initiation and traversal pixels; and 4) evaluate these alternatives by comparing the total area encompassed and by demonstrating how substituting these for current riparian management zones on headwater channels may affect the area receiving special consideration for aquatic conservation.

Study Area

The study addresses 5,730 km^2 of the central Coastal Province in western Oregon, USA, with particular focus on the Knowles Creek basin (58 km^2), a tributary to the Siuslaw River (2,000 km^2) (Fig. 1). Rainfall-triggered translational landslides of shallow soils that cause debris flows are a primary process in the study area for transporting sediment from upper slopes to valley floors and affecting valley and channel morphology (Benda 1990, Robison et al. 1999, Bigelow et al. 2007). Numerous debris-flow studies have been located in Knowles Creek (Benda 1990, May and Gresswell 2004, Montgomery et al. 2003). The study area is an actively uplifting region (e.g., Mitchell et al. 1994) and is underlain by shallow-water marine sedimentary rocks (Orr et al. 1992). The resulting landscape is of relatively low relief (elevations range from sea level to 1,200 m) but highly dissected, with soil-mantled ridge-and-valley terrain of steep slopes as illustrated in Fig. 2. Drainage networks are dense and dendritic with short, steep headwater channels in the uplands and larger, lower-gradient alluvial rivers downstream. The area has a maritime climate characterized by mild, wet winters with occasional long-duration storms, and by warm, dry summers (Taylor and Hannan 1999). Mean annual precipitation ranges from 125 cm in lowland areas to 500 cm at higher elevations.

The coastal rainforest is dominated by Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), western hemlock

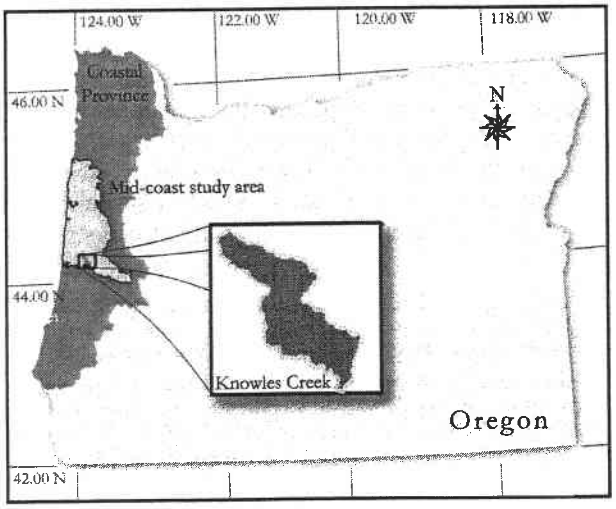

Figure 1. Map of study area in the Oregon Coastal Province, USA.

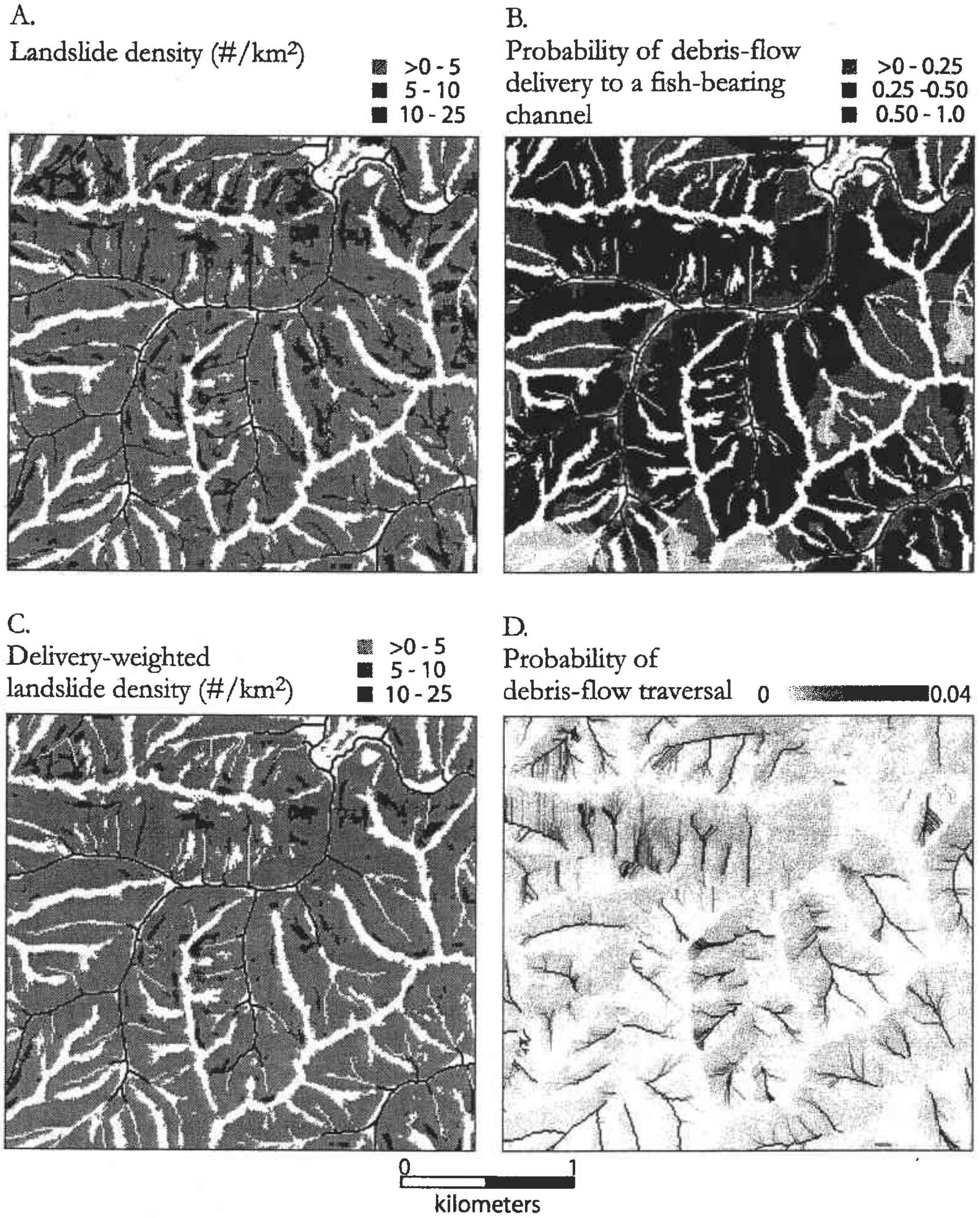

Figure 2. Outputs of the coupled debris-flow initiation and delivery model (Miller and Burnett 2007; Miller and Burnett in review) illustrated for a portion of the Knowles Creek basin in the central Oregon Coastal Province, USA. (A) Modeled landslide density. (B) Probability of debris-flow delivery to a fish-bearing channel. (C) Delivery-weighted landslide density expressed for each pixel as the product of the landslide density and the probability of debris-flow delivery to a fish-bearing channel. (D) Probability that a pixel is traversed by a debris flow that traveled to a fish-bearing channel. This probability is presented over a hill-shade view of the underlying DEM.

(*Tsuga heterophylla* (Raf.) Sarg.), and along the coast, Sitka spruce (*Picea sitchensis* (Bong.) Carr). Typical additions in riparian areas are western redcedar (*Thuja plicata* Donn ex D. Don) and big leaf maple (*Acer macrophyllum* Pursh). Forests span early successional to old-growth seral stages due to a disturbance regime driven by timber harvest and recent fire suppression and by past infrequent but intense wild fires and windstorms (Franklin and Dyrness 1988). Most of the current forestland is in relatively young seral stands, but the larger river valleys have been cleared for agriculture. The study area supports five salmonid species - steelhead (*Oncorhynchus mykiss* Walbaum), coho salmon (*O. kisutch* Walbaum), cutthroat (*O. clarkii clarkii* Richardson), chinook salmon (*O. tschawytscha* Walbaum), and chum salmon (*O. keta* Walbaum).

Methods

Delineating Debris-flow Initiation and Traversal Alternatives

The methods for delineating boundaries of alternative initiation and traversal zones are presented by: 1) summarizing the approach for modeling probabilities of debris-flow initiation (Miller and Burnett in press) and delivery

(Miller and Burnett in review); 2) showing how these modeled probabilities are combined to calculate the probability of initiating a debris flow that delivers to a fish-bearing channel and the probability of being traversed by a debris flow that delivers to a fish-bearing channel; 3) ranking DEM pixels relative to these separate debris-flow initiation and traversal probabilities; 4) identifying threshold probabilities based on these ranks that are required to encompass the percentage (25%, 50%, or 75%) of initiation and traversal pixels specified in an alternative; 5) flagging pixels with probabilities exceeding these thresholds; and 6) extending a boundary on either side of traversed pixels in headwater channels.

To demonstrate these methods, we approximated the extent of the fish-bearing network as those channel reaches having no downstream reach with a gradient >20%. This follows guidance of the Oregon Department of Forestry (ODF 1997). Channel locations were based on DEM-inferred topography, using algorithms described by Tarboton (1997) and by Garbrecht and Martz (1997). Channel initiation points were based on slope-area thresholds (Montgomery and Foufoula-Georgiou 1993) set to extend channels as far upslope as possible without forcing channels onto planar hill slopes, as described in Miller (2003). Delineated channels extend beyond the blue-line network depicted on the 1:24,000-scale US Geological Survey (USGS) topographic maps and include all headwater channels resolvable with the 10-m DEMs.

All terrain modeling in this study used gridded USGS 10-m DEMs. These were created (Underwood and Crystal 2002, Clarke and Burnett 2003) by interpolating elevations at DEM grid points from the digital line graph (DLG) contours on standard 7.5-minute USGS topographic quadrangles (USGS 1998). Accuracies of the 10-m DEMs and of the source USGS topographic quadrangles are identical but vary by quadrangle consistent with USGS standards.

Debris-flow Model

Debris-flow Initiation

Landslides in shallow, saturated soils on steep slopes can trigger debris flows (Iverson et al. 1997). To identify locations susceptible to such landslides in the Oregon Coast Range, mapped landslide initiation points were overlaid on 10-m DEMs (Miller and Burnett 2007). Landslide locations were determined by the ODF through field surveys after a large storm in 1996 (Robison et al. 1999). Each landslide initiation site was characterized in terms of a topographic index that is readily calculated for each DEM pixel. The index was based on the SHALSTAB model (Dietrich et al. 2001) and incorporated topographic attributes of slope gradient, convergence, and contributing area (Miller and Burnett 2007).

The influence of these topographic attributes on landslide susceptibility was quantified in terms of landslide density: the number of landslides per unit area. Landslide density was determined as a function of the topographic index (Miller and Burnett 2007). For any increment of the topographic index, the number of pixels with index values in that increment and the number of landslides mapped within those pixels were counted. The result is an empirical landslide density given as a function of the topographic index. Calculated for each pixel in a DEM, this is a spatially distributed estimate of topographically controlled landslide density (Fig. 2A). The density translates directly to the probability P_I that a mapped debris flow initiated in a pixel. For example, a landslide density of 1 landslide per square kilometer indicates a 0.0001 probability of finding a landslide initiation point within a 100-m^2 pixel.

It is important to note that the magnitude of calibrated landslide densities reflects the number of landslides mapped in the calibration data. This number depends on the timing, purpose, and methods of landslide mapping. The model was calibrated with landslide inventories collected after an extreme storm (Miller and Burnett 2007), and so the maximum calibrated landslide density is relatively large. Our aim is to delineate the area needed to encompass a certain percentage of the landslide initiation points, starting with the least stable slopes (highest landslide densities) and progressing to the most stable (lowest landslide densities). For this purpose, it is the spatial variation in relative magnitude, and not the absolute magnitude, that is important.

Debris-Flow Delivery

We invoke a simple postulate to devise a topographically based empirical approach for estimating the probability that a debris flow travels from its initiating point to any point downslope: the terminus of a debris flow indicates the point where the volume entrained equals the volume deposited. We cannot calculate these volumes directly, but we can estimate their relative magnitudes from characteristics of the travel path (Miller and Burnett in review).

Debris flows scour material, and thus increase in volume, along steep, topographically confined portions of their travel path and deposit material, and thus reduce their volume, along lower-gradient and less confined portions of the travel path (Benda and Cundy 1990). Fannin and Rollerson (1993) found that the ratio of slope gradient to channel width provided a measure to differentiate zones of scour from zones of deposition. In addition to landslide initiation sites, the ODF field-mapped locations of scour, transitional flow, and deposition for a large number of debris-flow tracks after the 1996 storms (Robison et al. 1999). The slope gradient and the width of the confining valley or swale are calculated from 10-m DEMs for each pixel along these mapped debris-flow tracks (Miller 2003), and the ratio of gradient to width is determined. We bin these ratio values and examine the proportion of debris-flow track length in each bin that was mapped as scour, transitional, and deposition. Where the ratio is small (low-gradient, unconfined swales and channels), deposition predominated. Where the ratio is large (high-gradient, confined swales and channels), scour predominated. From these proportions, we estimate the potential for debris flow scour, transitional flow, or deposition as a function of the ratio of DEM-inferred gradient and confining width, a value that can be calculated for every pixel of the DEM.

Because debris flows entrain material and increase in volume through zones of scour, we assume that debris-flow volume is proportional to the length of the scour zone. This ignores the volume of the initiating landslide but is a first-order approximation of volume as a function of the travel path. Furthermore, the assumption is consistent with observations that the volume of a debris-flow deposit is proportional to travel length (May 2002). Debris flows lose material and decrease in volume when traveling through zones of deposition. We assume that the volume deposited per unit travel length is proportional to the width of the valley and the total volume entrained. Along each ODF-mapped debris-flow track, we calculate a ratio of entrained to deposited volume. This varies with the cumulative length of scour and depositional zones based on the ratio of DEM-inferred gradient to confining width along the travel path. The ratio of entrained to deposited volume at the terminus of each debris-flow track (excluding debris flows that stopped at channel junctions) yields a distribution of values centered on one. The width of this distribution expresses variability in the volume entrained and the volume deposited per unit travel length. It also estimates the probability that a debris flow stopped along any increment of travel depending on the value of the ratio of entrained to deposited volume. Assuming this distribution reflects general debris-flow behavior, we calculate the probability that a debris flow initiated in any pixel travels to any downslope pixel as a function of slope gradient and confining width along the flow path between the two pixels.

Debris flows also stop at channel confluences that result in large changes in debris-flow travel direction and/or gradient (Benda and Cundy 1990, May and Gresswell 2004). To characterize the potential for a debris flow to stop at a channel junction, we examine the ODF-mapped debris-flow tracks relative to all channel junctions either traversed by a debris flow or where a debris flow stopped. Junction angles were estimated from the DEM by fitting a second-order polynomial to pixels extending 100 meters up- and downstream along the receiving channel and 100 meters upstream along the tributary channel.

We define a three-dimensional data space with junction angle along one axis, the entrained volume minus the deposited volume along a second axis, and the probability for deposition in the receiving channel (based on the ratio of gradient to confining width described earlier) along the third axis. Each junction represents a specific point within this data space. Along a three-dimensional grid of bins within this space, we determine the proportion of points representing junctions traversed to points representing junctions where debris flows stopped. The proportion is dominated by debris flows that stopped where junction angles are large, the receiving channel is flat and wide, or the difference between entrained and deposited volume is small. Conversely, the proportion is dominated by debris flows that continued where the junction angle is small, the receiving channel is steep, or the difference between entrained and deposited volume is large. These proportions provide a measure of the probability that a debris flow will stop at a channel junction. Each DEM-derived channel junction encountered by a "potential" debris flow can be described by a point in the three-dimensional data space. The location of the point in that data space gives the probability that the debris flow stops at the junction.

For every pixel with a potential debris-flow initiation point (i.e., with a landslide density greater than zero), we can follow the flow path downslope. We can calculate a probability that the debris flow reaches any downslope pixel as a function of the slope gradient, confining width, and tributary junctions encountered along the way. Once calibrated, this model works well for estimating the extent of the low-order (headwater) channel network affected by debris flows (Miller and Burnett in review). For a debris flow initiating from any pixel in the DEM, we trace the flow path downslope until encountering a pixel flagged as containing a fish-bearing channel. The probability that the debris flow reaches the fish-bearing channel is then assigned to the pixel where the debris flow originated. This provides a map of P_D, the probability for debris-flow delivery (Fig. 2B).

Delivery-weighted Landslide Density

Each source pixel has an associated probability for a debris-flow-triggering landslide, P_I (Fig. 2A), and an associated probability for debris-flow runout and delivery to a fish-bearing channel, P_D (Fig. 2B). The product $P_I P_D$ is the probability that a debris flow was initiated in the source pixel and traveled to a fish-bearing channel. We refer to this product as a delivery-weighted landslide density. It can be used to identify the most likely source areas for debris flows that travel to fish-bearing channels (Fig. 2C).

Debris-flow Traversal

Even during a high-magnitude storm, the potential for a debris flow to initiate from any particular location is small. Recurrence intervals for a single hill-slope site span hundreds to thousands of years (Reneau et al. 1990, Dunne 1991). However, recurrence intervals of debris flows through headwater channels may span tens to hundreds of years, depending on the number of potential sources (Benda and Dunne 1997, May and Gresswell 2004). This is because topography acts to route debris flows, just as it does water, into distinct corridors, and a single headwater channel may be fed by multiple debris-flow source areas.

To account for all potential upslope debris flows, we start with the probability that there are no debris flows, which for a single source pixel is given by $(1 - P_I P_D)$, multiplied over all potential upslope debris-flow source pixels,

$$P_{\text{no debris flow}} = \prod(1 - P_I P_D). \qquad (1)$$

This product gives the probability that none of the upslope source pixels produced a debris flow that ran out to a fish-bearing channel. The probability that a debris flow did occur, traversed the pixel, and ran out to a fish-bearing channel is designated as P_T, the probability of traversal, which is determined from

$$P_T = 1 - P_{\text{no debris flow}} = 1 - \prod(1 - P_I P_D). \qquad (2)$$

We calculate P_T for all DEM pixels in the study area. The empirical probability P_T calculated for a pixel translates directly to the potential for debris-flow delivery of material from the pixel to a fish-bearing channel (Fig. 2D). The debris-flow material is expected to include sediment and any entrained large wood.

Encompassing Different Percentages of Debris-flow Initiation Sites and Traversal Area

The delivery-weighted landslide density ($P_I P_D$) provides a relative ranking of the potential for initiating a debris flow that delivers to a fish-bearing channel. Its sum over any set of DEM pixels is the predicted number of debris flows initiated within those pixels that traveled to fish-bearing channels. By ranking pixels from the largest to smallest $P_I P_D$ values and summing, we determine the density values needed to encompass any specified percentage of the total number of predicted debris-flow initiation sites that delivered to fish-bearing channels (Fig. 3). We demonstrate the approach by delineating alternatives that encompass 25%, 50%, and 75% of the expected initiation sites that deliver debris flows to fish-bearing channels.

Similarly, the total number of pixels traversed by debris flows (that traveled to fish-bearing channels) is estimated by integrating P_T (Equation 2) over the area of interest, i.e., summing over all DEM pixels starting with the largest P_T values and progressing to the smallest. The sum overall pixels indicates the total number predicted to be traversed by debris flows that travel to fish-bearing channels. We used this cumulative sum to identify the threshold P_T value required to encompass any specified percentage of the pixels traversed by debris flows that reached fish-bearing channels (Fig. 3). As for initiation sites described above, we flag pixels with P_T values greater than or equal to the threshold. We demonstrate the approach by delineating three alternatives required to encompass 25%, 50%, and 75% of the pixels traversed by debris flows that deliver to fish-bearing channels.

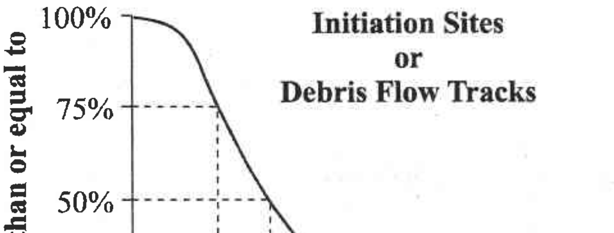

Figure 3. A sketch illustrating the threshold probabilities necessary to include different percentages of initiation or traversed pixels. Probabilities are of initiating ($P_I P_D$) a landslide that delivers to a fish-bearing channel or of being traversed (P_T) by a debris flow that delivers to a fish-bearing channel.

Extending Traversal Zones for Headwater Channels

A buffer was extended perpendicular to the traversal zone for DEM pixels that contained a nonfish-bearing channel. Extensions were approximately equal to one-half the height of a site-potential tree. A site-potential tree "is the average maximum height of the tallest dominant trees (200 years or older) for a give site class (USDA and USDI 1994)." This height is approximately 70 m for the study area (Johnson et al. 2007). The extensions are meant to incorporate adjacent hill-slope and streamside areas that may affect headwater channels (FEMAT 1993), for example, through delivery of large wood by processes other than debris flows (May and Gresswell 2003b, Hassan et al. 2005). Despite having some ecological basis, this distance was chosen merely to illustrate the effect of adding streamside buffers on the percent area in traversal zones. For identified pixels that did not contain a nonfish-bearing channel (i.e., those on unchannelized hill slopes), the traversal zone was not extended.

Evaluating Debris-flow Initiation and Traversal Alternatives

We evaluated alternatives using area as a surrogate to assess potential effects on outcomes with direct policy relevance. This is based on the assumption that the percent of landscape area managed as debris-flow initiation and traversal zones is likely to be negatively related to resource production metrics, such as timber-harvest volume, and positively related to aquatic and riparian conservation metrics, such as percent of streamside area in older forests.

The alternatives were evaluated across the entire central Oregon Coastal Province using three approaches. One evaluation compared the percent of the study area encompassed separately in initiation zones and in traversal zones, with and without 35-m extensions around nonfish-bearing channels. The second evaluation examined only one alternative but compared the percent area encompassed in initiation and extended traversal zones when summarized at different spatial extents (i.e., for USGS 5th-field (~200 km^2) and for 7th-field (~20 km^2) Hydrologic Units (HUs)). The third evaluation substituted each of the traversal alternatives for current riparian management zones along headwater channels. The percent area of each landownership class encompassed under current riparian polices and under each alternative was compared.

We approximated current riparian management zones for all stream classes by mapping buffers around channels on federal lands according to the widths for riparian reserves specified in the Northwest Forest Plan (USDA and USDI 1994) and on private lands according to widths specified in the Oregon Administrative Rules (OAR, Chap. 629, Div. 635-0310) (Table 1). The ODF provided a digital map of current riparian management zones on state lands. For private and state lands, traversal zones for small nonfish-bearing channels were added to the network of mapped

Table 1. **Horizontal distances from stream channels in which timber harvest is generally restricted under current policies**

	Width (m)					
	Fish-bearing channels			Nonfish-bearing channels		
Ownership	Small	Medium	Large	Small	Medium	Large
Private	15.0	21.0	30.5	0.0	15.0	21.0
Federal	137.0	137.0	137.0	68.5	68.5	68.5

These distances were approximated for federal lands according to the Northwest Forest Plan (USDA and USDI 1994) and for private lands according to the Oregon Administrative Rules (OAR Chap. 629, Div. 635-3010). Stream sizes correspond to those in the OAR (small < 0.06 m^3/sec mean annual flow; medium 0.06–0.28 m^3/sec; large > 0.28 m^3/sec) and were modeled based on drainage area and mean annual precipitation according to Lorensen et al. (1994). Small nonfish-bearing channels include intermittent, nonfish-bearing channels on federal lands.

buffers because the extended traversal zones were wider than currently prescribed riparian management zones. For federal lands, extended traversal zones were substituted for mapped riparian buffers on intermittent nonfish-bearing channels. Intermittent streams were identified on the modeled stream network as having a drainage area less than 0.07 km^2 based on an empirical cumulative distribution function of drainage area. The drainage areas corresponding to the upper limit of field-determined perennial flow for 123 streams in the Siuslaw National Forest were digitized from 1:12,000-scale aerial photographs (Ellis-Sugai 2003).

Results

Delineating Debris-flow Initiation and Traversal Alternatives

The sum of the delivery-weighted landslide density ($P_I P_D$) over all pixels was 4,032, which we interpret as the total number of debris flows predicted to travel to fish-bearing channels. The total area necessary to encompass all such debris-flow initiation sites was 3,096 km^2. From these totals, we calculated the percent of initiation sites and the percent area in initiation sites associated with each value of $P_I P_D$ (expressed as number of landslides$*$km^{-2}) (Fig. 4A). When these were plotted against each other, we determined that a large percentage of the initiation sites were captured in a relatively small percentage of the area (Fig. 4B). For example, only 10% of the area was required to encompass 40% of the initiation sites delivering to a fish-bearing channel. From Fig. 4A, we determined the threshold $P_I P_D$ values corresponding to the 25%, 50%, and 75% initiation alternatives (Table 2).

Integrating P_T from Equation 2 over the study area gives a total of 6,180 pixels predicted to be traversed by debris flows that travel to fish-bearing channels. This includes only debris flows that travel to fish-bearing channels and excludes any travel length within fish-bearing channels. The total area required to encompass all pixels with $P_T > 0$ was 3,786 km^2. These two values allowed us to calculate for each P_T value the percent of pixels traversed and the percent of area required to encompass these pixels (Fig. 4C). Plotting one against the other, we found that a relatively small percentage of the traversed area was necessary to contain the pixels with the largest traversal probabilities (Fig. 4D). From Fig. 4C, we determined the threshold P_T values corresponding to the three traversal alternatives (Table 3).

The alternatives were mapped for the Knowles Creek basin to illustrate the landscape distribution of initiation and traversal zones (Fig. 5). Pixels with $P_I P_D$ values exceeding the threshold were highlighted to delineate each initiation alternative (Fig. 5A). For the 25% alternative, these pixels tended to be in bedrock hollows aligned with the flow direction of the receiving channel ("trigger hollows," Benda and Cundy 1990) and hollows that fed directly into fish-bearing channels. In addition to these, the 50% and 75% alternatives included pixels with lower initiation probabilities and that were further away from fish-bearing channels.

The spatial arrangement of highlighted pixels differed also among the traversal alternatives (Fig. 5B). Pixels with P_T values exceeding the threshold for the 25% alternative fell almost entirely along small, headwater channels rather than on unchannelized hill slopes. This was true for the 50% alternative as well, but pixels with P_T values exceeding the threshold for this alternative expanded traversal zones further up headwater channels. Due to the relatively low P_T threshold in the 75% alternative, many pixels were included on unchannelized hill slopes.

In numerous cases, initiation zones and traversal zones, including the 35-m extensions around identified pixels in nonfish-bearing channels, were spatially coincident (Fig. 5A and B). The degree of overlap between the initiation and extended traversal zones increased from the 25% to the 75% alternative.

Evaluating Debris-flow Initiation and Traversal Alternatives

Pixels identified for the 25% initiation alternative ($P_I P_D > 4.6$ km^{-2}) occupied 2.5% of the study area (Table 2) and pixels identified in the analogous traversal alternative ($P_T > 5.8 * 10^{-3}$) occupied 0.2% of the study area (Table 3). Buffers of 35 m along nonfish bearing channels added 1.8% for a total of 2.0% of the study area in extended traversal zones for the 25% alternative (Table 3). Alternatives with lower threshold values required a greater percentage of the study area to encompass the pixels representing initiation and traversal zones (Tables 2 and 3).

Only half the area in initiation zones was not spatially coincident with area in extended traversal zones. The area of overlap between initiation zones and extended traversal zones was subtracted before calculating the total area encompassed by a combined initiation and traversal alternative. Consequently, the percentage of the study area encompassed when summing the area for the separate initiation and extended traversal zones (Tables 2 and 3) was greater

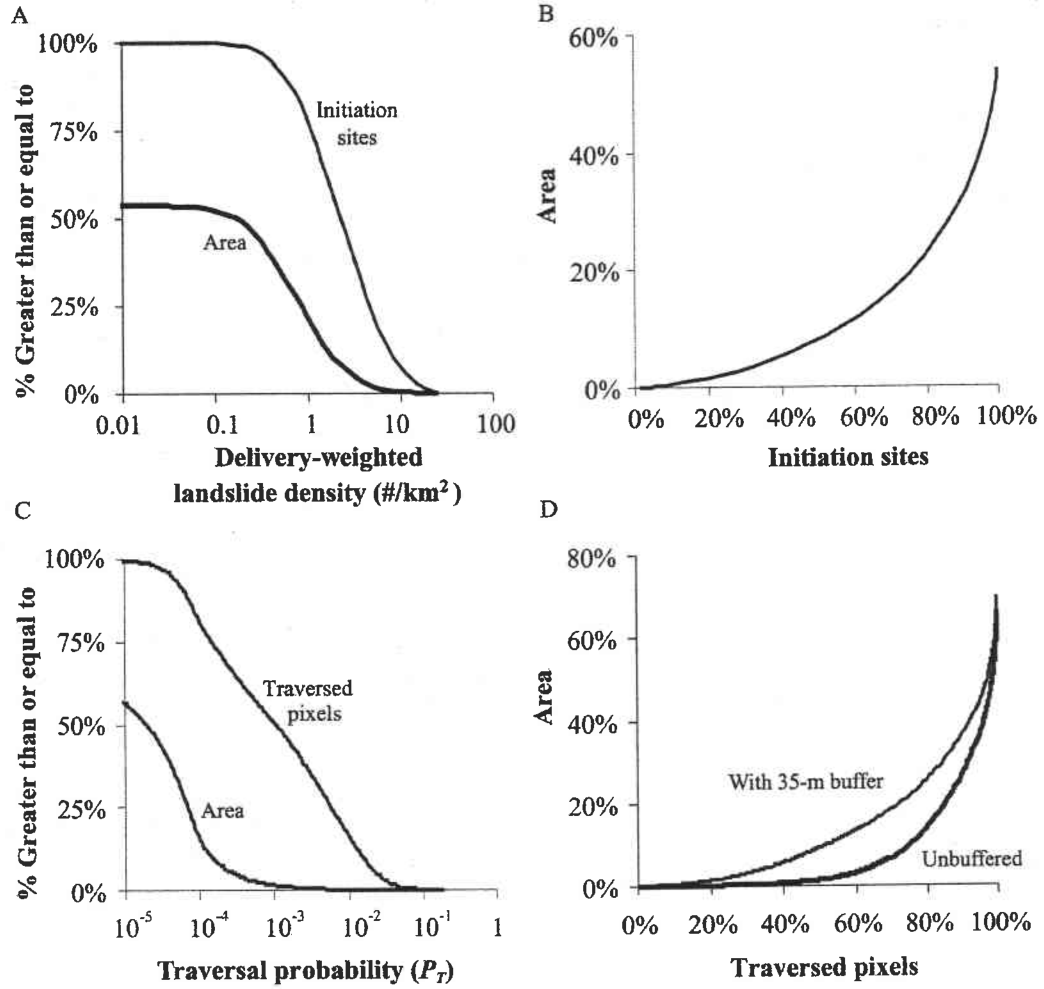

Figure 4. Modeled results for the study area in the central Oregon Coastal Province. (A) Cumulative distributions of landslides that delivered to a fish-bearing channel expressed as the percent of landslide initiation sites and the percent DEM area in landside initiation sites with a value greater than or equal to that on the horizontal axis. (B) Percent of DEM area in landslide initiation sites plotted against the percent of landslide initiation sites. (C) Cumulative distributions of the percent of pixels traversed by debris flows that delivered to fish-bearing channels and of the percent DEM area traversed with a value greater than or equal to that on the horizontal axis. (D) Percent of DEM area traversed plotted against the percent of pixels traversed with and without 35-m extensions around traversed pixels in nonfish-bearing channels.

Table 2. Results of delineating initiation alternatives for the study area

% Initiation sites	Threshold $P_I\ P_D$ (number/km²)	% Study area in initiation sites
25	4.6	2.5
50	2.3	8.1
75	1.1	19.0
100	$4.7*10^{-8}$	54.1

Alternatives were based on the modeled percent of debris flows that initiated and delivered to a fish-bearing channel. P_IP_D is the probability-weighted landslide density (number/km²). Areas with a probability-weighted landslide density exceeding the threshold P_IP_D are included in the percent of study area in initiation sites.

Table 3. Results of delineating traversal alternatives for the study area

% Area traversed by debris flows	Threshold P_T	% Study area in traversal zones	% Study area in extended traversal zones
25	$5.8*10^{-3}$	0.2	2.0
50	$1.1*10^{-3}$	1.4	9.1
75	$1.5*10^{-4}$	9.7	21.6
100	$2.21*10^{-17}$	66.1	69.9

Alternatives were based on the modeled percent of area traversed by debris flows that delivered to a fish-bearing channel. P_T is the probability of traversal for hill slopes and headwater channels. The percent of study area in traversal zones includes only pixels for hill slopes and nonfish-bearing channels identified with a probability of debris-flow traversal exceeding the threshold P_T. The percent of study area in extended traversal zones includes 35-m buffers on either side of traversed nonfish-bearing channels.

than that when combining the zones. Using the 75% alternative as an example, 40% of the study area was included in the sum of initiation and extended traversal zones (Tables 2 and 3), but only 30% of the study area was encompassed after subtracting the overlap and combining the zones.

The percent area occupied by initiation and extended traversal zones varied from basin to basin across the central Coastal Province. For the combined 75% alternative, the

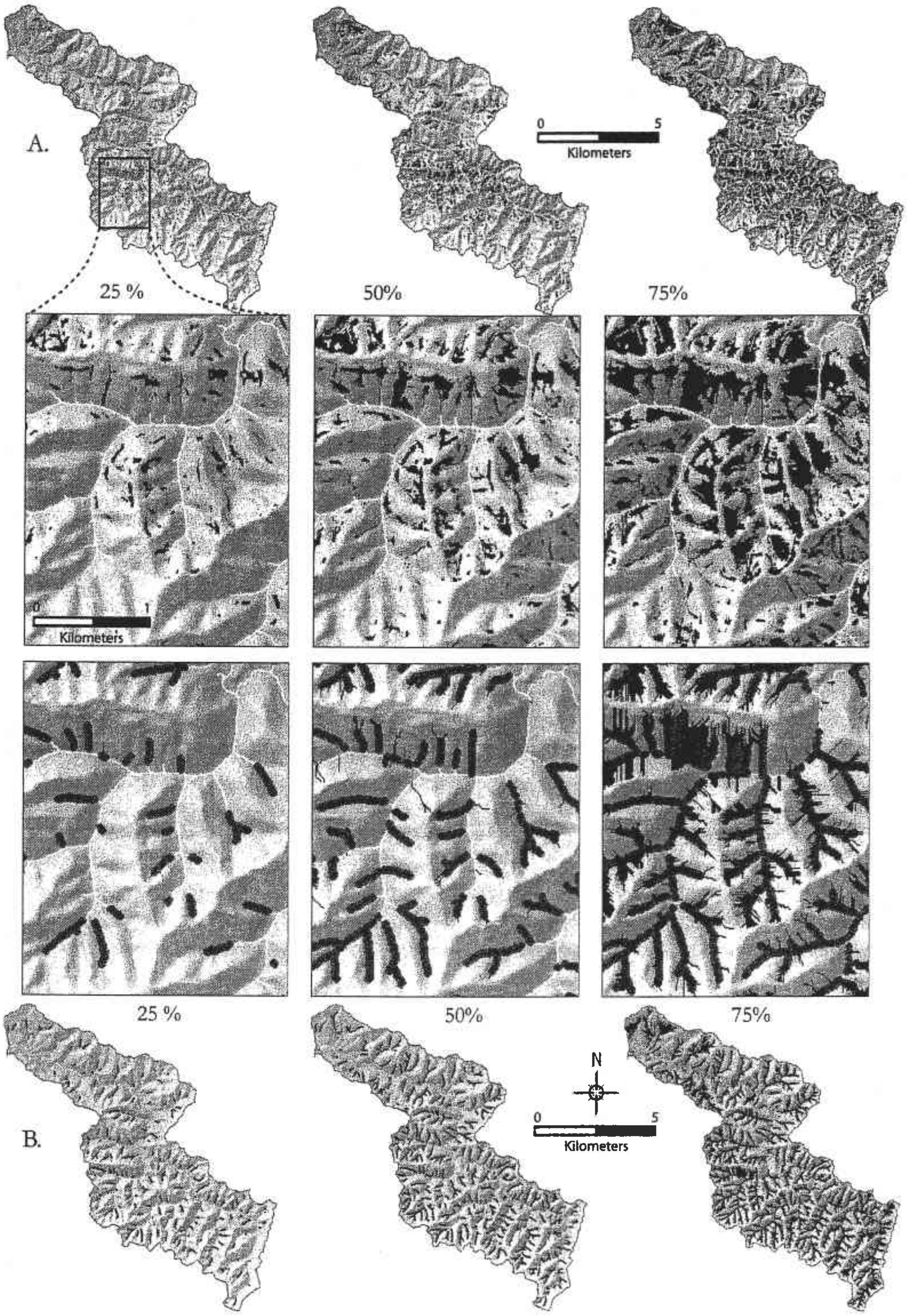

Figure 5. Initiation and traversal zones illustrated for the Knowles Creek basin. The modeled fish-bearing channel network is shown in white. (A) Initiation zones are in dark gray and include 25%, 50%, and 75% of initiation sites for landslides that delivered to fish-bearing channels. (B) Traversal zones are in black and include 25%, 50%, and 75% of pixels traversed by debris flows that delivered to fish-bearing channels. Gray polygons include 35-m extensions for traversal zones along all nonfish-bearing streams.

percent of basin area in initiation and extended traversal zones varied by a factor of three over 5th-field HUs and a factor of twenty-five over the smaller 7th-field HUs (Fig. 6).

To evaluate how land owners in the region might be affected, we compared the percent of each ownership class encompassed by riparian management zones prescribed under current policy (Table 1) and when just the zones for headwater channels were replaced by the 25%, 50%, and 75% alternatives (Fig. 7). Private, state, and federal lands are distributed heterogeneously across the study area (Fig.

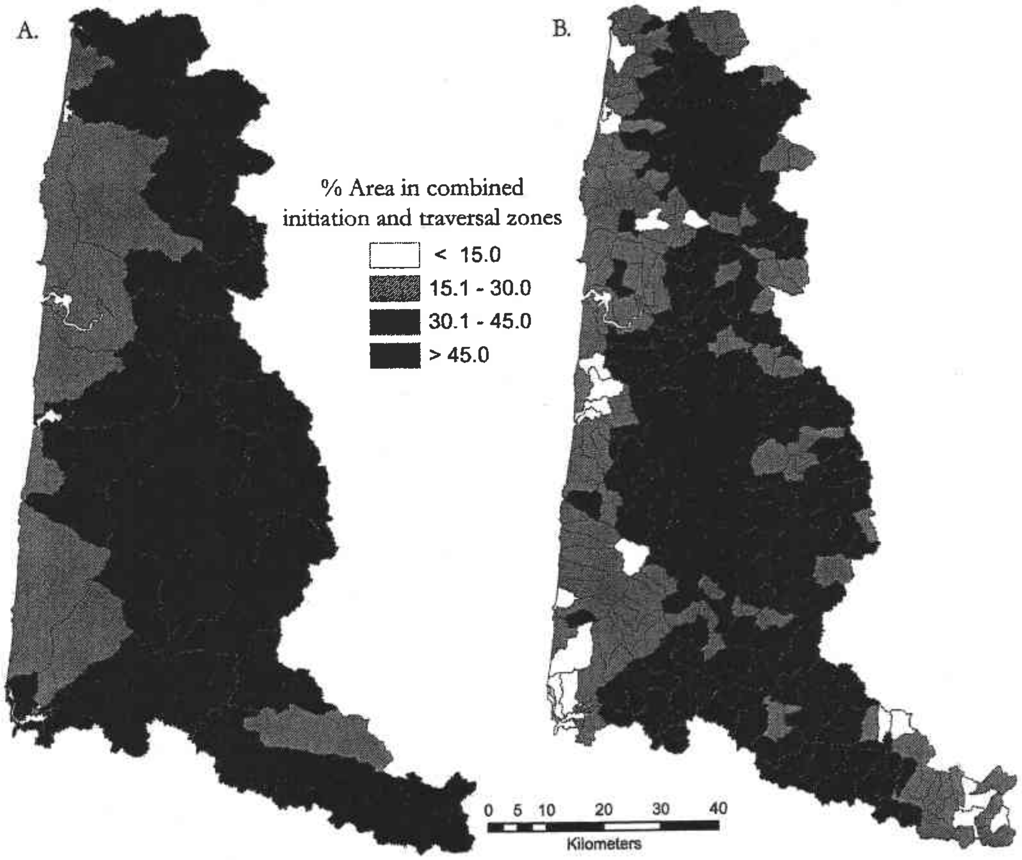

Figure 6. Spatial variation across the study area in the distribution of initiation and traversal zones for the combined 75% alternative. The percent of basin area encompassed by the alternative summarized by (A) 5th-field HUs and (B) in 7th-field HUs.

8A). For each alternative, a relatively small percentage of the area in each landownership class was occupied by initiation zones that were not included in extended traversal zones (Fig. 8B). On private and state lands, the percent area encompassed by current riparian management zones was less than that encompassed by extended traversal zones in each of the three alternatives (Fig. 8C). The opposite was true for federal lands; the percent area was greater in current riparian management zones. The absolute increase in percent area over current policy for private lands was less than 2% in the 25% alternative but ranged from 9% (private nonindustrial) to 19% (private industrial) in the 75% alternative.

Discussion

Delineating Debris-flow Initiation and Traversal Alternatives

Using readily available digital elevation data, we were able to delineate alternative management zones for hill slopes and headwater channels across a large area. We identified locations likely to initiate or be traversed by debris flows that deliver to a fish-bearing channel and estimated associated probabilities of debris-flow initiation and traversal. For example, both hillslopes and headwater channels may be traversed by debris flows. However, modeled traversal probabilities for headwaters channels were orders of magnitude greater than those for adjacent hillslopes due to convergent topography that directs debris flows into low-order channels. Once identified, the likely initiation and traversal locations were ranked based on the separate probabilities of initiating and of being traversed by debris flows.

The rankings allow hill slopes and headwater channels inferred from a DEM to be prioritized as potential sources of debris-flow transported sediment and wood to fish-bearing channels and to be better considered within the context of overall forest management goals. It is important to recognize that many of the potential debris-flow initiation and traversal locations could be captured in relatively little area (Fig. 4B and D). Thus, locations with the highest probabilities can be effectively managed by concentrating on a relatively small percentage of the landscape (Tables 2 and 3). Alternatives designed to include larger percentages of the debris-flow initiation and traversal locations will encompass lower probabilities and more area. Such alternatives may be most consistent with forest management goals that emphasize ecological objectives. In contrast, alternatives targeting higher probabilities of debris-flow initiation and traversal appear more consistent with forest management goals that emphasize timber production. It may be neither practical nor desirable to apply a single alternative

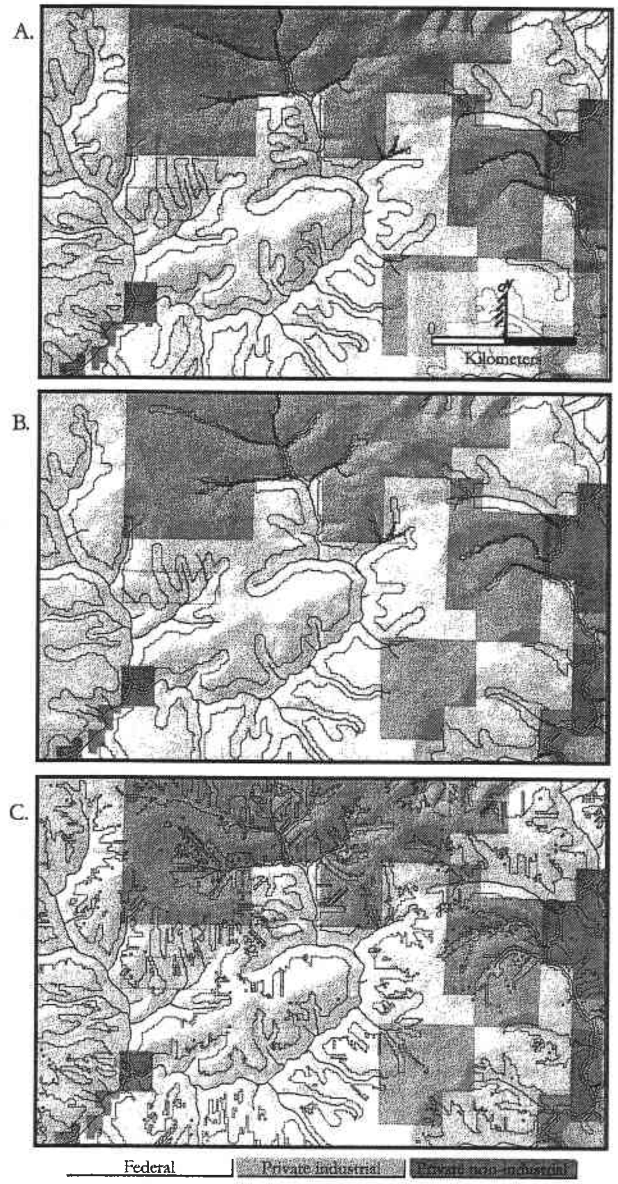

Figure 7. Riparian management zones under current policy and traversal alternatives illustrated for an area in the Oregon Coastal Province. (A) Riparian management zones mapped by landownership class. (B) Current riparian management zones along all fish-bearing channels plus traversal zones that include 25% of traversed pixels, with 35-m extensions along all included channels. (C) Same as B, but with traversal zones defined to include 75% of the traversed pixels.

over an area as large as the central Coastal Province given complex patterns of ownership. Instead applying a range of alternatives may better achieve regional forest-management goals.

Although we combined alternatives at each level, initiation and traversal alternatives could be implemented independently or in different combinations (e.g., 50% traversal and 25% initiation). These would be determined in accordance with debris-flow related management objectives and easily encompass percentages of initiation or traversal zones that differ from those we examined (e.g., 30% traversal and 10% initiation). Debris flows can be important sources of large wood (May and Gresswell 2003b, Hassan et al. 2005), which is a fundamental component of habitat complexity for salmonids and other aquatic organisms (Bilby and Bisson 1998, Gregory et al. 2003). Consequently, if maintaining and restoring sources of large wood for fish-bearing channels is a key management objective, then protecting forests adjacent to some percentage of headwater traversal zones is a defensible priority in debris-flow-prone terrain. If management objectives also include maintaining or restoring other components of the debris-flow regime, such as frequency and magnitude of occurrence, then adding initiation zones to forest protection strategies is prudent. Our results for each alternative indicated that approximately half of the initiation zones were subsumed in extended traversal zones. Because of this overlap, protecting streamside forests along traversal zones will also affect aspects of the disturbance regime related to debris-flow initiation.

Evaluating Debris-flow Initiation and Traversal Alternatives

We compared alternatives using the percent landscape area encompassed, but evaluations could include metrics with more direct policy relevance. Timber-harvest volumes, riparian-forest conditions, landslide rates, large-wood delivery, and debris-flow impacts are all likely to vary with the landscape area in riparian management zones. A variety of tools are available to estimate implications for such metrics over broad temporal and spatial extents. For example, landscape simulation models of forest dynamics (e.g., Hulse et al. 2004, Johnson et al. 2007) could incorporate delineated initiation and traversal alternatives to estimate timber-harvest volumes and forest-cover conditions over time under diverse management prescriptions. Modeled forest-cover types would then become inputs for estimating a variety of other metrics, including wildlife habitat (McComb et al. 2002, Schumaker et al. 2004, Spies et al. 2007) or rates of wood recruitment to streams (Beechie et al. 2000, Bragg 2000, USDA Forest Service 2003). Thus, managers are not limited to evaluating the policy implications of alternatives with percent area as a surrogate for other metrics.

Variation we observed among 5th- and 7th-field HUs for the percent area in combined initiation and extended traversal zones reflected underlying topography and may present implementation hurdles. The percent area encompassed by the 75% alternative varied due to differences across the study area in topographic factors such as slope steepness and convergence that can affect probabilities of debris-flow initiation and delivery (e.g., Benda and Cundy 1990, Dunne 1998, Dietrich et al. 2001). This variation was much greater among finer-scale (7th-field) than coarser-scale (5th-field) HUs. Given the above considerations, impacts of a given alternative may differ among forestland owners depending on where their property is located and how much property they own. Economic impacts are likely to be greatest for landowners with small holdings in unstable terrain. Thus, challenges related to regulatory equity may arise in applying this or any other approach that distinguishes among headwater channels.

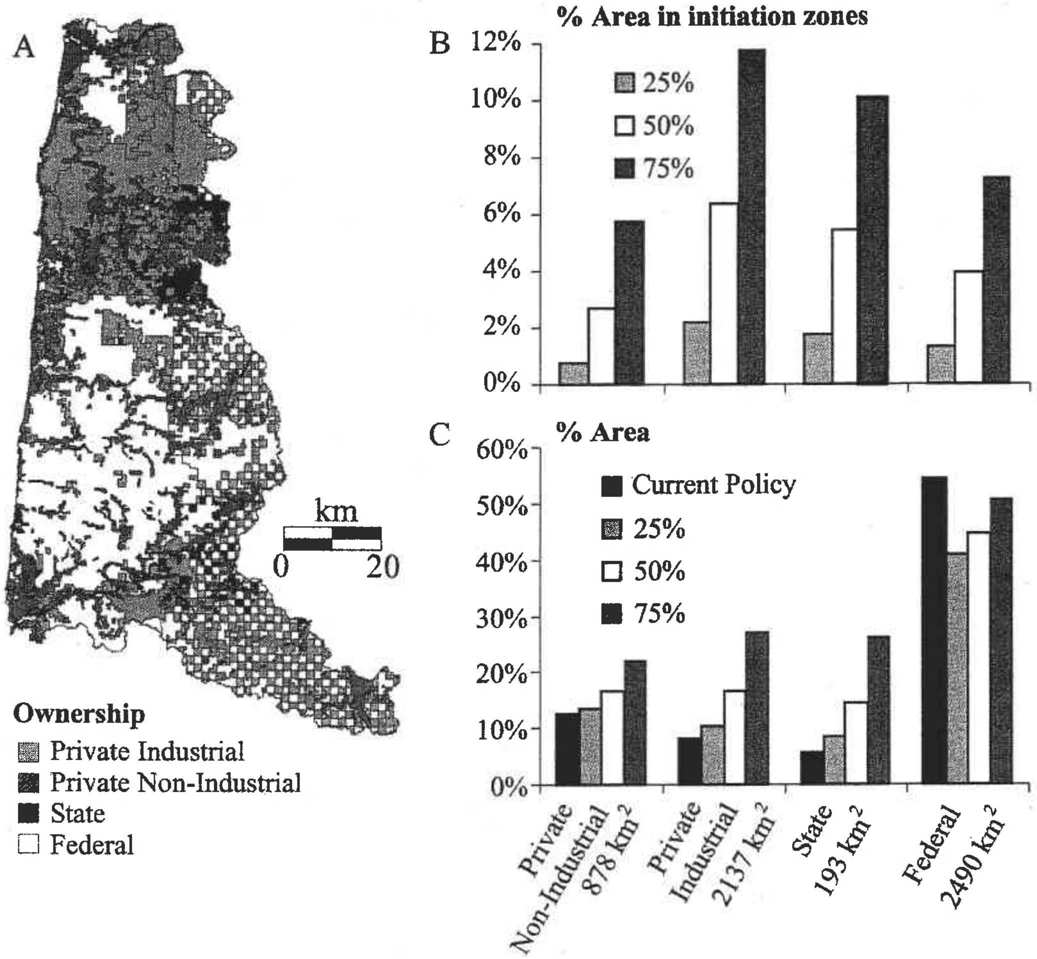

Figure 8. Distribution of landownership and percent of each ownership class encompassed by alternatives. (A) Map of landownership in the study area. (B) Histogram of the percent area in initiation zones (not encompassed by traversal zones) for each ownership class under the 25%, 50%, and 75% alternatives. (C) Histogram by ownership class (total area in each class is provided) of the percent area encompassed in current riparian management zones and the percent area encompassed when current riparian management zones along headwater channels are replaced by traversal zones under the 25%, 50%, and 75% alternatives.

Landownership

The percent area encompassed under the three alternatives varied among landownership classes due to differences in current policy and topography. For private lands, the area encompassed in current riparian management zones was less than that encompassed after adding to these the initiation and extended traversal zones under each alternative (Fig. 8B and C). This is because riparian management zones were mapped on private lands to reflect current policies that generally do not prohibit logging along small nonfish-bearing channels (OAR, Chap. 629, Div. 640) or for landslide-associated concerns beyond public safety (OAR, Chap. 629, Div. 623). The small increase (< 4%) on private lands for the combined 25% alternative indicated that little area beyond current riparian management zones would be necessary to protect locations most likely to initiate or be traversed by debris flows. Private nonindustrial lands in the Oregon Coastal Province tend to be lower gradient (Burnett et al. 2007), with lower initiation and traversal probabilities, than private industrial lands. This helps explain the smaller increase (18% versus 31%) over current policy on nonindustrial lands for the combined 75% alternative (Fig. 8B and C). The large area required to protect locations with lower probabilities may be untenable for private lands, particularly industrial lands that emphasize timber production objectives within environmental constraints (Johnson et al. 2007).

The large percentage of area in mapped riparian management zones under current policy on federal lands (Fig. 8) stems from an emphasis on ecological objectives (USDA and USDI 1994, Johnson et al. 2007). Accordingly, timber harvest for other than aquatic conservation objectives is prohibited along all nonfish-bearing channels, in part to protect unstable areas (FEMAT 1993, USDA and USDI 1994). Slight decreases in percent area between current policy and the traversal alternatives were estimated for federal lands. This was partially a consequence of our decision to substitute extended traversal zones for mapped riparian management zones on only intermittent, and not on all small, nonfish-bearing channels. The decision was motivated by the fact that intermittent channels are the only portion of the nonfish-bearing network differentiated in federal policy. Extended traversal zones could be substituted for mapped riparian management zones along more of the nonfish-bearing network. This would increase the area available for timber production but could conflict with other ecological objectives associated with these channels.

For the sake of simplicity, we demonstrated the approach by extending traversal zones a fixed distance (35 m) from headwater channels. We recognize that the costs and benefits of riparian management zones can vary with their width (Ice et al. 2006). Therefore, it would be informative to vary the distance of extensions from headwater channels when delineating and evaluating traversal zones. Results could help policy makers craft strategies for headwater channels by landownership class that strike the desired balance among the social, economic, and ecological goals for forest management.

Limitations and Applications

Accuracies of model outputs that were the basis for delineating initiation and traversal zones were limited by the 10-m resolution of the DEMs. These outputs should, however, be sufficiently accurate for delineating the alternatives, given that our intent was to consider riparian policies over broad spatial extents rather than to guide site-level riparian planning. The alternatives may inform such fine-scale planning but will likely contribute most in evaluating policies that target different probabilities of debris-flow initiation and traversal at basin (e.g., 4th-field HU) to regional scales.

Although landslide densities (Robison et al. 1999, Miller and Burnett 2007) and travel distances (May 2002, Ishikawa et al. 2003, Lancaster et al. 2003) may vary with forest cover or amount of entrained wood, we did not account for vegetation influences in our analysis. Modeling initiation and traversal probabilities under a uniformly unforested condition removed confounding effects of forest cover and allowed us to focus on spatial variability in topographic controls. Results, therefore, better reflect inherent susceptibilities of the landscape to debris-flow initiation and traversal. If desired in future applications, topographically derived probabilities could be modified by forest-cover type. The empirical debris-flow models were calibrated to forest cover and so can account for this as well as topography when estimating probabilities (Miller and Burnett 2007, Miller and Burnett in review).

The gradient-based method we used for identifying fish-bearing channels undoubtedly generated local errors. However, the method should have minimally affected the accuracy and interpretation of results over the spatial extents examined. Therefore, it provided an efficient means for demonstrating our approach. Prior to site-specific actions, land managers typically have fish use validated through field surveys. Where the fish-bearing channel network has been delineated from field surveys, the maps can be substituted for the gradient-based criteria. The debris-flow models are adaptable and can be implemented to address debris-flow delivery for any user-specified channel network (Miller and Burnett in review).

Conclusions

Our intent with this article was not to advocate for any particular headwater protection alternative. Rather, we wanted to demonstrate how knowledge about differences among headwater channels over broad spatial extents can help inform policy. We developed methods for delineating alternative streamside management zones in a forested, montane region based on estimating and ranking probabilities of initiating and of being traversed by a debris flow. This is a first, but important, step in illustrating how streamside protection may be tailored through considering the role of headwater channels in stream ecosystems across a landscape. Headwater channels and adjacent forests have importance in processes other than debris flows and in a variety of functions, including temperature regulation, nutrient filtration, and bank stabilization (Moore and Richardson 2003; this volume 2007). Consequently, we expect that policy makers will consider the full suite of processes and functions in any local or regional decision to modify extant riparian management zones.

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