Alex D. Foster[1], USDA Forest Service, PNW Research Station, 3625 93rd Avenue SW, Olympia, Washington 98512

and

Joan Ziegltrum, 8310 Lynch Road SE, Shelton, Washington 98584

Riparian-associated Gastropods in Western Washington: Community Composition and the Effects of Forest Management

Abstract

We evaluated the abundance of riparian gastropod communities along headwater streams and their response to logging in southwestern Washington State. Terrestrial mollusks near logged streams with ~15 m fixed-width buffers were compared to logged streams with no buffers and to unlogged controls. Mollusk communities varied among sites relative to vegetative composition, the amount of understory cover and presence of seeps or small wetland features in the riparian areas. After logging, slug and snail abundance were significantly different between streams with no buffers compared to fixed-width buffers and control streams, however the effect size was relatively small suggesting site variability may override the effects of logging. Our findings illustrate that site variability can affect mollusk community structure and influence taxa resiliency to disturbances such as logging.

Key words: buffer, logging, thinning, retention, mollusk

Introduction

Riparian areas along headwater streams can make up 75-80% of the total area of a given watershed (Gomi et al. 2002) and thus constitute a significant portion of the forested land-base in the Pacific Northwest. Natural disturbance processes affecting these areas are typically low-frequency events such as floods, landslides and forest fires (Benda et al. 2004). However, given the large amount of forested land these riparian areas represent, logging is typically a common disturbance mechanism. Protection standards for riparian areas have been adopted by state, federal, and provincial governments in the region, and most regulations require that a "buffer" (unharvested corridor of trees and vegetation) be left along the stream channel during timber harvest (Richardson et al. 2012). A buffer is typically required along small headwater streams on federal lands (USDA, USDI 2001), however it is usually not required on non-fish-bearing perennial and ephemeral headwater streams on state and private lands in western Washington (WADNR 2006). Headwater streams, typically first and second-order channels, are characterized by both physical and biological processes requiring special consideration in forest management (Olson et al. 2007, Richardson and Danehy 2007). For example, headwater riparian areas have unique vegetative communities (Sheridan and Spies 2005), and provide habitats for endemic and sometimes rare terrestrial mollusks.

Terrestrial mollusks are a relatively unstudied group of potential biological indicators for use in evaluating on-site logging effects. For instance, mollusks have little dispersal capacity, with many species having a range of just a few square meters (Baur 1986, Giokas and Mylonas 2004); however, passive dispersal systems over long distances by birds, for example, have been documented (Baur and Baur 1995, Gittenberger 2012). Several factors can influence mollusks locally, including physical site characteristics such as aspect, vegetation and proximity of surface waters such as streams, seeps, and small wetlands. For example, southwest-facing oak [*Quercus spp.*] forests in central Europe have lower mollusk abundance and

[1]Author to whom correspondence should be addressed: Email: alexfoster@fs.fed.us

taxa richness than northeast-facing beech [*Fagus spp.*] forests (Kappes et al. 2006). The distance from a stream related to microclimate gradients influenced the abundance of three common snail species in the Cascade Range of western Oregon (Rykken et al. 2007b). At larger spatial scales, landscape patterns such as the juxtaposition of forest and agricultural land can influence mollusk abundance and richness, and thus populations are not only dependent on site and microhabitat factors (Gotmark et al. 2008).

In summary, little is known about the biology, distribution and habitat requirements of endemic mollusks in the Pacific Northwest. Additionally, local and regional mollusk species identification guides provide morphological characteristics for identification purposes and also describe preferred habitats (Kelley et al. 1999, Forsyth 2004, Burke 2013), although habitat accounts are often anecdotal or based on the modest amount of research done on related taxa, some of which do not occur in the Pacific Northwest. This is problematic because several species with unknown distributions, populations and tolerances to disturbance are being considered for protection under the federal Endangered Species Act (USFWS 2011).

In the few studies that specifically tested terrestrial mollusk response to logging, some suggested that mollusk communities were responsive to change, while others were not conclusive. For example, in variable-retention forest management plots in British Columbia, some taxa were suppressed after timber harvest, but others showed little difference compared to pre-harvest conditions (Ovaska and Sopuck 2010). Herbicide and mechanical conifer release effects on mollusks in spruce plantations in Ontario, Canada showed that immediately after treatments, mollusk densities remained unchanged or increased (Hawkins et al. 1997) but decreased 50-60% two and three years after treatments (Prezio et al. 1999). The difference cited may have been a result of decreased deciduous litterfall and changes in microclimate due to loss of vegetative ground cover in the treated areas. Reduced mollusk density and species richness after clear-cutting, forest fires and agricultural practices were short-lived in New Hampshire and Maine forests related to the rapid recovery of the vegetation (Strayer et al. 1986). In boreal forests of Sweden, streamside buffers reduced effects of clear-cut logging on snails compared to sites with no buffers, and where soil moisture levels were high, land snails were not affected by clear-cutting (Hylander et al. 2004). In comparing burned areas to clear-cuts in Sweden, the burned areas had depleted mollusk fauna, while clear-cuts showed no difference from adjacent forests (Hylander 2011). Finally, in German broadleaf forests, there was a direct relationship between downed wood accumulation, stand age, and slug density (Kappes 2006). The study suggested that slug communities were relatively unaffected by forest management with longer rotation periods, and when unmanaged patches or islands that enhance habitat heterogeneity were retained. A common theme amongst forestry effect studies was that site characteristics had a strong influence on mollusk communities thus influencing the effects of forest management disturbances.

Little is known about endemic mollusks in the Pacific Northwest, but because they are strongly associated with moist environments and may be sensitive to environmental change associated with tree harvest, we investigated the effects of logging on mollusk abundance in headwater riparian areas. We first identified the various mollusks that were present and investigated how these communities differed across our study sites. Second, we addressed three questions that helped us understand the factors that may have influenced the mollusk communities: (1) was there a difference between fall and spring abundance of the mollusks? We chose to investigate seasonality based on mollusk affinities to humid conditions that can vary widely between seasons, plus we could find very little information about seasonality in the literature. (2) How did environmental conditions influence the mollusk communities; and lastly, (3) what were the impacts of forest management on mollusk abundance? This exploratory analysis highlights possible relationships between mollusk abundance, local environmental conditions and logging disturbance.

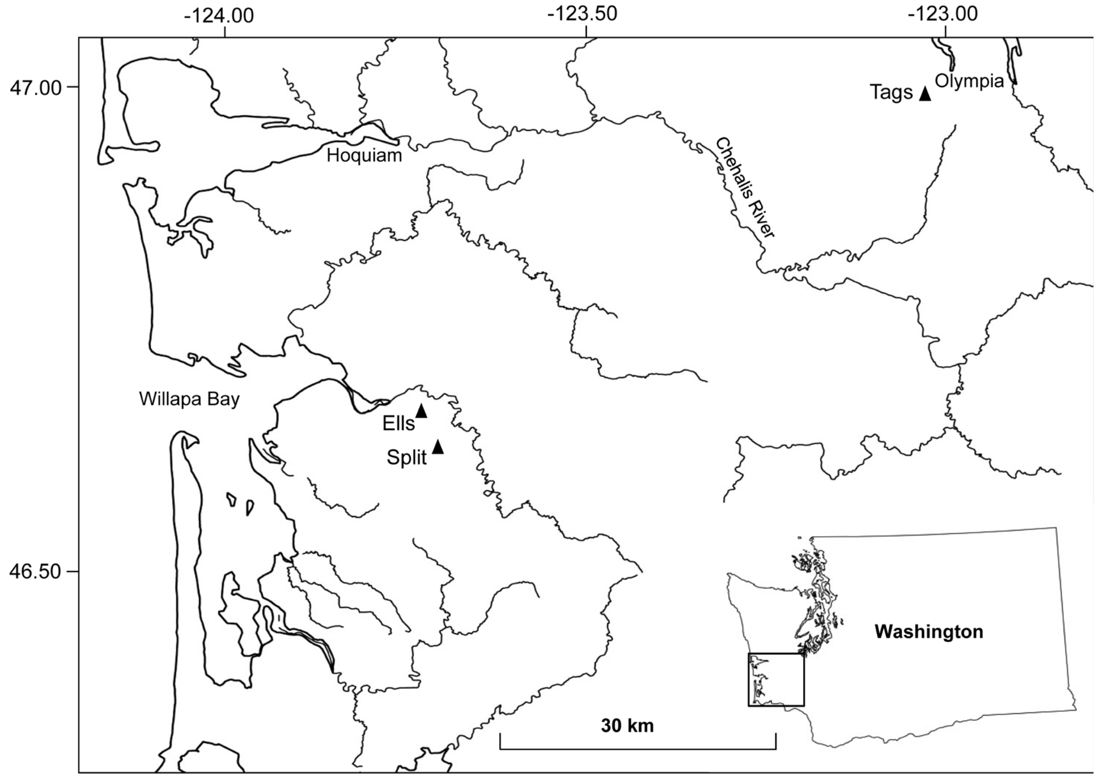

Figure 1. Study site locations in southwest Washington State, USA; adapted from Foster and Claeson (2011).

Methods

Study Area

The research was conducted at three sites (Tags, Split and Ells) in southwest Washington (Figure 1). All sites were in managed forests administered by the Washington Department of Natural Resources and were part of a larger integrated study that examined both physical and biological aspects of different riparian buffer configurations along headwater streams from 2002 through 2006 (Bisson et al. 2013). The experiment compared riparian mollusks in three different experimental conditions including (1) a continuous, fixed-width buffer approximately 15 m wide on each side of the stream; (2) a clear-cut with no buffers, but with heavy equipment exclusion 15 m from the channels, and (3) unlogged controls that were at least 30 m from adjacent logging (Figure 2).

The Tags site was located in the Black Hills of Thurston County (46.99°N, 123.10°W, NAD 1983), approximately 15 km west of the city of Olympia, Washington. The other two sites, Split (46.58°N, 123.69°W) and Ells (46.64°N, 123.71°W) were located in the Willapa Hills of Pacific County about 17 km from the Pacific coastline. All sites share a maritime climate where the average annual precipitation is approximately 125 cm, reaching its peak in November and low in August.

Study streams at the Tags site were parallel to each other on a northeasterly aspect with stream gradients averaging 40%. The riparian forests were second-growth, mixed-conifer stands of Douglas-fir [*Pseudotsuga menziesii*] and western hemlock [*Tsuga heterophylla*]. The overstory tree age was about 50 years old. The dense understory was composed of deciduous tree species including red alder [*Alnus rubra*], black cottonwood [*Populus trichocarpa*], and vine maple [*Acer circinatum*]. The woody shrub devil's club [*Oplopanax horridus*] and swordfern [*Polystichum munitum*] were the dominant ground covers.

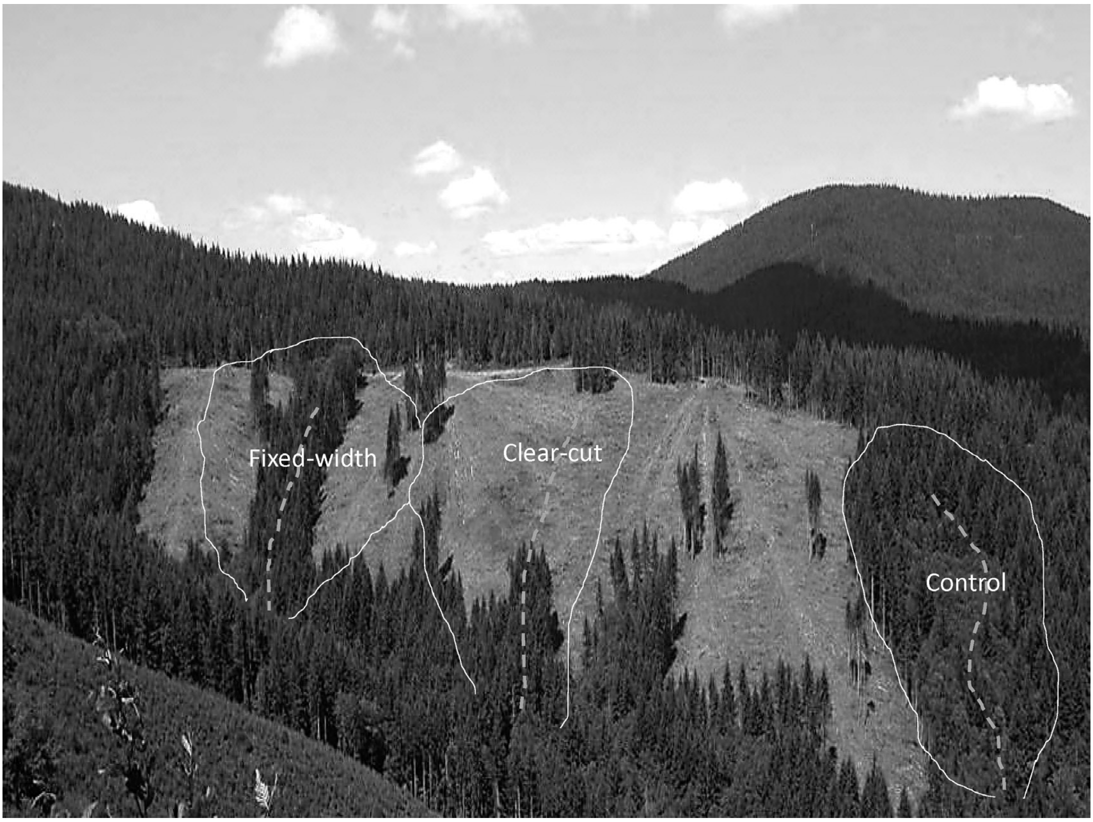

Figure 2. Typical site layout after logging showing buffer configurations on headwater streams. Catchments ranged from 3 to 6 ha in size. Courtesy of Randy Wilk.

The Split site was located on undulating topography with a stream gradient of 6–10%. Forests were even-aged, 45 year-old western hemlock. There was little understory vegetation in the riparian areas. In contrast, streams at the Ells study site were somewhat parallel to each other on a southwesterly aspect, with stream gradient averaging 5%. The dominant trees were 60 year-old Douglas-fir intermixed with western hemlock and Sitka spruce [*Picea sitchensis*]. A much younger understory tree layer was comprised of western hemlock with sporadic patches of swordfern as the dominate ground cover.

Overall, the watersheds were very small (range 3-6 ha) so that timber sales covered the entire area of a site, and control watersheds were always located adjacent to the site (Figure 2). All study streams were first-order (Strahler 1952), and although most had perennial flow, some would cease surface flow for short periods in late summer. Buffered or unbuffered streams were randomly assigned and logged simultaneously. None of the sites where mollusks were sampled received any post-logging slash or understory brush removal treatments.

We measured various environmental factors as potential explanatory variables for mollusk abundance and community composition (Table 1). Air and soil temperatures (°C) were measured with a pocket thermometer for each stream at 1 m above and 15 cm below ground, respectively, at the start and end of each day's survey. We acquired precipitation data from the National Climate Data Center weather stations closest to each sample site ('Hoquiam' ~40 km from the Split and Ells sites, 'Olympia' ~16 km from Tags) to calculate the precipitation totals for 7 days prior to each survey day (NCDC 2012). The data are thus specific to sample times and sites, but not to individual streams. Once per stream, we measured the percent area occupied by small

TABLE 1. Environmental variables describing site characteristics. The ranges of values, minimum-maximum, are from the streams within each site. For variables that change over time (temperatures, precipitation, canopy and downed wood), individual stream values were averaged over the study period; please see the methods section for additional information.

Environmental variable	Split	Ells	Tags
Elevation (m)	222–342	45–76	239–279
Slope (%)	21–27	14–18	38–46
Precipitation (cm, 7-days)	1.5–1.9	1.7–2.3	1.9–3.0
Aspect	NE	SW	NE
Wetland (% area)	0–10	0–2	13–30
Canopy (% cover)	7.7–76.2	0.2–76.2	4.6–76.8
Hardwood (% cover)	0 - 1.4	0.1–2.4	12.6–31.6
Fern (% cover)	6.0–16.9	22.5–33.3	22.8–79.7
Downed wood (m^3/ha)	246–390	125–776	207–313
Shrub (% cover)	2.8–6.2	3.3–22.5	5.3–24.2
Herb (% cover)	12.6–33.0	3.1–28.3	5.5–31.0
Lithology	sandstone	sandstone	basalt

wetland features (% wetland) within a 10 m band on each side of the stream channel by surveying hydrophytic and wetland-obligate plant species along with soils and surface hydrology using a locally adapted method for small, forested wetland delineation (Janisch et al. 2011). For each stream, once per year during the summer, we measured understory vegetation cover, overstory canopy cover and downed wood volume within 12 m on each side of the channel (Ricklefs 2009). We estimated understory vegetation cover (%) from 24 plots (3 x 3 m each) per stream with species grouped into five categories: 1) herbs, 2) ferns, 3) woody shrubs, 4) small hardwoods <10 cm diameter, and 5) small conifers <10 cm diameter. Overstory canopy cover (%) was estimated from hemispherical photographs with a 20% filter around the periphery of the aperture to block out topographical variation. Downed wood volume (m^3/ha) was estimated using three L-shaped transects, with each leg of the L being 10 m long. Wood pieces measured had a diameter ≥10 cm and a length ≥ 0.3 m, and wood volume was calculated using the Van Wagner (1968) method.

Mollusk Sampling

Pre-treatment sampling of the Tags and Split sites commenced in fall 2002; logging took place in spring of 2004. The Ells site was first sampled in spring 2004, one year before it was logged, thus before and after logging replicates differed amongst sites. All study sites were sampled until fall 2006. Sampling was limited to spring and fall, because snow sometimes hindered access to sites in winter, and because mollusks were usually less active during the summer aestivation period (Forsyth 2004). Two sub-season surveys were conducted within each season, one month apart, to address possible effects attributed to atypical weather patterns. Sampling took place at fixed sampling stations established prior to initiation of the study. Two transects were established parallel to stream channels, each with five sample stations lettered consecutively. The five stations were spaced 25 m apart on each side of the channel. To adjust for micro-habitat differences in the riparian area, stations were alternately placed 2 m and 5 m from the stream's edge. Each sampling station consisted of four artificial cover objects (Boag 1982) placed about 1 m from each other. A cover object was a 30 cm x 30 cm square consisting of two corrugated cardboard sheets, stapled to a flat piece of cardboard for rigidity, and held to the ground with a small wooden stake. In addition to mollusks, the cardboard provided a good sample medium for other forest floor organisms such as millipedes which were evaluated in a separate analysis (Foster and Claeson 2011).

The artificial cover objects were placed approximately one month before being sampled, so they could become thoroughly moist and mollusks would occupy spaces within the corrugations and underneath the cover object. When sampled, the layers of cardboard were peeled back in situ and the mollusks viewed under magnification with a flashlight to reduce misidentifications. Sampling was done primarily during the day in low-light conditions under closed forest canopies when the weather, especially in the fall, was mostly overcast and raining. During the first survey of each season, the mollusks were removed from the cover objects after being tallied by brushing them to the ground away from where the cover object had been placed. The cleaned cover objects were then repositioned in the same location on the ground to be reoccupied prior to the second survey 30 days hence. Voucher specimens were collected early in the study to confirm identifications.

Cardboard cover objects can be an efficient means of collecting small terrestrial mollusks and this method often detects species that samples of forest soil and litter frequently miss (Strayer et al. 1986; Hawkins et al. 1997; Ovaska and Sopuck 2010); however artificial habitats are known to exhibit sampling bias (Boag 1982, 1990; McCoy 1999). To evaluate whether the cardboard was providing a fair example of the snail community, we collected 73 forest floor samples (one liter loosely packed) at random cardboard sample stations across all three sites. The forest floor samples were air dried, sieved and sorted, and snail identities were determined from snail shell features. We then compared the findings to the cardboard sample stations where the forest floor samples were collected.

Statistical Analyses

Mollusk species were assembled into family or sub-family groups because many of the minute snails were difficult to identify accurately to lower taxonomic levels in the field under low-light conditions. Slugs however could be readily identified to species, but were grouped by sub-family for analysis consistency across all mollusk groups. Rare species were also put into their appropriate groups. We combined the minute and morphologically similar snail families Punctidae and Valloniidae to minimize misidentifications between them. The two sub-season surveys of 40 cardboard sample stations each were combined for an average abundance count per season consisting of 80 cardboard sample stations per buffer treatment observation.

Environmental covariates and community aspects were evaluated using nonmetric multidimensional scaling (NMS) with a Sorenson (Bray-Curtis) distance measure due to the heterogeneity of our data (McCune and Grace 2002; PC-ORD® v.5.21). Asymmetry amongst species group mean abundances was first standardized using a $\log_{10}(x+1)$ transformation (Legendre and Birks 2012) to form a matrix of ten species groups and 77 sample points (77 stream riparian area observations over 5 years); a second matrix consisting of the environmental variables was constructed for the ordination. Two hundred fifty runs were performed for the ordination, and the run with the lowest stress (14.0) and a stability criterion of (0.000001) was selected. In addition, differences in mollusk abundance were compared using multi-response permutation procedures (MRPP) to test the hypothesis of no difference before vs. after logging between buffer treatments (McCune and Grace 2002). Like the ordination, a Sorenson measure was used and the chosen *P*-value (0.05) was Bonferroni corrected ($\alpha = 0.02$) for the three pairwise buffer comparisons made in the before and after logging periods.

Results

Mollusk Communities—Site Differences

Over the entire study, we counted 6221 mollusks categorized into ten species groups (Table 2). Overall, snails made up 93% of the total detections, while slugs were only 7% of the mollusk community. In general, snails were more abundant in the fall than spring, while slugs tended to be more plentiful in the spring. For the slugs [*Zacoleus leonardi*] was the only species of the Zacoleinae group and was common at all sites in both fall

TABLE 2. Mollusk species group abundance by site and season. Species listed in each group were confirmed by voucher identification. Common names are in parenthesis.

Species Group	Site	Fall	Spring
Slugs			
Anadeninae—*Prophysaon foliolatum, P. dubium, P. vanattae, P. coeruleum, P. andersoni*	Tags	23	18
(taildropper slugs)	Split	21	29
	Ells	4	3
Ariolimacinae—*Ariolimax columbianus*	Tags	0	16
(bananaslugs)	Split	18	48
	Ells	4	35
Zacoleinae—*Zacoleus leonardi*	Tags	7	7
	Split	2	6
	Ells	7	4
Binneyinae—*Hemphillia glandulosa/burringtoni, H. malonei, H. dromedarius*	Tags	50	61
(jumping-slugs)	Split	16	7
	Ells	11	12
Subtotal: All Slugs		163	246
Snails			
Ellobiidae—*Carychium occidentale*	Tags	108	124
(minute thorn snails)	Split	1	0
	Ells	0	0
Haplotrematidae—*Haplotrema vancouverense, Ancotrema sportella*	Tags	87	92
(lancetooth snails)	Split	34	20
	Ells	16	8
Polygyridae—*Vespericola columbianus, Cryptomastix germana*	Tags	223	142
(hesperian and Oregonian snails)	Split	351	121
	Ells	183	69
Pristilomatidae—*Pristiloma sternsi, P. langsingi, P. arcticum*	Tags	525	175
(tightcoil snails)	Split	1339	561
	Ells	463	157
Valloniidae & Punctidae—*Planogyra clappi, Punctum sp.*	Tags	14	27
(minute flatwhorl and spot snails)	Split	0	4
	Ells	0	1
Vertiginidae—*Columella edentula,Vertigo columbiana*	Tags	574	322
(column and vertigo snails)	Split	15	27
	Ells	12	17
Subtotal: All Snails		3945	1867
Total: All Mollusks		4108	2113

and spring. Anadeninae (taildropper) slugs were also common at all sites in both seasons. The Pacific bananaslug [*Ariolimax columbianus*] of the Ariolimacinae group was found primarily at the Split and Ells sites and was more abundant in the spring. In contrast, the Binneyinae (jumping-slug) species group was found both fall and spring, but was most abundant at the Tags site.

The snail groups Ellobiidae, Valloniidae/Punctidae and Vertiginidae were found almost exclusively at the Tags site (Table 2). Pristilomatidae was the most abundant snail and mollusk group occurring at all three sites primarily in the fall, and drove the difference between fall and spring abundances, while the other snail groups except Polygyridae tended to have similar numbers in

TABLE 3. Snail species group comparison between forest floor samples (one liter) and adjacent cardboard sample stations. Total, mean and SD for all samples (n = 73) by species group.

	Cardboard				Forest Floor			
Species Group	Tot.	%	Mean	SD	Tot.	%	Mean	SD
Vertiginidae	371	51.2	5.08	10.34	673	61.1	3.07	6.59
Pristilomatidae	160	22.1	0.55	1.48	130	11.8	0.45	1.75
Ellobiidae	53	7.3	0.73	1.79	105	9.5	1.44	2.56
Vespericola sp.	45	6.2	0.31	0.81	1	0.1	0.01	0.08
Cryptomastix sp.	36	4.9	0.16	0.76	9	0.8	0.04	0.22
Haplotrematidae	34	4.7	0.09	0.37	102	9.2	0.28	1.77
Valloniidae/Punctidae	25	3.4	0.17	0.71	81	7.3	0.55	1.62
All Mollusks	724	100			1101	100		

both seasons. Pristilomatidae was also found most often at the Split site. The Haplotrematidae group was common at all three sites but less abundant at the Ells site. The Polygyridae group was common at all three sites and like Pristilomatidae, was more abundant in the fall. We encountered no non-native slug or snail taxa.

We found that species groupings greatly minimized observer misidentifications. Surveyed air temperature had an optimal range for peak mollusk abundance and richness between 4 °C and 7 °C. In comparing forest floor sampling to cardboard habitats, the sifted forest floor samples tended to contain proportionately more small snails, whereas the cardboard attracted more large snails, in addition to slugs, that would not be counted by forest floor sampling alone (Table 3).

The NMS ordination recommended a 2-dimensional solution explaining 87% of the variability. Of this total, axis 1 explained 75% and axis 2 explained 12% of the variation. The remaining 13% of the variation was due to factors not included in the study or to factors that were measured in the study but at insufficient resolution. Mollusk communities showed site differences, along with relationships to some environmental variables (Table 4). Communities in the Ells and Split sites were similar but the Tags site was distinctly different (Figure 3). Of the environmental variables included in the ordination, presence of hardwood vegetation had the greatest influence on the mollusk community composition ($r = 0.730$), along with total understory cover ($r = 0.644$), fern cover ($r = 0.629$), and woody shrub ($r = 0.534$). All of these were positively and strongly ($r \geq 0.500$) correlated with axis 1, while herb cover was moderately correlated to axis 2

TABLE 4. Mollusk species group with environmental variables and their correlation (Pearson's r) with axis 1 and 2 in the nonmetric multidimensional scaling (NMS) ordination of 77 sample points over 5 years (see Figure 3).

Variable	Code†	Axis 1	Axis 2
Species Group			
Anadeninae	ANAD	0.326	-0.324
Ariolimacinae	ARIO	-0.333	-0.143
Zacoleinae	ZACO	0.313	0.048
Binneyinae	BINN	0.670	0.021
Haplotrematidae	HAPLO	0.797	0.209
Ellobiidae	ELLO	0.702	-0.219
Polygyridae	POLY	0.280	0.826
Pristilomatidae	PRIST	0.149	0.661
Valloniidae & Punctidae	VAL/PUNC	0.815	-0.233
Vertiginidae	VERT	0.827	-0.165
Environmental			
Air Temp		-0.272	-0.221
Soil Temp		-0.301	-0.302
Precip 7 day		-0.046	0.271
Overstory Canopy		0.089	0.210
Wetland %		0.573	-0.458
Ferns		0.629	-0.071
Herbs		-0.188	0.491
Conifers		-0.168	0.197
Hardwoods		0.730	-0.250
Woody Shrubs		0.534	-0.043
Understory Cover		0.644	0.016
Down Wood		0.011	0.141

†Abbreviation used in Figure 3.

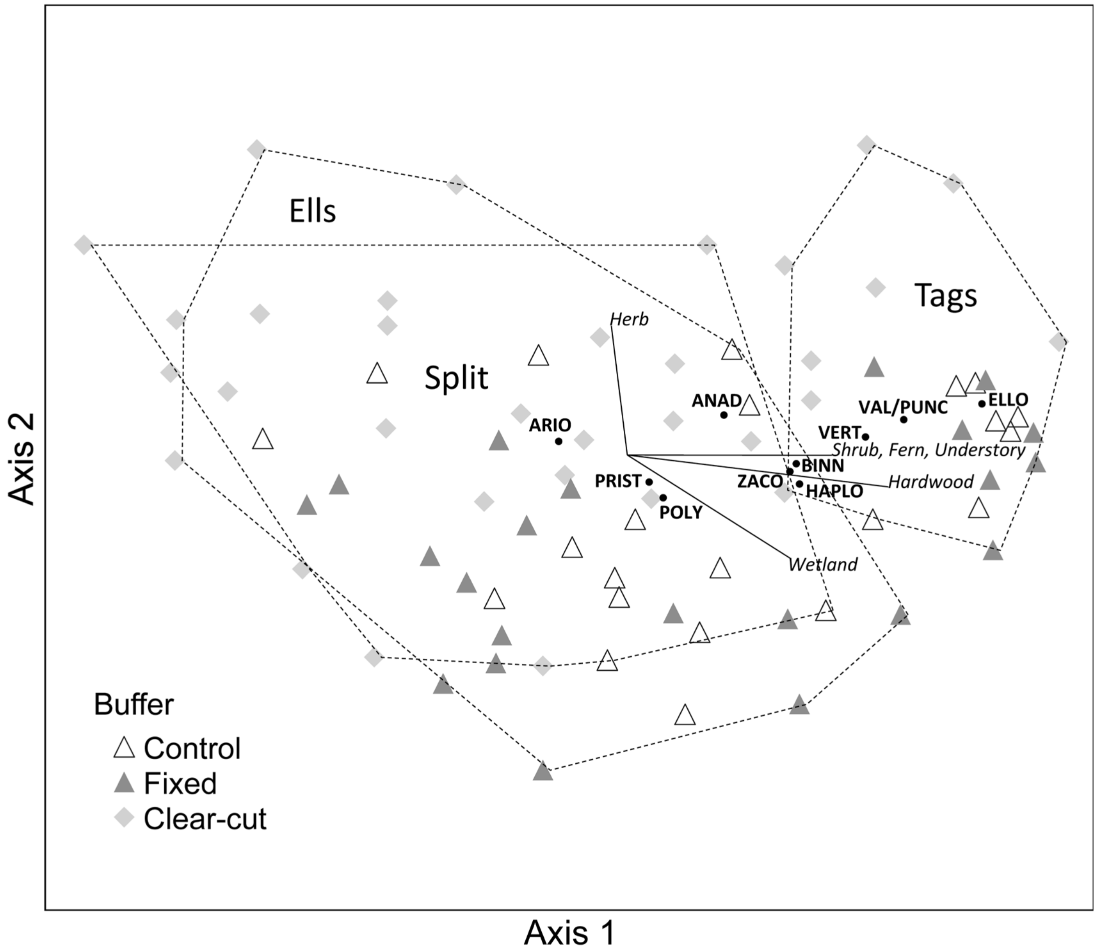

Figure 3. Nonmetric multidimensional scaling (NMS) ordination of ten mollusk species groups for 77 sample points at 3 sites (77 stream riparian area observations in 3 riparian buffer treatments at 3 sites over 5 years). The 2D solution explained 87% of the variability. Axis 1 (r = 0.754) indicates moist conditions and increasing vegetative cover; axis 2 (r = 0.119) is correlated to increasing herb cover. Vectors indicate the strength (r ≥ 0.500) and direction of correlations between environmental variables and axis scores. Species group names are abbreviated.

(r = 0.491). Wetlands were strongly correlated with axis 1 (r = 0.573) but negatively correlated to axis 2 (r = -0.458). Correlations were weak (r ≤ ~0.300) for air and soil temperature, 7-day precipitation, overstory cover, and downed wood. Season and buffer were not found to be correlated with either axis in the NMS ordination. Species groups strongly correlated with axis 1 included Binneyinae (r = 0.670), Haplotrematidae (r = 0.797), Ellobiidae (r = 0.702), Vertiginidae (r = 0.827), Valloniidae & Punctidae (r = 0.815). Polygridae had a strong correlation to axis 2 (r = 0.826), as did Pristilomatidae (r = 0.661). Slug groups Anadeninae, Ariolimacinae and Zacoleinae were weakly correlated to both axes 1 and 2.

Logging Effects

Before logging, when all buffer treatment streams had undisturbed riparian forest, mollusk abundance in the buffer treatments was similar with corrected alpha $P \leq 0.02$ (Table 5). After logging, mollusk abundance was significantly different between streams with no buffers compared to fixed-width buffers and control streams, but while the buffer treatments were different from each other more than by chance alone, the magnitude of the

TABLE 5. Buffer treatment differences for mollusk abundance using multi-response permutation procedure (MRPP) analysis. Sample points for before (n = 30) and after logging (n = 47) showing *P*-value and *A*-value statistics. Significant differences ($P \leq 0.02$) are shown with asterisk.

	A-value	*P*-value
Before logging		
Control vs. Clear-cut	0.0418	0.0624
Control vs. Fixed-width	-0.0172	0.6060
Clear-cut vs. Fixed-width	0.0444	0.0467
After logging		
Control vs. Clear-cut	0.0522	0.0021*
Control vs. Fixed-width	0.0100	0.2114
Clear-cut vs. Fixed-width	0.0375	0.0147*

differences or effect size was relatively small indicated by *A*-values less than 0.10.

Discussion

Mollusk Communities

Slug and snail species groups varied in the strength of their relationships to environmental variables that affect moisture conditions, habitats and forage availability such as the composition of the understory, hardwoods, and wetlands (Table 4). For example, the large bananaslug (Ariolimacinae) had weak associations to both axes of the NMS ordination suggesting it may be a habitat generalist. Bananaslugs consume a variety of plant species including several woody shrub and herb species, as well as fruits from some of these (Richter 1976; Hamilton and Wellington 1981), yet we found the slugs less often at the Tags site where understory forage density was higher (Figure 3). In contrast, the jumping-slugs (Binneyinae) were strongly associated with NMS axis 1 indicating a preference for moist conditions and/or dense vegetative cover, yet we found them in a variety of forest age classes including the clear-cuts in our study; like the findings of others, we found that moist conditions rather than age class are an important factor for their occurrence (COSEWIC 2003; Wainwright and Duncan 2005). We could find very little published information about the Zacoleinae slug group. This group was weakly associated to both NMS axes most likely due to their low capture numbers thus the ordination was not informative about preferred habitats. The taildropper slug group (Anadeninae) was weakly associated with both NMS axes, and like the bananaslug, may also be somewhat of a habitat generalist. We found the Anadeninae group in a wide variety of habitats documented by others (Burke and Duncan 1999; Leonard et al. 2003), however we also found them less often at Ells, the site with the most variability in temperature and humidity.

We found the snail species group Pristilomatidae the most common mollusk occurring at all the sites in all the treatments both before and after logging. Surprisingly, the group was most abundant at the Split site and strongly associated with NMS axis 2 where understory vegetation was sparse contrary to preferred habitats in other accounts (Forsyth 2004). Polygridae was the next most abundant snail group comprised of the species [*Vespericola columbianus*] and [*Cryptomastix germana*] (Table 2). This group had a strong association with axis 2 of the ordination suggesting a preference for habitats with increased herb and less understory vegetation. However, in looking at species separately, *C. germana* and a closely related species not encountered in the study [*Crytomastix devia*] are both found in lowland forests with a developed understory always including swordfern and hardwood species such as big-leaf maple [*Acer macrophyllum*] (Burke 1999; BCIRT 2008) while [*Vespericola columbianus*] can be found in open sites (Forsyth 2004). Given that the Split site had a higher abundance of Polygridae than Tags, combining both species into the same group despite being of the same family, may have confounded our results. The snail species group Haplotrematidae was strongly associated with axis 1 of the NMS ordination (moist and dense understory conditions) having a position very close to the slug group Binneyinae (Figure 3). Members of the Haplotrematidae group are omnivorous (Forsyth 2004), and unlike work done with [*Haplotrema concavum*] in the eastern United States (Pearce and Gaertner 1996), trophic relationships in mollusk community structure in the Pacific Northwest are unknown and merit exploration. The remaining three snail groups, Ellobiidae, Vertiginidae, and

Valloniidae-Punctidae were all strongly associated with moist and dense understory conditions and primarily found at the Tags site. As with other accounts, these three snail groups have also been found in sites similar to Tags—those having deep humus and dense understories (Forsyth 2004; Burke 2013).

We found the cardboard sample method both cost and time efficient compared to litter sampling. Repeat sampling could be done at the same locations without depleting taxa or habitat substrates that would have happened with repeated litter sampling. However, we found the method underestimated abundance and diversity as in other comparisons (Boag 1982, 1990; McCoy 1999). When coupled with species groupings, our results portray a somewhat coarse representation of the actual mollusk communities, yet we found the method satisfactory for our study objective of evaluating logging effects.

In summary, mollusk communities were similar at the Ells and Split sites in comparison to Tags. Site differences, mostly those regarding vegetation, were substantial and had an effect on the mollusk communities. The sites were also unique in terms of aspect, wetland features and lithology that probably affected the communities as well. All these attributes can affect moisture and temperature regimes in the riparian areas and may be factors that, to varying degrees, influence the effects of disturbances such as logging.

Logging Effects

We found differences in mollusk populations between buffer treatments after logging, but the magnitude of the treatment effects were small (Table 5). This may have been a function of climatic conditions making logging effects hard to detect, heterogeneity of the sites, or because it was simply too soon to see large differences caused by timber harvest.

Logging effects are often attributable to a change in site microclimate due to partial or complete overstory removal. Microclimate parameters show distinct gradients from headwater streams through the riparian zone into adjacent upland forest stands (Chen et al. 1993, Brosofske et al. 1997). For example, Rykken et al. (2007a) found that microclimate in uncut buffers ~30 m wide along headwater streams tended to counterbalance the edge effect from adjacent clear-cuts in Oregon forests. However, continuous, fixed-width buffers with a total width of 30 m such as ours likely had somewhat altered microclimate gradients that differed from unlogged controls and may have been a contributor in part to the small size of the logging effect. We were also constrained with different before/after replicate observations to determine if individual buffers were more effective at one site compared to another. Nevertheless, species group associations relative to environmental variables in the NMS ordination provide some insight for applicable buffer or protective forest management prescriptions. For example, although we found differences across all sites between clear-cut vs. fixed-width buffers and controls after logging, sites with dense riparian vegetation were probably less sensitive to logging.

Predicting short as well as long-term effects of logging would be most useful for species viability and conservation. Our results agree with those of Hylander et al. (2004) that mollusk populations declined after clear-cutting at least short term, but were less affected in moister locations and along buffered streams. In addition, Rykken et al. (2007b) had similar results for mollusks where riparian buffers ~30 m wide were comparable to controls but were significantly different than clear-cuts in Oregon forests. Regional climate models project rates of warming in the Pacific Northwest of 0.1 °C to 0.6 °C per decade with rainfall tending toward wetter autumns and winters with drier summers (Mote and Salathe 2010) which may affect mollusk species in unanticipated ways. Variable density logging practices can moderate ground-level microclimate variation and could be considered for sites on southerly aspects prone to wide variations of temperature and humidity like our Ells site. For example, studies that evaluate thinning effects on mollusks in western Oregon and in western Washington showed that thinning had little effect on mollusks (McDade 2002, Schowalter et al. 2003, Wessell 2005). Retention patches 0.8–1.2 ha in size and 30% dispersed retention treatment sites were more effective than clear-cutting in maintaining sensitive mollusks in coastal British Columbia forests (Ovaska and Sopuck 2010), however, as we also found, the communities and responses of the mollusks varied among the sample sites, most likely related to local environmental factors.

Unexpectedly, we found weak associations between mollusk abundance and recent rainfall and temperature in the NMS ordination. The rainfall data we used were from weather stations many kilometers from the mollusk sample sites, plus temperature was only spot recorded at the time of survey thus local variability likely played a role in our observations. Changes in mollusk density caused by forest management can be large, but changes mediated by variation in local weather patterns can be of similar magnitude (Prezio et al. 1999). Regardless, mollusk relationships to microclimate change could be more precisely understood by installing on-site weather stations in future studies. Additionally, although we found only weak associations for downed wood in the NMS ordination, micro-habitats for mollusks created by downed wood may be an important consideration in timber harvest designs (Kappes 2006, Kappes et al. 2006). Concerning the duration of logging effects, short-term declines after clear-cutting were transient for most species in Swedish forests, and within a few decades mollusk populations increased as the second-growth forest re-emerged (Strom et al. 2009). Continued monitoring of our study sites may uncover important relationships between short and long term effects of forest succession on the mollusk communities.

Conclusions

Although the treatment effects were small, we found that riparian-associated mollusks were sensitive to disturbances from clear-cut logging without riparian buffers and were relatively unaltered along steams with forested buffers. Our findings illustrate that sites with a well-developed understory including hardwoods, shrubs and ferns, together with physical features such as northerly aspects and presence of seeps and wetland features, can influence mollusk abundance, diversity and taxa resiliency to disturbances such as logging. We also acknowledge there is a scarcity of life history information for endemic mollusks, and species most likely have developed specialized niches with poorly-understood responses to the effects of both short- and long-term environmental change. Given these uncertainties, we advocate continued research to provide further guidance for adaptive forest management necessary for the conservation of endemic mollusks of the Pacific Northwest.

Acknowledgements

We thank the USDA Forest Service Pacific Northwest Research Station and the Washington State Department of Natural Resources for their support. We gratefully acknowledge Tom Burke, Pete Bisson, Shannon Claeson, Kim Gridley, Tom Kogut, Bill Leonard, Kristiina Ovaska, Deb McConnell, Casey Richart, Robin Shoal, Wren Wolf and others for their help with initial taxa identification, field surveys and helpful comments. This work was part of a larger collaborative effort with the Washington State Departments of Natural Resources and Ecology and the University of Washington. Funding for this study was primarily through the USDA Forest Service PNW Research Station, with in-kind assistance from the other named collaborators. Comments from the reviewers of Northwest Science greatly improved the manuscript. Additional review was provided by Kathryn Ronnenberg. We appreciate Kelsey Shimada and E. Ashley Steel for their statistical assistance and contributions to the analysis.

Literature Cited

Baur, B. 1986. Patterns of dispersion, density and dispersal in alpine populations of the land snail *Arianta arbustorum* (L.) (Helicidae). Holarctic Ecology 9:117-125.

Baur, B., and A. Baur. 1995. Habitat related dispersal in the rock-dwelling land snail *Chondrian clienta*. Ecography 18:123-130.

BCIRT [British Columbia Invertebrates Recovery Team]. 2008. Recovery strategy for Puget Oregonian Snail (*Cryptomastix devia*) in British Columbia. Prepared for the British Columbia Ministry of Environment. Victoria, Canada.

Benda, L., N. L. Poff, D. Miller, T. Dunne, G. Reeves, G. Pess, and M. Pollock. 2004. The network dynamics hypothesis: how river networks structure riverine habitats. BioScience 54:413-427.

Bisson, P. A., S. M. Claeson, S. M. Wondzell, A. D. Foster, and E. A. Steel. 2013. Evaluating headwater stream buffers: lessons learned from watershed-scale experiments in southwest Washington. *In* P. D. Anderson and K. L. Ronnenberg [editors], Density management in the 21st century: west side story. General Technical Report PNW-GTR-880. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR. Pp. 169-188.

Boag, D. A. 1982. Overcoming sampling bias in studies of terrestrial gastropods. Canadian Journal of Zoology 60:1289-1292.

Boag, D. A. 1990. On the effectiveness of artificial shelters in the study of population attributes of terrestrial gastropods. Canadian Journal of Zoology 68:254-262.

Brosofske, K. D., J. Chen, R. J. Naiman and J. F. Franklin. 1997. Harvesting effects on microclimate gradients from small streams to uplands in western Washington. Ecological Applications 7:1188-1200.

Burke, T. E. 1999. Management recommendations for terrestrial mollusk species. *Cryptomastix devia*, Puget Oregonian snail. V. 2.0. Bureau of Land Management, Oregon State Office, Salem.

Burke, T. E., and N. Duncan. 1999. Management recommendations for terrestrial mollusk species. *Prophysaon coeruleum*, Blue-gray taildropper & *Prophysaon dubium*, Papillose taildropper. V. 2.0. Bureau of Land Management, Oregon State Office, Salem.

Burke, T. E. 2013. Land Snails and Slugs of the Pacific Northwest. Oregon State University Press. Corvallis.

Chen, J., J. F. Franklin and T. A. Spies. 1993. Contrasting microclimates among clearcut, edge, and interior of old-growth Douglas-fir forest. Agricultural and Forest Meteorology 63:219-237.

COSEWIC [Committee on the Status of Endangered Wildlife in Canada]. 2003. Assessment and status report on the warty jumping-slug *Hemphillia glandulosa* in Canada. Ottawa.

Forsyth, R. G. 2004. Land Snails of British Columbia. Royal BC Museum Handbook. Royal British Columbia Museum. Victoria, Canada.

Foster, A. D., and S. M. Claeson. 2011. Habitats and seasonality of riparian-associated millipedes in southwest Washington, USA. Terrestrial Arthropod Reviews 4:203-220.

Giokas, S., and M. Mylonas. 2004. Dispersal patterns and population structure of the land snail *Albinaria coerulea* (Pulmonata: Clausiliidae). Journal of Molluscan Studies 70:107-116.

Gittenberger, E. 2012. Long-distance dispersal of molluscs: "Their distribution at first perplexed me much." Journal of Biogeography 39:10–11.

Gomi, T., R. C. Sidle, J. S. Richardson. 2002. Understanding processes and downstream linkages of headwater systems. Bioscience 52: 905-916.

Gotmark, F., T. Proschwitz, and N. Franc. 2008. Are small sedentary species affected by habitat fragmentation? Local vs. landscape factors predicting species richness and composition of land molluscs in Swedish conservation forests. Journal of Biogeography 35:1062-1076.

Hamilton, P. A., and W. G. Wellington. 1981. The effects of food and density on the movement of *Arion ater* and *Ariolimax columbianus* (Pulmonata: Stylommatophora) between habitats. Researches on Population Ecology 23:299-308.

Hawkins, J. W., M. W. Lankester, R. A. Lautensclager, and F. W. Bell. 1997. Effects of alternative conifer release treatments on terrestrial gastropods in northwestern Ontario. Forestry Chronicle 73:91-98.

Hylander, K., C. Nilsson, and T. Gothner. 2004. Effects of buffer-strip retention and clearcutting on land snails in boreal riparian forests. Conservation Biology 18:1052-1062.

Hylander, K. 2011. The response of land snail assemblages below aspens to forest fire and clear-cutting in Fennoscandian boreal forests. Forest Ecology and Management 261:1811-1819.

Janisch, J. E., A. D. Foster, and W. J. Ehinger. 2011. Characteristics of small headwater wetlands in second-growth forests of Washington, USA. Forest Ecology and Management 261:1265-1274.

Kappes, H. 2006. Relations between forest management and slug assemblages (Gastropoda) of deciduous regrowth forests. Forest Ecology and Management 237:450-457.

Kappes, H., W. Topp, P. Zach, and J. Kulfan. 2006. Coarse woody debris, soil properties and snails (Mollusca: Gastropoda) in European primeval forests of different environmental conditions. European Journal of Soil Biology 42:139-146.

Kelley, R., S. Dowlan, N. Duncan, and T. E. Burke. 1999. Field guide to survey and manage terrestrial mollusk species from the northwest forest plan. Bureau of Land Management, Oregon State Office, Salem.

Legendre, P., and H. B. Birks. 2012. From classical to canonical ordination. *In* H. J. B. Birks, A. F. Lotter, S. Juggins and J. P. Smol (editors), Tracking Environmental Change Using Lake Sediments, Volume 5: Data handling and numerical techniques. Springer, New York, NY.

Leonard, W. P., L. Chichester, and K. Ovaska. 2003. *Prophysaon dubium* Cockerell, 1890, the papillose taildropper (Gastropoda: Arionidae): Distribution and anatomy. The Nautilus 117:62-67.

McCoy, K. D. 1999. Sampling terrestrial gastropod communities: using estimates of species richness and diversity to compare two methods. Malacologia 41:271–81.

McCune, B., and J. B. Grace. 2002. Analysis of Ecological Communities. MjM Software Design. Gleneden Beach, OR.

McDade, K. 2002. Habitat relationships of small terrestrial vertebrates and invertebrates in managed forests in the southern Oregon Cascades. M. S. thesis. Oregon State University. Corvallis.

Mote, P., and E. Salathe. 2010. Future climate in the Pacific Northwest. Climatic Change 102:29-50.

NCDC [National Climate Data Center]. 2012. National Oceanographic and Atmospheric Agency, USA. Available at http://www.ncdc.noaa.gov/oa/ncdc.html (accessed January 2008).

Olson, D. H., P. A. Anderson, C. A. Frissell, H. H. Welsh, and D. F. Bradford. 2007. Biodiversity management approaches for stream-riparian areas: perspectives of Pacific Northwest headwater forests, microclimates, and amphibians. Forest Ecology and Management 246:81-107.

Ovaska, K., and L. Sopuck. 2010. Short-term effects of variable-retention logging practices on terrestrial gastropod faunas in coastal forests of British Columbia: an experimental approach. Unpublished report prepared by Biolinx Environmental Research Ltd. Sidney, British Columbia, Canada.

Pearce, T. A., and A. Gaertner. 1996. Optimal foraging and mucus-trail following in the carnivorous land snail *Haplotrema concavum* (Gastropoda: Pulmonata). Malacological Reviews 29:85-59.

Prezio, J. R., M. W. Lankester, R. A. Lautensclager, and F. W. Bell. 1999. Effects of alternative conifer release treatments on terrestrial gastropods in regenerating spruce plantations. Canadian Journal of Forest Research 29:1141-1148.

Richardson, J. S., and R. J. Danehy. 2007. A synthesis of the ecology of headwater streams and their riparian zones in temperate forests. Forest Science 53:131-147.

Richardson, J. S., R. J. Naiman, and P. A. Bisson. 2012. How did fixed-width buffers become the standard practice for protecting water from forestry? Freshwater Science 31:232-238.

Richter, K. O. 1976. The foraging ecology of the banana-slug *Ariolimax columbianus* Gould (Arionidae). Ph.D. Thesis. University of Washington. Seattle, USA.

Ricklefs, J. 2009. Data from the Riparian Ecosystem Management Study (REMS), ver. 2.00. Unpublished report on file at the Land Management Division, Washington Department of Natural Resources. Olympia.

Rykken, J. J., S. S. Chan, A. R. Moldenke. 2007a. Headwater riparian microclimate patterns under alternative forest management treatments. Forest Science 52:270-280.

Rykken, J. J., A. R. Moldenke, and D. H. Olson. 2007b. Headwater riparian forest-floor invertebrate communities associated with alternative forest management practices. Ecological Applications 17:1168-1183.

Schowalter, T. D., Y. L. Zhang, and J. J. Rykken. 2003. Litter invertebrate responses to variable density thinning in western Washington forest. Ecological Applications 13:1204-1211.

Sheridan, C. D., and T. A. Spies. 2005. Vegetation-environment relationships in zero-order basins in coastal Oregon. Canadian Journal of Forest Research 35:340-355.

Strahler, A. N. 1952. Hypsometric (area-altitude) analysis of erosional topography. Bulletin Geological Society of America 63:1117-1142.

Strayer, D., D. H. Pletscher, S. P. Hamburg, and S. C. Nodvin. 1986. The effects of forest disturbance on land gastropod communities in northern New England. Canadian Journal of Zoology 64:2094-2098.

Strom, L., K. Hylander, and M. Dynesius. 2009. Different long-term and short-term responses of land snails to clear-cutting of boreal stream-side forests. Biological Conservation 142:1580-1587.

USDA, USDI [U.S. Department of Agriculture, U.S. Department of the Interior]. 2001. Record of Decision and Standards and Guidelines for Amendments to the Survey and Manage, Protection Buffer, and other Mitigation Measures Standards and Guidelines. USDA Forest Service, USDI Bureau of Land Management.

USFWS [U.S. Fish and Wildlife Service]. 2011. A 90-day finding on a petition to list 29 mollusk species and subspecies as threatened or endangered, under the Endangered Species Act of 1973. Docket No. FWS-R8-ES-2011-0076; MO-92210-0-0008; Department of Interior, U.S. Fish and Wildlife Service.

Van Wagner, C. E. 1968. The line intersect method in forest fuel sampling. Forest Science 14:20-26.

WADNR [Washington State Department of Natural Resources]. 2006. Forest Practices. Available online at http://www.dnr.wa.gov/Pages/default.aspx (accessed January 2012).

Wainwright, M., and N. Duncan. 2005. Conservation Assessment for four species of the genus Hemphillia: Burrington jumping-slug (*Hemphillia burringtoni);* Warty jumping-slug (*Hemphillia glandulosa*); Malone jumping-slug (*Hemphillia malonei*); Panther jumping-slug (*Hemphillia pantherina*). Originally issued as Management Recommendations by T. E. Burke, 1998. U.S. Forest Service Region 6 and USDI Bureau of Land Management, Oregon and Washington.

Wessell, S. J. 2005. Biodiversity on managed forests of western Oregon: Species assemblages in leave islands, thinned and unthinned forests. M.S. thesis. Oregon State University, Corvallis.

Received 10 July 2012
Accepted for publication 15 April 2013