Effects of Forest Land Management on Terrestrial Mollusks: A Literature Review

Salmon coil, *Helicodiscus salmonaceous.* Photograph by William Leonard, used with permission.

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Under an Agreement
With the Interagency Special Status and Sensitive Species Program
USDA Forest Service, Region 6 and
USDI Oregon/Washington Bureau of Land Management

Dedication: This report is dedicated to Suzanne Abele, 27 year old ecologist who tragically lost her life in an ATV accident August 18th, 2011 while researching the impact of forestry practices on terrestrial snails and slugs. Although cut far too short, Suzanne's contributions to this field are significant and deeply appreciated.

Foreword: National policies for the Forest Service (Forest Service Manual (FSM) Section 2670) and the Bureau of Land Management (BLM Manual Section 6840) establish categories of "Sensitive" species, where analysis is required to ensure the conservation of these species during land management actions. Under Forest Service policy, agency botanists and biologists complete a Biological Evaluation in which programs and activities are reviewed to determine their potential effects on Sensitive species. Proposed management actions "must not result in a loss of species viability or create significant trends toward Federal listing" (FSM 2670.32) of any Sensitive species. Similarly, under BLM policy, BLM personnel must assess, review and document the effects of a proposed action on Bureau Sensitive species. These effects are documented through a systematic, interdisciplinary evaluation following the decision making process as described in the National Environmental Policy Act of 1969. The BLM must also ensure that project decisions would not contribute to the need to list Bureau Sensitive species under the Endangered Species Act.

In order to conduct Sensitive species evaluations, BLM and Forest Service personnel document species habitat requirements and distribution, assess likelihood of species occurrence, and evaluate the risk of impacts from proposed management actions. Both the Region 6 Forest Service and Oregon/Washington BLM Sensitive species lists contain a large number of mollusks, and some of these species, as well as additional mollusk species, are also covered under the Survey and Manage Standards and Guidelines of the Northwest Forest Plan. As such, agency field unit personnel are frequently faced with gastropod conservation issues, and the usefulness of a comprehensive review of terrestrial mollusk responses to the types of land management activities prevalent on Oregon/ Washington federal lands was recognized.

Working through an agreement with the Xerces Society for Invertebrate Conservation, the Interagency Special Status and Sensitive Species Program developed "Effects of Forest Land Management on Terrestrial Mollusks: A Literature Review" as a tool for use in Sensitive species evaluations and other conservation efforts. This document is designed to help agency biologists better understand and evaluate the effects of certain land management actions on terrestrial mollusks, and implement effective conservation measures to meet agency Sensitive species policy goals. Along with the literature review (Section 1) summarizing the effects of logging, road building, and burning on terrestrial mollusks, this document includes an annotated bibliography of papers addressing these effects (Section 3), and a list of citations by management action (Section 2).

We are hopeful that this document will be a useful tool not only for Forest Service and BLM personnel, but also for other federal, state, and private land managers and biologists.

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Section One: Research Summary

EXECUTIVE SUMMARY

Snails and slugs are essential components of forest ecosystems. They decompose forest litter, recycle nutrients, build soils, and provide food and calcium for birds, amphibians, reptiles, small mammals, and invertebrates. Although mollusks have been a crucial part of the ecology of temperate forests for millennia, recent loss and fragmentation of natural habitats due to clear-cut logging, road-building, and altered fire regime have resulted in both extinction and extinction risk for many mollusk species (*e.g.*, Curry *et al.* 2008). Mollusks (including aquatic species) represent 20% of all threatened animals, and 37% of known animal extinctions since 1600 A.D. (Seddon 1998 *in* Dunk *et al.* 2004). In an era where the extinction rate is an estimated 400 times the natural rate (*reviewed in* Werner & Raffa 2000), it is important for land managers to take mollusks into consideration when developing or re-evaluating strategies for managing forests ecosystems to achieve forest health and biodiversity conservation goals.

This review presents a synthesis of the current understanding of terrestrial gastropod ecosystem functions, habitat associations, and response to forest disturbances. Key findings include:

- While some level of exposure in the physical environment is tolerated by certain mollusks, most species are extremely sensitive to temperature and moisture extremes.

- Research suggests that the majority of snails and slugs are dependent on litter from deciduous trees and have higher abundances in multispecies forests with strong broadleaf components. Additionally, mollusks in deciduous forests appear to rebound from disturbance more quickly than in coniferous forests.

- Forests with old-growth characteristics supply microhabitat and microclimate conditions capable of supporting a diversity of mollusks, and forest age is often positively correlated with mollusk richness and abundance.

- Numerous studies stress the importance of refugia in gastropod recolonization potential and community resilience following forest disturbance. Since land mollusks are small animals with limited mobility and dispersal capabilities, the maintenance of refugia in disturbed habitat is particularly important for this group. Refugia should include logs, snags, fallen branches, and other forms of coarse woody debris, as well as areas with thick leaf-litter. Woody debris and litter provide islands of habitat, food, and protection from microclimatic extremes, increasing species' tolerance of temporarily inhospitable environments.

- Research suggests that in order to reduce microclimate extremes and protect gastropods, partial cuts should be favored over clearcuts, aggregated (group) retention over dispersed retention or thinning, and larger group retention over smaller group retention. In particular, harvesting with large group retention helps to maintain pre-harvest boreal gastropod assemblages and will likely conserve boreal gastropod species if used as a tool for biodiversity management.

- Fragmented habitat limits the dispersal and post-disturbance recolonization potential of gastropods. Tracts of intact forest and connected groups of old trees help provide dispersal corridors for gastropods and can lead to significant increases in the survival of disturbance-sensitive species**.**

- Research suggests that techniques that minimize soil compaction and damage to (or removal of) the organic layer favor survival of gastropods. For example, Timberjacks have been found to cause less damage to the organic mat and resident invertebrate populations than feller bunchers, single-grip harvesters, and grapple skidders.

- Due to the tendency of mollusks to avoid non-vegetated and/or dry environments, even narrow, unpaved roads with low traffic densities are barriers to the dispersal of mollusks.

- Numerous studies have found negative and long-lasting responses of gastropods to fire, including population extirpation and reductions in abundance and species richness. Small burns surrounded by unburned plots have been most successful at maintaining gastropod community structure. Although there is little information comparing gastropod responses to differences in burn severity and frequency, it is presumed that a fire regime involving low-intensity burns at infrequent fire-return intervals (>5 years) would best maintain gastropod communities.

ECOSYSTEM FUNCTIONS OF TERRESTRIAL MOLLUSKS

Snails and slugs are vital components of healthy forest ecosystems, aiding in decomposition and soil building processes, and providing food and essential nutrients to wildlife. Densities of 2 to 38/m² have been reported for snails and slugs active on the forest floor, and 80 to 1607/m² for gastropods in the litter and underlying soil (*reviewed in* Hawkins *et al.* 1997a). Terrestrial gastropods make a significant contribution to the biomass and energy in boreal forests, where they comprise at least 2.5% of the animal biomass and 6% of the animal energy (highly conservative estimates based only on active gastropods on the forest floor) (Hawkins *et al.* 1997a).

Decomposition and nutrient cycling

As primary consumers of plant, animal, and fungal matter, gastropods aid in forest decomposition processes and contribute to nutrient cycling, soil formation, and soil productivity (Jennings & Barkham 1979, Mason 1970a,b). For example, the slug *Ariolimax columbianus* speeds up nutrient cycling by ingesting large amounts of living and senescing plants, and subsequently excreting the partially digested plant tissue (Richter 1979). Snails and slugs further contribute to the breakdown of forest floor litter by aiding in the dispersal of some fungi (Burke 1999), and by physically and chemically altering plant material in ways that appear to promote fungal and bacterial growth (Jennings & Barkham 1979).

Food and calcium for wildlife

Gastropods are an important food source to a vast number of species, including salamanders, frogs, toads, turtles, snakes, lizards, birds, shrews, voles, moles, rats, mice, chipmunks, and squirrels (*e.g.* South 1980, Churchfield 1984, Martin 2000). Invertebrate predators of terrestrial mollusks include sciomyzid fly larvae, firefly larvae, parasitic wasp larvae, carabid and staphylinid beetles, ants, spiders, and harvestmen (Martin 2000, Frest & Johannes 1995, Nyffeler & Symondson 2001). Additionally, the reproductive cycles of some nematodes and trematodes (flatworms) are dependent on snails and slugs as intermediate hosts for their parasitic eggs and larvae (*e.g.*, Ball *et al.* 2001).

Since snail shells are very high in calcium, terrestrial snails have an important role in storing, releasing, and cycling calcium in the ecosystems they inhabit (Caldwell 1993). Snail shells are the primary calcium source for the eggs of some bird species, and declines in mollusk abundance in forest ecosystems have been significantly linked to eggshell defects, reduced reproductive success, and population declines in the song bird, *Parus major* (Graveland *et al.* 1994, Graveland and van der Wal 1996). Empty snail shells are used as shelters and egg laying sites by insects and other arthropods (Frest & Johannes 1995), and broken down shells return calcium to the soil (Martin 2000).

Plant pollination and seed dispersal

Although pollination by snails (malacophily) is a rare and obscure phenomenon, at least one study clearly demonstrates the significant role of a snail (*Lamellaxis gracile*) in the pollination of a flowering plant (Convolvulaceae: *Volvulopsis nummularium*), especially on rainy days when the activity of bees is completely lacking (Sarma *et al.* 2007). Since some slugs consume fruit and excrete seeds, these animals can play a significant role in seed dispersal (albeit over short distances) and also appear to increase seed germination rates of some flowering plants (Gervais *et al.* 1998).

Indicators of environmental health

Due to limited mobility, small home ranges, defined habitat preferences, and acute sensitivity to environmental conditions, snails and slugs are excellent and unique indicators of ecosystem health (Strayer *et al.* 1986, Frest and Johannes 1995, Kappes 2006). Since terrestrial gastropods cannot easily escape areas that are subjected to disturbance (Strayer *et al.* 1986), changes in gastropod abundance and diversity reflect the immediate impact of natural or experimental disturbance in their habitat (Hawkins *et al.* 1997b). As such, gastropods provide managers with a valuable tool for site-specific assessment of environmental and community change (Hawkins *et al.* 1997b).

HABITAT CHARACTERISTICS OF TERRESTRIAL MOLLUSKS

Snails and slugs are limited-mobility organisms with highly specific habitat requirements. Both local conditions (*e.g.*, microclimate, soil chemistry, vegetation, and available food and refugia) and landscape conditions (*e.g.*, forest type, age, and size) influence gastropod survival, abundance, and spatial distribution in forest systems.

Microclimate conditions

Land mollusks require moisture for respiration and locomotion, and moist-to-wet, humid microenvironments are known to be a prerequisite for the occurrence of many gastropod species (Kappes 2005). As a group, terrestrial mollusks are relatively intolerant of prolonged xeric conditions (Asami 1993, Baur & Baur 1993), and protection from water loss is a major concern for these animals. Specifically, snails and slugs are extremely sensitive to intense sun exposure, elevated temperatures, and reduced humidity, to the point that dessication is considered the primary cause of land snail mortality, even in undisturbed habitats (Solem 1984 *in* Frest & Johannes 1995). Gastropod eggs and early growth stages are particularly vulnerable to dessication (Baur & Baur 1993).

While gastropods as a group are extremely sensitive to temperature and moisture extremes, some level of changes in the physical environment may be tolerated by some species. Asami (1993) found that gastropod species vary in their tolerance to desiccation according to their structure, physiology and evolutionary history. Snails with geographic distribution in arid habitats where the forest litter often dries up and daytime temperatures are relatively high were more tolerant of desiccation in the laboratory than snails distributed in less arid, upland habitats (Asami 1993). Moreover, juvenile snails of some species were found to differ in survival and dehydration rate in low humidity conditions depending on their parents, indicating an inheritable (genetic) component to desiccation tolerance. Likewise, Jacot (1935) found a direct correlation between the drought resistance of species (as indicated by spire length) and occurrence in more severely disturbed habitat.

Soil chemistry

It is generally accepted that the diversity and abundance of gastropods is strongly influenced by the presence of exchangeable calcium ions and pH values in the upper soil and litter layers (Kappes 2005). Snails rely on calcium for shell construction, reproduction, and various physiological processes (Gärdenfors *et al.* 1995). Hylander (2011) reports pH (or possibly calcium content, related to pH) as a key factor in explaining species composition in both disturbed and undisturbed boreal forests, with a positive relationship between pH and species density and abundance in all the stand types. In a study of 25 forest reserves in Sweden, Götmark *et al.* (2008) found the pH of plant litter to be the strongest predictor of both gastropod species richness and composition. On poor soils in the Netherlands, snail density was positively correlated with calcium content and to a lesser extent with pH of the litter layer (Graveland & van der Wal 1996).

Graveland *et al.* (1994) presented the first experimental evidence that anthropogenic acid deposition over the last two decades has caused a decline of soil calcium in forests with poor soils, resulting in reduced snail density. Graveland and van der Wal (1996) report that calcium reductions due to acid deposition may be remedied, in part, by calcium additions. In forests with calcium-poor soil that contained few snails, the addition of lime to the soil resulted in snail densities comparable to those on calcium-rich soils after 4 years (Graveland & van der Wal 1996).

Slugs (not having the need for calcium in shell production), may be less influenced by soil acidity variables. In a study of slug assemblages in 68 broad-leaf forests in Western Europe, slug species richness was highest on soils with pH values between 4 and 5, although soil acidity did not influence abundances, and slug assemblages were concluded to be more sensitive to forest management than to soil acidification (Kappes 2006).

Trees and vegetation

Living, senescing, and dead vascular plants are important nutritional sources for gastropods. While gastropods are not often thought of as having dependencies on specific plant species, a significant amount of research suggests otherwise. For example, slugs exhibit preferences for the fruit (Gervais *et al.* 1998) and flowers (Sarma *et al.* 2007) of certain flowering plants, and certain snails prefer the bark characteristics of specific tree species (Roth & Pressley 1986). Most discussed, however, is the preference of gastropods for certain tree species or forest types due to leaf-litter requirements. Although one study reports higher snail density in a coniferous forest (Locasciulli & Boag 1987, see below), the majority of studies show that snails and other soil invertebrates are dependent on litter from deciduous trees and have higher abundances in multispecies forests with strong broadleaf components (Addison & Barber 1997, Abele 2010, Kralka 1986, Niemelä 1997). For example, a study exploring the ecological relationships in thirty-two species and subspecies of terrestrial snails across three states found that 99% of the individuals were associated with some form of deciduous tree, usually aspen, while the coniferous forests exhibited an almost complete absence of snails (Karlin 1961). Similarly, a recent study examining gastropod diversity in the boreal mixedwood forest of northern Alberta found gastropod assemblages were strongly influenced by canopy composition, with most gastropods showing a strong affinity for deciduous forests (Abele 2010). In this study, deciduous dominated forests supported higher gastropod abundance and species richness than the other forest types. Even in conifer dominated forests, gastropod distribution was influenced by the basal area of broadleaf trees, suggesting that single or small patches of deciduous trees can be important factors in the distribution of gastropods on the landscape (Abele 2010). An Ohio study examining slug assemblages with regard to forest variables found species richness of slugs was greater in forests containing *Quercus* (oak) (Brady & Pearce 2007). Another study of terrestrial gastropods in five boreal forest types found that most species showed a statistical preference for deciduous forests, while a few species aggregated in multiple habitat types, and just one species (*Vertigo gouldii*) showed a preference for coniferous forests (Kralka 1986). Suggested reasons for the less-hospitable nature of coniferous forests to terrestrial gastropods include reduced food resources, lack of calcium in pine litter, and resinous extracts from coniferous trees (Karlin 1961, *reviewed in* Kralka 1986). Despite these negative factors, Locasciulli and Boag (1987) found that snail density was highest in a coniferous forest, intermediate in a deciduous forest, and minimal in a mixed-wood forest. Since snail density was also strongly correlated with litter depth in this study, the importance of litter depth and associated moisture levels may have outweighed tree and litter composition effects.

Abele (2010) found that although gastropod species richness was highest in deciduous forests, there were species-specific responses among deciduous- and coniferous-dominated cover types, suggesting that a mixed composition litter is actually better for gastropods as a whole. Mixed-wood stands are generally comprised of a combination of conifer and broadleaf specialists, and may also be distinct habitats that are preferred by certain species (*i.e.,* not simply juxtapositions of deciduous and coniferous forests) (*reviewed in* Abele 2010).

Leaf-Litter

Leaf-litter provides critical microhabitat and food for land mollusks, and both the abundance and composition of this resource are important to gastropods. In a study of deciduous dominated forest types in Alberta, Abele (2010) found most gastropod species were associated with deep leaf-litter. Likewise, in a study encompassing coniferous, deciduous, and mixed-wood forests, Locasciulli and Boag (1987) found snail density to be strongly correlated with litter depth. By increasing moisture retention on the forest floor, leaf-litter offers gastropods protection from dessication in dry periods. Additionally, litter provides protective insulation for gastropods in winter (*reviewed in* Prezio *et al.* 1999). Since gastropod winter-kill can be very high (*e.g.*, 44% of adults and 18% of juvenile gastropods), winter conditions (*e.g.*, temperatures and snowfall timing and amount) can strongly influence gastropod densities the following summer (Livshits 1983, Prezio *et al.* 1999). Abundant leaf-litter is thought to buffer the effects of limited snow cover during cold periods, both via insulative properties and by energy released from leaf decomposition, the latter of which contributes to warming and thawing at the soil surface under the snow (*reviewed in* Prezio *et al.* 1999).

Although leaf-litter is inarguably an important gastropod food source, leaves from different tree species differ in their chemical composition and nutritive value to gastropods. For example oak and beech leaves are rich in oxalate-bound calcium, while leaves of ash, lime, maple, and elm are dominated by calcium citrate and other more soluble forms of calcium (Wäreborn 1979). In an experimental examination of snail reproductive success in response to additions of calcium salts in the substrate, it was found that both calcium citrate and calcium oxalate additions increased reproductive success (number of offspring), although calcium citrate generated significantly higher number of offspring than calcium oxalate. These differences may thus be related to habitat preferences of mollusks between different types of deciduous woods, especially in calcium-poor environments.

Coarse Woody Debris

As a result of their need for high humidity, snails and slugs are particularly sensitive to the shelter and shade provisions of their microhabitats (*reviewed in* Kiss and Magnin 2006). Many mollusks require logs, shallow hollows, crevices next to stumps, and other moist, sheltered microsites for oviposition, aestivation, hibernation, feeding, breeding, and refuge during dry weather (*reviewed in* Kappes 2006, Hylander *et al.* 2004). Decaying wood can absorb and retain water for several weeks during periods of low precipitation, providing a buffer from microclimate extremes (Kappes 2005). Logs, in particular, are associated with a large number of snail species, and gastropods susceptible to low soil moisture may benefit from environmental conditions occurring beneath logs (*reviewed in* Kappes 2006).

In addition to microclimate effects, coarse woody debris has a significant influence on gastropod food availability. Dead and decaying wood promote a diversity of fungi, an important food resource for many slugs and snails (*reviewed in* Kappes 2005). Coarse woody debris can also influence soil chemistry in gastropod habitat. Microhabitat analysis by Müller *et al.* (2005) showed higher pH values and higher calcium content at the bottom of large snags and under large lying pieces of dead wood relative to litter, upper mineral soil, and substrate at the bottom of living trees. Moreover, snail species richness and abundances were significantly linked to these patterns of chemical parameters.

In a study specifically examining the influence of coarse woody debris on forest gastropod assemblages, coarse woody debris was found to have a strong influence on gastropod fauna in all seasons, while the other variables examined in the study (location and season) had little to no influence on community structure (Kappes 2005). In this study, two dominant snail species occurred independently of the three factors analyzed, while seven snail species clearly preferred sites high in coarse woody debris. Additionally, life-stage analysis of the five most abundant species revealed clear dependence of one species on the sheltered microclimate of coarse woody debris for reproduction (Kappes 2005). These results are consistent with other studies (*e.g.*, Caldwell 1993) highlighting the importance of coarse woody debris to a large percentage of land snails. With regard to slugs, Kappes (2006) found that forest slugs benefit from older, less-disturbed forests high in coarse woody debris, and the proportion of sensitive slug species increase with the amount of woody debris on the forest floor.

Coarse woody debris can also mitigate the effects of disturbance. In one study, the presence of decomposing woody debris on logging trails appeared to reduce the adverse effects of clearcuts on soil invertebrate populations (Addison & Barber 1997). In another study, Bros *et al.* (2011)

found that post-fire management in which branches were spread on the ground generated a positive response for snails, presumably due to moist refugia provided by the accumulation of wood debris on the ground.

Müller *et al.* (2005) identified coarse woody debris cutpoint values separating beech stands with low snail density and richness from stands with high snail density and richness. In this study, 50 to 57 m^3/ha total dead wood and 15 to 40 m^3/ha advanced decomposed dead wood resulted in significantly higher snail richness and density.

Forest Age

Numerous studies suggest that gastropod abundance and community composition are positively influenced by forest age (*e.g.,* the older the forest, the greater diversity of land mollusks). For example, a German study examining the impact of forest age (ranging from zero to 400 years) on mollusk richness found the number of species per plot significantly increased with forest age, and significant forest age threshold ranges for mollusk species richness ranged from ~140 to 205 years (Moning & Müller 2009). Similarily, Reinink (1979) found a strong correlation between gastropod species richness and forest plantation age in the Netherlands, Kappes (2006) found the proportion of stenoecious (narrow environmental tolerances) forest slug species increased with forest age and the amount of woody debris on the forest floor, and Cameron *et al.* (1980) found increases in mollusk diversity related to habitat-age. In a study of beech forests in Germany, Müller *et al.* (2005) identified stand-age cutpoint values separating stands with low snail density and richness from stands with high snail density and richness; cutpoints for significantly higher snail richness and density were defined at stand ages of 170 and 187 years, respectively.

A series of studies in boreal forests in Sweden also point to the importance of forest age in governing gastropod species composition, although in this case gastropod richness was found to be highest in intermediate-age stands. Hylander *et al.* (2004) found both richness and abundance of mollusks were significantly depressed in 2.5 year-old regenerating forests relative to mature stands, but when regenerating forests were in later successional stages (40–60 years old), gastropod richness was higher in regenerating stands, and only two of sixteen species were more abundant in the old forest plots (Ström 2004, Ström *et al.* 2009). In the long-term studies, differences in litter composition were noted between regenerating (mostly deciduous) and mature (mostly coniferous) forests, and abundance and species richness were strongly correlated with the cover of moist ground and litter pH (significantly higher in regenerating forests) (Ström *et al.* 2009).

Contrary to these studies reporting positive correlations between stand age and gastropod community structure, Hawkins *et al.* (1997b) found no difference in gastropod species richness between a nine-year-old spruce plantation and a mature 70-year-old mixed wood forest, although mean density was higher in the regenerating forest than in the uncut forest, primarily due to greater numbers of a few species in the regenerating forest. Similarly, Strayer *et al.* (1986) found no clear relationship between gastropod density, species richness, or community composition and time elapsed since clearcutting disturbance (2 to >60 years). Species richness and density declined following disturbance, but declines seemed short-lived; sites disturbed five years earlier had already returned to pre-disturbance levels. The quick recovery of gastropod communities following forest disturbance in this study was attributed to the rapid recovery of the vegetation, and to the small size of disturbed areas (cut areas were mostly less than 10 ha), facilitating recolonization from surrounding, undisturbed areas (Strayer *et al.* 1986). Another explanation posed by later researchers (*e.g.*, Hawkins *et al.* 1997b) is that a large reservoir of gastropods in the soil was the source of colonizers. Vertical movement of these organisms can quickly restore the detectable community on the surface, provided that suitable microclimate is re-established for all of the original species. Anderson (2004) warns against applying the results of Strayer *et al.* (1986), a New England study, directly to western forests, due to several factors including the generally higher moisture levels and deciduous components of eastern forests relative to western forests. Similar to Strayer *et al.* (1986), another eastern forest study examining snail diversity and abundance in eleven forests of different compositions, ages, and with differing disturbance histories found that snail abundance and diversity were not correlated with forest age (Jacot 1935). In this study, the proximity of cut forests to old growth stands and the amount of shelter available in a stand both influenced the repopulation of cut sites (Jacot 1935).

Forest size and distance to forest edge

Due to high variability in microclimate conditions at forest edges (*e.g.*, Chen *et al.* 1993), it is expected that forest size and distance to forest edge should be important landscape variables in structuring gastropod communities. However, very little research has been done in this regard. An Ohio study examining slug assemblages with regard to forest patch size and distance to forest edges found no significant relationships, although there was a non-significant trend for greater slug diversity at larger forest patches (Brady & Pearce 2007). At the landscape scale, Götmark *et al.* (2008) found that the area of conservation forest (woodland key habitat) within 10 km of gastropod survey plots was positively associated with species richness and also related to species composition.

GASTROPOD RESPONSE TO SILVICULTURE PRACTICES

Realized and potential impact of logging on snails

As a group, forest snails depend on various forest attributes that are frequently associated with old growth or intact forests, including shadiness and humidity, a stable microclimate, adequate calcium content, diverse vegetation, a sufficient amount of litter and coarse woody debris, and habitat continuity (Müller *et al.* 2005). These habitat dependences, coupled with limited mobility with which to escape unfavorable conditions, suggest that silviculture activities and associated microhabitat changes would negatively impact snails and slugs at logged locations. This review identifies five ways in which tree harvest can significantly impact terrestrial gastropods, as indicated by biological characteristics and habitat needs of the group, as well as results of direct studies.

Increases in microclimate extremes
Reductions in canopy cover lead to increases in microclimate extremes in snail habitat. The microclimate of canopy gaps and clearcuts is characterized by increased soil temperatures, air temperatures, wind velocity, and short-wave radiation; enhanced rates of evaporation; and decreased relative humidity compared with undisturbed forest (*reviewed in* Bloch & Willig 2006, Chen *et al.* 1993). Additionally, daily differences (*i.e.*, maximums minus minimums) of these variables is greater in canopy gaps than in intact forest, resulting in consistently greater microclimate variability in cleared habitat (Chen *et al.* 1993). Since terrestrial gastropods are particularly vulnerable to elevated temperatures and reduced humidity (Asami 1993, Baur & Baur 1993), and since desiccation is a major cause of snail mortality (Solem 1984 *in* Bloch & Willig 2006), the hot, dry conditions found in canopy gaps can have serious negative effects on gastropods, decreasing population densities, and even resulting in local extirpation of less abundant species (Bloch & Willig 2006).

Changes in forest vegetation and litter
Logging is well-known to alter natural successional processes and influence the diversity, abundance, and composition of forest vegetation over both the short and long-term (Battles *et al.* 2001, Halpern & Spies 1995). Such changes, in turn, alter the composition, abundance, and chemistry of litter reaching the forest floor (France 1997). As reviewed above, leaf-litter is an important food and habitat resource for gastropods, providing essential nutrients and offering protection during drought and winter (Asami 1993, Prezio *et al.* 1999). Although traditional forestry practices often favor the establishment of simple stand structures that produce coniferous wood, a number of studies (reviewed above) show that snails are dependent on litter from deciduous trees and have higher abundances in forests with strong broadleaf components. Thus, conifer plantations managed to reduce competition from hardwoods are expected to be unsuitable to many gastropod species (Hawkins *et al.* 1997b).

Reductions in coarse woody debris
Coarse woody debris is an important structural component of natural forests and a critical habitat resource for gastropods (reviewed above). If logging slash is left on site, tree harvest can result in a dramatic initial increase in coarse woody debris available to gastropods (*e.g.,* Abele 2010). However, clearcut logging with no slash retention directly reduces the abundance of coarse woody debris on the forest floor by removing branches, limbs, and bark (France 1997). Such reductions can continue even after forest regeneration; France (1997) report reductions of coarse woody debris over the long-term (4 to 10 years) via dramatic shifts in overstory composition from conifers to deciduous trees. According to Kappes (2005), woody debris is often rare in managed forests.

Soil compaction and other changes in microhabitat structure
The use of heavy equipment in logging can affect snails and their habitat via direct mortality, soil compaction, and damage to (or removal of) the organic layer. Although the specific impact of logging equipment on terrestrial mollusks has not been examined (Anderson 2004), a study measuring the effects of human trampling on mollusks in leaf litter found that changes in litter structure, decreases in litter depth and volume, decreases in air space, penetration of soil into the litter, and physical impacts of treading all combined to cause drastic declines (generally

over 50%) in abundance of both snails and slugs in the treaded treatments (Duffey 1975). Although this study examined treading by humans, even stronger effects are expected to occur as a result of treading by logging equipment and vehicles. Mechanisms by which invertebrates are impacted by treading include direct destruction (crushing) of individual animals by foot or machinery contact, and (more significantly) changes in microhabitat structure, such as disturbance or removal of ground vegetation, litter, decaying logs, or rocks (Duffey 1975).

Population fragmentation and changes in genetic population structure
By altering microclimate and reducing or eliminating snail resources, logging can cause large breaks in snail habitat. Since gastropods generally have dispersal potential too low to enable them to bridge such habitat breaks (Moning & Müller 2009, Baur & Baur 1993, Baur 1993), isolated populations may result. Small and fragmented populations are generally at greater risk of extinction from normal population fluctuations due to predation, disease, and changing food supply, as well as from natural disasters such as floods or droughts (*reviewed in* Shaffer 1981). Small populations are also threatened with extinction from a loss of genetic variability and reduced fitness due to the unavoidable inbreeding that occurs in such small populations (*reviewed in* Shaffer 1981). Indeed, logging disturbance has been found to cause changes in the genetic population structure of gastropods. Stiven (1989) studied the genetic properties of two terrestrial gastropods (*Mesomphix* spp.) in paired control and previously logged forests, and conclude that over the short term disturbed populations may show classical declines in heterozygosity and fitness resulting from founder effects, drift, and inbreeding, while over the long-term (*e.g.*, ~60 years) sites with historical disturbance exhibit increased genetic variation.

Gastropod responses to logging vary with silviculture method.
Clearcutting is a widely used even-age silvicultural method involving removal of an entire stand in one cutting. Alternative, uneven-aged management strategies such as green-tree retention (also known as variable retention) and thinning involve retention of some mature trees in the stand, either scattered or in groups. In the Pacific Northwest, retention of live (green) trees in harvest units is an integral part of forest management practices on federal lands (Aubry *et al.* 2009), motivated by the expectation that such practices provide structural complexity (*e.g.*, live and dead trees of varying sizes, multi-layered canopy, coarse woody debris on the forest floor) which renders regenerating stands habitable either continually or earlier than regenerating clearcuts (Huggard *et al. in press*, Ovaska & Sopuck 2010). A recent review of 214 green-tree retention studies found that, relative to clear-cutting, green-tree retention lowers the harvest related loss of organisms and improves biodiversity by (1) 'lifeboating' species over the regeneration phase, (2) providing microhabitats both for old-forest species in re-established forest stands and for disturbance-phase species on the recent cuts, and (3) enhancing species' dispersal by increasing landscape connectivity and facilitating dispersal of organisms from retained forested refuges to logged areas (Rosenvald & Lõhmus 2007). However, the success of this method at maintaining microhabitat conditions and lowering the loss of populations or individuals due to tree harvest depends heavily on the density, spatial arrangement, and species of retained trees (Rosenvald & Lõhmus 2007). The current federal standard for regeneration harvest (not thinning) requires retention of 15% of each harvest unit. According to

Aubry (2009), this standard does little to achieve the intended goal of microclimatic amelioration, and considerably greater levels of retention are needed to effectively reduce solar radiation and air or soil temperatures.

With regard to gastropods, several studies have examined community structure responses to clearcutting, thinning, and variable retention harvest. Overall, clearcutting has been found to have drastic negative effects on gastropods, at least over the short term. For example, in a study comparing gastropod abundance in undisturbed forests with forests that had been clearcut 5 to 10 years previously, Kralka (1986) found all but one of thirteen species had higher abundance in the undisturbed forest sites. Logging in this study involved removal of mature trees, destruction of the understory vegetation, and stripping or redistribution of topsoil by machinery, all of which may help explain observed abundance losses in gastropods (Kralka 1986).

Studies comparing relative impacts of clearcutting and other harvest practices on mollusks generally report stronger negative impacts from clearcutting. Hylander *et al.* (2004) examined the initial effects (2.5 years) of clear-cutting versus clear-cutting with buffer retention on the litter dwelling snail community in riparian forests along small boreal streams in Sweden. Two different silviculture treatments were applied at each of fifteen sites: clear-cutting across the stream channel, and retention of 10 m-wide buffer strips on each side of the stream. Additionally, 10 unlogged riparian reference sites were examined. Clear-cutting had profound effects on land-snail communities in this study, with most species negatively affected. Following clear-cutting, mean snail abundance and species richness in a 0.5 m^2 sample both decreased significantly, from 107 to 87 individuals, and from 9.9 to 7.7 species, respectively. In the uncut reference sites, no significant differences were detected between the years. Buffer strips with green tree retention were found to have reduced snail abundance, but species diversity was not lower relative to uncut sites, indicating that leaving small groups of intact trees is a good practice for snail conservation in riparian habitats and can lead to significant increases in the survival of species. Similar to the above study, McDade (2002) examined forest floor animal abundance and habitat relationships under three different silviculture conditions: clearcuts, commercial thins, and uncut areas in the Umpqua National Forest of the Southern Oregon Cascades. Both species richness and diversity were found to decrease with harvest intensity, and commercial thinning affected forest gastropod populations less severely than clearcut harvesting. Gastropod abundances were similar between thinned and uncut stands, but gastropod abundance was significantly lower in clearcuts than uncut areas.

In contrast, in a study of the impact of strip clearcutting and selective cutting on soil fauna abundance in a northern hardwood forest of Québec, Moore *et al.* (2002) report no difference between the two logging methods six to twelve years post-treatment. Moreover, although species richness was not examined in this study, snail abundance was found to be higher in the treated forests than in the adjacent undisturbed forest (control sites). The authors attribute this finding to (1) the presence of uncut forest near the harvested areas, (2) the retention of the majority of the forest canopy in the selective cut areas, (3) the fast recovery of vegetation cover in strip clearcuts, and (4) the abundance of coarse woody debris left after the cuts.

In a study examining gastropod assemblages in response to dispersed retention harvesting in mixedwood boreal forests of northwestern Alberta (clear cut, 10% retention, 20% retention, 50% retention, 75% retention, and unharvested controls (100% retention)), increases in retention levels had no observable effect on gastropod species richness nine years post-harvest (Abele 2010). Moreover, rather than reducing gastropod abundance, increased harvest intensity was associated with overall increases in gastropod abundance in this study, with several species responding favorably to low retention (intense harvest) treatments. Other species, however, responded negatively to intense tree harvest. Overall, increased retention was found to help to maintain pre-harvest boreal gastropod assemblages and promote the abundance of certain logging-sensitive species that were less common, uncommon, or absent in sites with the lowest retention levels.

Increases in leave island size result in increased mollusk abundance and richness.
In another comparison study, Ovaska & Sopuck (2010) examined the short-term (2 to 4 year) effects of variable retention (VR) treatments and clearcutting on terrestrial gastropod abundances in coastal forests of British Columbia. In the VR-treatments, trees were retained either in groups or were dispersed within the logged area. It was found that VR-treatments with large (0.8 – 1.2 ha) groups of trees were more effective at promoting gastropod abundance than clearcuts and small (0.2 – 0.5 ha) groups, and were equivalent to the un-cut control in terms of species richness, but lower in individual species' abundance values. In small VR-groups, gastropod abundance and richness was similar to clearcuts (depressed values) regardless of the overall retention level (10%, 20%, or 30%) in the cutblock. The lack of difference between small VR-group treatments and clearcuts may be attributed to the fact that although the forest floor in the VR-groups remained physically undisturbed during logging, they were relatively unprotected from changes in microclimate that decrease habitat quality for gastropods (*e.g.*, edge effects, exposure to wind, elevated temperatures, drying). For the VR-dispersed treatment, 30% retention was more effective than 5% and 10% retention at promoting gastropods. Overall, this study concluded that large groups of retained trees (0.8 – 1.2 ha) and retention levels above 30% may be needed to maintain pre-logging abundance of most sensitive gastropod species. This is consistent with findings in a review paper by Aubry *et al.* (2009) in which retention in 1-ha aggregates was more beneficial than dispersed retention for a wide variety of response variables. In this review, aggregate retention greatly reduced damage to and mortality of residual trees (particularly at lower levels of retention) and provided short-term refugia for forest organisms sensitive to disturbance or environmental stress (Aubry *et al.* 2009). Other studies indicate still higher retention levels may be necessary for maintaining gastropod abundance. For example, in a study of high-elevation coniferous forest in British Columbia, Huggard and Vyse (2002) found the relative abundance of slugs was most similar to that of the control in a uniform individual tree selection treatment with 80% tree retention, and was reduced by up to 35% in treatments with 10 ha clearcuts, 1 ha clearcuts, and 0.1 ha patch cuts with 300 m leave-strips.

Wessell (2005) also examined short-term (2 to 5 yr.) differences in the abundance and diversity of mollusks and other biota with respect to thinning and leave island size in four western Oregon managed forests. Five forest types were studied: unthinned (600 trees/ha), thinned (200 trees/ha), and thinned with three sizes of leave islands (0.1, 0.2, and 0.4 ha) embedded in the thinned forest matrix. In this study, leave island size was positively correlated with mollusk density, suggesting that the greater the retention area, the more positive effects on mollusks. Significant negative effects of thinning were detected for the most abundant of the five mollusk species examined.

Conifer release by motor and manual clearing is less detrimental to gastropods than herbicide treatments.

Conifer release treatments are used to reduce the effects of competition from undesirable vegetation (hardwoods, shrubs and herbs) in young conifer plantations. Hawkins *et al.* (1997b) and Prezio *et al.* (1999) examined terrestrial gastropod species richness and density in regenerating spruce plantations before and 1 to 3 years after four different conifer release treatments: application of the chemical herbicide Vision® [a.i. glyphosate], application of the chemical herbicide Release® [a.i. triclopyr]), cutting by mechanical means, and motor-manual cutting with brush saws. Despite marked changes in vegetation structure on the conifer released sites, no differences were evident in species richness and density of gastropods following either chemical, mechanical, or motor-manual treatments in the first year after treatment (Hawkins *et al.* 1997b). However, during both the second and third year after the treatments, gastropod densities in untreated control areas were significantly greater (50–60%) than those in chemically treated areas (but still did not differ from motor-manual and mechanical cutting treatments) (Prezio *et al.* 1999). Gastropod densities in nonchemical, cutting treatments started to recover more quickly than those in herbicide-treated sites (Prezio *et al.* 1999). Observed density patterns in this study may be attributable to differences in litter deposition and near-ground microclimate between the treated and untreated sites (Prezio *et al.* 1999).

Gastropod responses to logging are often species-specific.

Old-growth specialist invertebrates tend to disappear from clear-cuts, while forest generalists may persist and open-habitat species may appear (Niemelä 1997).

Old-forest dependent species

At the landscape scale, intensive logging tends to homogenize forest habitats and lead to declines of sensitive, old-growth dependent species (Niemelä 1997). The literature identifies several mollusk species which are sensitive to logging disturbance. On Vancouver Island, studies of mollusk response to clearcut and variable retention logging found that the robust lancetooth (*Haplotrema vancouverense*), western flatwhorl (*Planigyra clappi*), and tightcoil snails (genus *Pristiloma*) all exhibit reduced abundance in response to logging (Ovaska & Sopuck 2010). Consistent adverse effects were also detected for small snails as a group (Ovaska & Sopuck 2010). Wessell (2005) also found that of 5 species examined, *Haplotrema vancouverense* was the only one with a significant negative response to decreasing leave island size in thinned forests in western Oregon. Another study examining gastropod response to clearcuts and commercial thins in the Umpqua National Forest identified *Haplotrema* snails as particularly sensitive to tree removal, based on their positive relationship with canopy cover and tree basal area (McDade 2002). In a study of variable retention harvest in boreal forests in Alberta, the slug *Deroceras laeve* was the second most dominant gastropod in unharvested treatments, but exhibited notable declines in response to even the lowest amount of canopy removal (Abele 2010). The snail *Discus shimekii* showed a drastic decline in abundance with increasing harvest intensity, and was uncommon or absent in sites with the lowest (dispersed) retention levels (Abele 2010). Higher levels of retention seemed to better conserve these harvest sensitive species (Abele 2010). Hylander *et al.* (2004) identified eight species negatively impacted by clearcut logging: *Clausilia cruciata, Columella aspera, C. edentula, Discus ruderatus, Euconulus fulvus, Nesovitria hammonis, N. petronella,* and *Vertico ronnebyensis.* In this study, the snail species most affected by clear-cuts were those with habitat preferences for relatively oligotrophic, shady, moss-rich forests (Hylander *et al.* 2004).

Generalist species

Conversely, some species (especially those with some tolerance to desiccation) may benefit from conditions generated by canopy-opening disturbance, either by reductions in predation or competition, or by exploitation of a new or increased resource (Bloch & Willig 2006, Niemelä 1997). This may be particularly true of species that have evolved in arid or disturbance-mediated environments (Asami 1993, Bloch & Willig 2006), or are good colonizers (Kralka 1986). For example, a study of 13 terrestrial gastropod species in boreal forests in Alberta found that while most species had lower abundance in disturbed forests, one species (*Punctum minutissimum*) showed a statistical preference for logged forests in early stages of succession, possibly due to this species' greater recolonization potential and/or greater tolerance of habitat conditions in early successional stages of regenerating forests (Kralka 1986). Similarly, a study of slug response to logging, roads, and other anthropogenic disturbance in 68 broad-leaf forests in Western Europe found that exotic slug species profited from high anthropogenic disturbance, while stenoecious species (*i.e.*, with narrow environmental tolerances) were more abundant in older, comparatively undisturbed forests (Kappes 2006). In another study, the abundance of the slug *Ariolimax columbianus* decreased in clearcut treatments, relative to the control and pre-logging values, but increased in logged stands with 20% and 30% of the trees retained in groups, suggesting a positive effect of retention treatments on this species (Ovaska & Sopuck 2010). Similarly, the relative abundance of the slug *Prophysaon foliolatum* tended to be higher in all VR-group treatments when compared to both control and clearcut sites, again suggesting a positive effect of VR-group treatments on this species (Ovaska & Sopuck 2010). In this study, groups of trees in VR-treatments may have provided shaded micro-sites on the forest floor from which these slugs could take advantage of the abundant forage of herbaceous vegetation in the surrounding harvested areas (Ovaska & Sopuck 2010). In the aforementioned study of variable retention harvest in boreal forests in Alberta, *Discus whitneyi, Zonitoides arboreus,* and *Euconulus fulvus* were each found to benefit from conditions generated by increased harvest intensity nine years post-harvest, possibly as a result of changes in vegetation and litter composition that favored these species (Abele 2010). According to Niemelä (1997), the persistence of forest generalists and appearance of open-habitat species in logged areas may result in increased invertebrate species richness at some sites, despite declines and losses of species directly associated with microhabitats characteristic of old growth forests (*e.g.*, coarse woody debris, large deciduous trees, and patches of wet swamp-forest) (Niemelä 1997).

IMPACTS OF ROADS ON GASTROPOD DISPERSAL AND POPULATION GENETICS

Road construction eliminates and degrades snail habitat.

Similar to clear-cut areas, roads result in open spaces void of trees, vegetation, leaf litter, and woody debris, all of which are important habitat components for snails and slugs. Moreover, the microclimate conditions in roadways (reduced shade and humidity; increased solar radiation and ground temperatures) further reduce suitability of the habitat for snails (Frest 2002). According to Frest (2002), mollusk populations are not only extirpated in the roadway proper, but impacts can extend into adjacent habitat as well, due to site preparation, road construction, vehicle use, and maintenance activities. The literature commonly cites a disturbed or polluted zone up to 5 m from the road, although impacts on ecological communities have been shown up to 100 m from a road (*reviewed in* Underhill & Angold 2000). Compacted soils and pollutant run-off are among the most obvious impacts of roads on invertebrates. Roads accumulate a variety of contaminants (*e.g.*, brake dust, heavy metals, deicing salts, and organic pollutants, which are carried as overland runoff into the surrounding habitats (Forman & Alexander 1998, Jones *et al.* 2000). Additionally, vehicle and foot traffic increase introductions of nonnative and/or noxious plant and animal species (Forman & Alexander 1998), changing the local plant community (*i.e.*, gastropod food sources) and often increasing vegetation management (*e.g.*, herbicide use and/or manual clearing of vegetation) presumed to further damage snails and/or their habitat. (Frest 2002, Wirth *et al.* 1999).

Roadways cause direct mortality in snails.

Traffic is generally considered to be the major source of mortality for animals that cross roads to move between habitats (*e.g.,* Wirth *et al.* 1999). For snails, both traffic and desiccation cause mortality in roadways (Baur & Baur 1990). In a study of the effect of road width/type on dispersal in the land snail *Arianta arbustorum,* numerous crushed snails were found along the road and the track verges, even on roads with low traffic density (Baur & Baur 1990). Road-induced mortality was exacerbated by the fact that snails were attracted to roadways in rainy weather, and often unable to find their way off the road when conditions became unfavorable.

> "During rainy nights, many snails were observed to move on the paved road parallel to the vegetation belt to which they returned when the pavement dried up in the morning. Snails, creeping on a dry substrate with a rough surface such as a paved road, have high costs (water loss and production of enormous amounts of mucus) Considering the pace of a snail, it can be estimated that an adult *A. arbustorum* needs 1-2 hours to

cross an 8 m wide road. However, snail paths were usually linear only when they were following humidity gradients. In the middle of the paved road the paths generally lost their directionality, resulting in random walk, which led to additional water loss and forced the snails to stop and spend the day somewhere on the road, with obvious fate" (Baur & Baur 1990).

Traffic related mortality may also vary seasonally. For example, traffic-deaths of *A. arbustorum* are thought to be highest in early summer, when maximum mating and feeding activities occur and individuals travel the greatest distances (Baur & Baur 1990).

Roadways hinder snails' ability to disperse.

Roads are well known to pose movement and dispersal barriers to large animals (Underhill & Angold 2000, Forman & Alexander 1998), and are considered to be even less passable to small, soft-bodied, slow-moving animals like snails and slugs (Frest 2002). The low-mobility of terrestrial gastropods is compounded by the general lack of directionality to what little movement they do have. For example, Baur and Baur (1993) found that apart from avoiding drier (non-vegetated) habitat, snails showed no preference in direction of movement. The directions chosen by an individual on consecutive days were independent from each other, consistent with the assumptions of a random movement model (Baur & Baur 1993, Baur 1993). Thus, even a narrow, low traffic road can be difficult for a snail to cross. According to Baur and Baur (1990), multiple factors influence the degree of dispersal restriction due to roads, including road width, road type, and traffic density. This study examined the effect of road width/type on dispersal in the land snail *Arianta arbustorum* by recording displacements of marked individuals during one activity season (3 months) at three sites in central Sweden: a paved road (8 m wide, low traffic density) and an unpaved track (3 m wide), and an overgrown path (0.3 m wide). At the paved road and unpaved track, the snails' movements were largely confined to roadside vegetation belts. After 3 months, only one (0.6%) of the 168 recaptured snails crossed the paved road, despite the fact that seven snails (4.1%) moved at least 8 m along the verges, a distance corresponding to the width of the paved road. Likewise, only two snails (4.3%) crossed the track, even though 23 individuals (49.0%) moved a distance longer than the 3 m track width. By contrast, the overgrown path did not influence the snails' movement (Baur & Baur 1990). In a similar study, Wirth *et al.* (1999) tested the effect of road width on dispersal and genetic differentiation in the land snail *Helicella itala*. Movements of marked snails were monitored over a one-month period across the following road types: 6- and 9-m wide high traffic paved roads, 3-m wide low traffic paved road, 3-m wide unpaved track, and 0.3-m wide overgrown path. Snail movement was found to be largely confined to roadside verges. Despite the observed capability of snails to cover large distances (*e.g.*, 17.45 m) none of the 560 marked snails crossed the 6- and 9-m wide roads with heavy traffic, suggesting that snail dispersal is inhibited by wide roads with high traffic density. Only one individual crossed the 3-m wide unpaved track, and 2 individuals crossed the 3-m wide low-traffic paved road. In contrast, snail movement was not restricted by a 0.3-m wide overgrown path. Results suggest that paved and unpaved roads of both high and low traffic densities act as barriers to dispersal between snail populations, and populations separated by roads may be isolated from each other (Baur & Baur 1990, Wirth *et al.* 1999).

Road-avoidance behavior is common in snails.

Although snails may be attracted to roads under wet conditions (see Baur & Baur 1990, above), research also highlights road avoidance behavior in snails, largely due to the lack of leaf litter (Meadows 2002) and vegetative cover (Baur & Baur 1993) on roadways. Meadows (2002) examined road avoidance and its proximate causes in the Ogden Rocky Mountain snail, *Oreohelix peripherica wasatchensis.* Movement preference relative to pathways was assessed in the field, while habitat features causing pathway avoidance were assessed with laboratory choice studies. Control site snails were found to have no directional movement preference, while snails at road and trail sites moved away from pathways. In the laboratory, snails preferred natural substrate with leaf litter to road material. Both the field and laboratory experiments revealed that the road avoidance exhibited by this species was due to the absence of leaf litter, indicating that even small paths (the smallest measured in this study was 0.7 m [2.3 feet] wide) have an effect on snail movement if no litter is present. Similarly, in a study of the daily movement patterns and dispersal in the land snail *Arianta arbustorum*, Baur and Baur (1993) found the snails' movements were confined to favorable vegetation; in a 1-m wide belt of tall grass and forbs, individuals did not enter into drier surroundings (mowed meadow) but continued to move in a new direction within the belt. This study is consistent with other reports that mollusks avoid pathways which lack vegetation cover (*e.g.*, Oggier 1997 *in* Underhill & Angold 2000).

Roads change the direction and intensity of gene flow across the landscape.

Regardless of the mechanism (roadkill vs. road-avoidance), roads impose significant barriers to gastropod dispersal (Wirth *et al.* 1999, Baur & Baur 1993), suggesting this group is especially prone to the effects of population subdivision by anthropogenic habitat fragmentation, including severely reduced gene flow between populations, increased inbreeding within populations, and increased random genetic drift (*e.g.*, Arnaud *et al.* 1999). Molecular studies of snail population genetics in relation to roads, however, have yielded varying results, and genetic isolation of gastropod populations by roads is not well documented. In a study of the effect of roads on genetic differentiation in the land snail *Helicella itala*, molecular data indicate a moderate amount of gene flow between populations on opposite sides of wide (6 - 9 m) roads, despite no observations of snail dispersal across such roads (Wirth *et al.* 1999). Similarly, in a study of the genetic structure of 15 populations of the land snail *Helix aspersa* in northwestern France, Arnaud *et al.* (1999) report that genetic structure did not show the clear pattern expected if roads acted as barriers on individual dispersal. The less-than-expected genetic impact of roads in these studies may be due to passive, wind-driven dispersal across roadways on leaf litter or mown vegetation (a common phenomenon in snails), which would allow for gene flow even when active dispersal is limited (Wirth *et al.*1999). Alternatively, the extent of genetic differentiation between subpopulations on opposite sides of the road might be strongly affected by the age of the road (*i.e.*, duration of isolation), although the variety of repeated road-building activities and disturbances on roadways often do not allow for such analysis (Wirth *et al.* 1999).

In highly modified landscapes, roadside habitat may restore some connectivity. Paradoxically, while roads are the source of much habitat fragmentation, roadside verges (vegetated strips parallel to roads) may be a mechanism by which to restore connectivity in a highly disturbed and fragmented landscape (Underhill & Angold 2000). Due to their linear nature, roads and their verges can link a range of different habitats, thus facilitating biotic movement through an otherwise unsuitable landscape (Underhill & Angold 2000). With regard to snails, Arnaud (2003) studied the spatial genetic structuring of a metapopulation (32 colonies) of the land snail *Helix aspersa* in an intensive agricultural area in France by genotyping 580 individuals. Different connectivity networks and geographical distances based on landscape features were constructed to evaluate extrinsic barriers to migration and their impact on the genetic distribution. Results showed a progressive decline of genetic similarity with physical distance, suggesting the genetic distances in this metapopulation are environmentally induced, based on genetic drift. Interestingly, a simple Euclidean distance model did not provide as good of a fit as a model based on landscape-based geographical distance, the latter of which took into account the tendencies for migration to occur along roadside verges, hedges, or irrigation canal embankments. Relationship trees suggest that in highly fragmented habitats, hospitable linear corridors like roadside ditches or hedges appear to impose directionality in genetic exchanges between local colonies of snails, allowing for moderate but effective genetic connectivity (Arnaud 2003).

Still, snail dispersal in roadside corridors is limited relative to dispersal in unlimited planes. Baur and Baur (1992) modeled the effect of corridor width on dispersal speed in the land snail, *Arianta arbustorum*, an animal repelled by unfavorable habitat at the corridor's edges. Using data on the movement pattern of this species in a natural population, snail dispersal was simulated in an unlimited plane and in corridors of different widths over periods of 120 days. The simulations showed that corridor width affects dispersal speed in land snails. Snail dispersal decreased with decreasing corridor width and never reached distances recorded in unlimited planes. Simulation results are supported by field data and are consistent with reports in the literature that snails disperse more rapidly in extensive, two-dimensional habitats than in corridors such as roadside verges, river embankments, and hedges. The reduced dispersal of snails in corridors may be a result of their behavior at the edges (Baur & Baur 1992). While some species (*e.g.*, carabid beetles and rodents) use the edges of corridors as guiding lines and exhibit more directed movements and rapid dispersal along corridors than in unlimited planes, land snails are repelled by corridor edges and rather than following the edge continue their movement in a new direction, thus dispersing more slowly than in unlimited habitats. Individuals reaching the edge of the vegetation belt generally do not enter the suboptimal surroundings, but turn back at random into the favorable habitat. For these animals, it follows that in narrow corridors, a high proportion of animals will frequently reach the corridor edges, reducing the dispersal speed and consequently resulting in a decreased number of migrants, and lowered gene flow among populations. For rare or narrowly distributed species, this, in turn, may lead to an increased probability of local extinction (Baur & Baur 1992, Akcakaya & Baur 1996).

Overall, while it is clear that roads limit gastropod dispersal, roadways have varying degrees of influence on gastropod genetic structure, highlighting the need for more research into the principal processes generating and maintaining genetic diversity in terrestrial gastropod populations. In order to restore habitat connectivity and prevent further fragmentation of gastropod habitat, it is recommended that efforts be made to protect the habitat adjacent to existing roads, and, when possible, to constrain further development of the existing road network (Underhill & Angold 2000).

GASTROPOD RESPONSE TO FIRE

Theoretical impacts of fire on gastropods

Although natural and anthropogenic fire have played major roles in shaping forest ecosystems in the Pacific Northwest (Agee 1993, Boyd 1999), the impacts of fire management on invertebrate communities are often highly variable (Swengel 2001). Fire has the potential to negatively influence gastropods in several ways: directly, by fire-related mortality, and indirectly, by altering microclimate conditions, and by reducing, eliminating, or otherwise altering resources, including vegetation, fungi, leaf-litter, duff, woody debris, and other habitat elements pertaining to shelter or food. For most animals, indirect effects of habitat loss influence communities much more dramatically than direct effects of heat, smoke, or flames (*reviewed in* Kiss & Magnin 2006).

The degree of fire-related impact and the potential for animals to rebound post-impact are related to a number of factors, namely, the degree of exposure to lethal temperature, the stress experienced in the post-fire environment, the suitability of post-treatment vegetation as habitat, and the ability to rebuild numbers in the site (from survivors and/or colonizers) (Swengel 2001). Direct mortality due to fire exposure can be avoided by animals either in space (*i.e.,* by escaping/retreating into shelter from fire) or in time (*i.e.,* by being in a physiologically least susceptible stage at the time of burn) (Hartley *et al.* 2007). In general, less decline has been recorded for species below ground, within or beneath unburned wood, or above flames in treetops, and greater decline for species in the herb (fuel) layer or near the soil surface, particularly for individuals with low mobility (Swengel 2001, *reviewed in* Kiss and Magnin 2006). Mobility is important in both fire avoidance (*e.g.,* the ability to escape approaching flames and reach suitable unburned habitat) and in post-fire recolonization (*e.g.,* the ability to reach burned sites from unburned sites) (Hartley *et al.* 2007). Since snails and slugs live for the most part on vegetation and in litter, have limited mobility and poor active dispersal aptitudes, and are very sensitive to desiccation, they are highly vulnerable to fire itself and to subsequent habitat destruction (Kiss & Magnin 2006, Burke 1999). In consequence, post-fire return of this group is expected to be slow. According to Burke (1999), intense fire events can result in the persistence of only a small fraction of mollusk fauna for many years (possibly a century or more). Less-severe fires leaving numerous large, minimally charred logs in the stand result in a greater portion of mollusk survival (Burke 1999). For example, Burke (1999) reports unpublished findings in which zero to two or rarely three species may be expected in burned stands without abundant logs remaining, while five to seven species may be expected to be found in stands similarly treated but with the logs remaining, and 13 to 20 or more species may be found in unburned stands. Whether the logs provide protection that allows gastropods to remain through the burn, or provide cover to enable dispersal of gastropods back into the stand has not been determined (Burke 1999).

Numerous studies have found negative responses of gastropods to fire.

Fire-driven population extirpation

A five-year study examining the survival of mollusks in burned aspen groves following fires in Yellowstone National Park found fire to have a major impact on snail survival and abundance (Beetle 1997). One severely burned site had only burned shells the first year following fire, and continued to support no live snails after five years. Other burned sites initially had a few species, but after five years (including two dry years) live snails were no longer present. Two lightly burned sites with hospitable conditions (*e.g.*, damp habitat, abundant litter, uncharred/charred rotten logs) maintained snail populations over the five year period, but species richness didn't increase over that time, and no evidence of migration into burned groves was found, possibly due to the fact that aspen groves in Yellowstone are fairly isolated, making recolonization difficult (Beetle 1997). Similarly, a short-term survey of burned sites with known *Vertigo authuri* snail populations 1 and 2 years post-burn resulted in no live snails of any species (Anderson 2004).

Fire-driven reductions in density (but not richness)

Kiss and Magnin (2006) examined the short, medium and long-term impact of fire on snail biodiversity in forests in southeastern France. Although fire drastically reduced snail abundance, species richness and community diversity were preserved, provided that the time lapse between two successive fires was longer than the time required for recovery (around 5 years). The observed resilience of gastropod communities in this study was largely attributed to the presence of cryptic refuges within burned areas, allowing land snail survival and persistence after successive fires. Similarly, in a study of controlled burns in an agricultural area of Germany, Page *et al.* (2000, 2004) found that while the number of live snails was reduced by more than 50 percent after controlled winter burning, no shift was found in species composition of snails relative to unburned plots (Page *et al.* 2004). Since the burned plots in these studies were relatively small (not more than a 50m wide portion of the slope) and surrounded by unburned plots, the immigration rate after fire was relatively high and rapid (Page *et al.* 2004).

Fire-driven reductions in richness (but not density)

In contrast to the findings above, a Mediterranean study of snail communities in burned and adjacent unburned sites found fire caused declines in snail richness and diversity, while total snail abundance values showed no differences among treatments (Bros *et al.* 2011). In this study, it appears that while some species were lost, other species took advantage of new habitats and expanded their populations, resulting in similar total numbers of snail individuals in burnt and unburnt treatments (Bros *et al.* 2011).

Fire-driven reductions in both richness and density

Hylander (2011) investigated the short-term impacts (2 to 7 years) of forest fires and clear-cutting on forest floor dwelling land snails in Fennoscandia. Snail fauna were sampled below surviving aspens in five burnt forests, and compared with samples under scattered aspens in seven adjacent undisturbed forests. Burnt sites had a significantly lower abundance of individual snails (11 vs. 30 in 0.5 liter sample) and 50% lower species richness (3 vs. 6 species) than undisturbed forests. Burning depleted the snail fauna considerably and some species may be dependent on dispersal and recolonization if they are to recover within the burnt area (Hylander 2011). Nekola (2002) conducted a large survey of land snail faunas from 72 upland and lowland grassland sites in the Midwest United States, including sixteen sites which had been exposed to fire management within the last 15 years. Over 90,000 individuals in 72 different species were observed. In all analyses, a highly significant reduction in richness and abundance was found on fire managed sites. Species richness was reduced by approximately 30% on burned sites, while abundance was reduced by 50–90%. Forty-four percent of 72 snail species experienced a significant reduction in abundance on fire managed sites, while only six species positively responded to fire. The effects of fire differed among snail species, depending on their ecological preferences; most turf–specialists were negatively impacted by fire, while duff–specialists tended to exhibit no significant response (Nekola 2002).

Fire effects can be long-lived.

Once extirpated from a site, populations of most gastropod species are slow to recover (Burke 1999). Sites that appear to be suitable snail and slug habitat, but which have been burned in the past, are reported to support few if any species or individuals even after 50 years and longer. Even abundant, larger species (*e.g.*, *Haplotrema* and *Vespericola*) may take several years to repopulate burned sites once habitat is restored (Burke 1999). In contrast, a much-discussed study by Strayer *et al.* (1986) reports only temporary fire-driven shifts in gastropod populations and no sustainable change in species composition due to fire, as indicated by multivariate ordination of disturbed and undisturbed study sites according to their gastropod community structures. The quick recovery of gastropod communities following forest disturbance in this study was attributed to the rapid recovery of the vegetation, and to the small size of disturbed areas, facilitating recolonization from surrounding, undisturbed areas. Another explanation posed by later researchers (*e.g.*, Hawkins *et al.* 1997b) is that a large reservoir of gastropods in the soil was the source of colonizers. Vertical movement of these organisms could quickly restore the detectable community on the surface, provided that suitable microclimate was re-established for all of the original species (Hawkins *et al.* 1997b).

Fire frequency, timing, severity, and extent can play major roles in the impact of fire.

Frequency

Kiss *et al.* (2004) assessed the impact of various fire regimes over the past 30 years on Mediterranean land snail communities. The role of biogeography in shaping the response patterns of these communities following fire disturbance was also studied. The composition of snail communities was not affected at sites with infrequent fire occurrence over the past three decades, presumably due to the ability of snails to survive in small refuges. At these sites, the overall community composition was more influenced by geography than by fire disturbance. However, in areas where regular disturbance (fire and/or other anthropogenic disturbances that altered the landscape) occurred over decades or centuries, the land snail communities appeared highly modified and shifted to species more specialized to dry areas (Kiss *et al.* 2004). With regard to mollusk conservation, both Page *et al.* (2000) and Agee (2001) recommend a minimum fire-return interval of three years, although some snails may require even more time for recolonization of burned areas (Page *et al.* 2000).

Timing

According to Page *et al.* (2000), burns should be planned for the time of year that all snails will be hibernating, considered by the authors to be at temperatures below freezing. With regard to rare mollusk species, Agee (2001) recommends a rotation of spring and fall burns.

Severity

Although there is little information comparing gastropod responses to differences in burn severity, it is presumed that a fire regime involving low-intensity burns would best maintain gastropod communities. According to Burke (1999), high intensity fire is particularly damaging to gastropod populations as it destroys both the snails and their habitats. Page *et al.* (2000) recommend the use of fast (low-severity) fires to minimize the effects on snails.

Extent

In a study by Page *et al.* (2000), small burn plots (not more than a 50m wide portion of the slope) surrounded by unburned plots enabled high immigration rates from unburned habitat and resulted in rapid post-burn recovery of snails (although small snails still had difficulty recolonizing burned areas). With regard to rare mollusk species, Agee (2001) recommends that greater than 20% of an individual burn unit be left untouched by fire.

Habitat structure can buffer negative impacts of fire.

Kiss and Magnin (2003) studied the immediate and long-term (up to ~30 year) impact of fire on Mediterranean land snail communities, as well as the subsequent patterns of recolonization within these communities. Although land snail communities decreased in diversity and abundance post-fire, distances from burned/unburned boundaries and vegetation refuges did not significantly influence recolonization patterns in this study, countering the original working hypothesis that land snail recolonization progresses from margins of the burned areas and from vegetation areas spared by the fire. In contrast, habitat structure was found to have a strong influence on post-fire community composition, presumably via habitat-related differences in the potential to survive fire. For example, areas with rocks did not burn as intensely as other habitats, and snails at those locations tended to survive in higher numbers. Likewise, areas with deep oak litter apparently promoted survival of certain species. Overall, snail communities in this study were found to be relatively resilient to fire perturbation and one year after a fire all ecological groups were represented (Kiss & Magnin 2006).

Different forest types have also been reported to generate differences in snail survival, probably due to differences in microhabitat structure. For example, Karlin (1961) report that no snails were found in coniferous forests five to seven years after a fire, but snails were present in a more recently burned aspen fire. The authors assert that chance distribution is unlikely to be the only method involved in post-fire recolonization, and certain forest types may allow for the occurrence of small, permanent populations.

Species-specific responses to fire

Similar to clearcuts, burned areas are more open and dry than pre-burn forests, and generally favor a more xerophilous fauna (*reviewed in* Kiss and Magnin 2006). Additionally, since fires typically result in simplified, grass-dominated vegetation structures, post-fire habitat favors gastropod species characteristic of grassy habitats. For example, Bros *et al.* (2011) found that fire resulted in population declines and extirpations of 25 forest species, while simultaneously generating increased abundances of four grassland species. In a study of the relationship between past occurrence of fire and mollusk presence across four national forests in California, Agee (2001) found species with both positive and negative relationships with burned sites. As a group, sensitive ("Survey and Manage") mollusks exhibited higher occurrence at sites with less fire evidence (*e.g.*, no fire or fire only in the distant past) when compared with recently burned sites (Agee 2001). At the species level, *Monadenia churchi* followed this same pattern, while *Helminthoglypta talmadgei* had higher proportions of occurrence in more recently burned sites (Agee 2001).

Fuel reduction treatments

In dry, fire-prone forests impacted by long periods of fire exclusion, protection of rare species may require restoration of firesafe conditions to forests. With regard to gastropods, Agee (2001) recommends that fuel treatments be designed to create firesafe forests by applying the following criteria: surface fuel reduction should result in lower flame length, ladder fuel should be reduced, increasing the height to live crown, and crowns should be thinned to reduce chances of independent crown fires. Specific effects of fuel reduction on gastropods are not well-studied.

Important remaining questions with regard to gastropods and fire include the difference in response between wildfire and prescribed burning, the effect of fire severity, the temporal pattern of recovery, and possible regional differences in fire responses (Hylander 2011).

LITERATURE CITED

Abele, S.E. 2010. Gastropod diversity in the boreal mixedwood forest of northern Alberta – variation among forest types and response to partial harvesting. M.S. Thesis. Edmonton, Alberta: University of Alberta. 107 pp.

Addison, J.A. and K.N. Barber. 1997. Response of soil invertebrates to clearcutting and partial cutting in a boreal mixedwood forest in Northern Ontario. Natural Resources Canada, Canadian Forest Service, Great Lakes Forestry Centre. Information Report GLC-X-1. 23 pp. Available at http://cfs.nrcan.gc.ca/pubwarehouse/pdfs/9135.pdf (Accessed 20 May 2011).

Agee, J.K. 1993. Fire Ecology of the Pacific Northwest. Island Press, Washington, D.C., 493 pp.

Agee, J.K. 2001. GOBIG2K: an analysis of fire and mollusk species in California National Forests covered by the Northwest Forest Plan. Final Report, USDA Forest Service, Klamath National Forest. Yreka, California, USA.

Akcakaya, H.R. and B. Baur. 1996. Effects of population subdivision and catastrophes on the persistence of a land snail metapopulation. Oecologia 105: 475–483.

Anderson, T. 2004. Callused Vertigo (*Vertigo authuri*): a technical conservation assessment. USDA Forest Service, Rocky Mountain Region. Available at: http://www.fs.fed.us/r2/projects/scp/assessments/callusedvertigo.pdf (Accessed 27 June 2011).

Arnaud, J.F., Madec, L., Bellido, A. and A. Guiller. 1999. Microspatial genetic structure in the land snail *Helix aspersa* (Gastropoda: Helicidae). Heredity 83: 110–119.

Arnaud, J.F., 2003. Metapopulation genetic structure and migration pathways in the land snail *Helix aspersa*: influence of landscape heterogeneity. Landscape Ecology 18: 333–346.

Asami, T. 1993. Interspecific differences in desiccation tolerance of juvenile land snails. Functional Ecology 7: 571-577.

Aubry, K.B., Halpern, C.B., and C.E. Peterson. 2009. Variable-retention harvests in the Pacific Northwest: a review of short-term findings from the DEMO study. Forest Ecology and Management 258: 398-408.

Ball, M.C., Lankester, M.W., and S.P. Mahoney. 2001. Factors affecting the distribution and transmission of *Elaphostrongylus rangiferi* (Protostrongylidae) in caribou (*Rangifer tarandus caribou*) of Newfoundland, Canada. Canadian Journal of Zoology 79:1265–1277.

Battles, *J.J.*, Shlisky, A.J., Barrett, R.H., Heald, R.C., and B.H. Allen-Diaz. 2001. The effects of forest management on plant species diversity in a Sierran conifer forest. Forest Ecology and Management 146(1-3): 211-222.

Baur, A. and B. Baur. 1990. Are roads barriers to dispersal in the land snail *Arianta arbustorum*? Canadian Journal of Zoology 68: 613–617.

Baur, A. and B. Baur. 1992. Effect of corridor width on animal dispersal: a simulation study. Global Ecology and Biogeography 2: 52–56.

Baur, A. and B. Baur. 1993. Daily movement patterns and dispersal in the land snail *Arianta arbustorum*. Malacologia 35: 89–98.

Baur, B. 1993. Population structure, density, dispersal and neighbourhood size in *Arianta arbustorum* (Linnaeus, 1758) (Pulmonata: Helicidae). Annalen des Naturhistorischen Museums Wien 94/95B: 307–321.

Beetle, D.E. 1997. Recolonization of burned aspen groves by land snails. Yellowstone Science 5(3): 6-8.

Bloch, C.P. and M.R. Willig. 2006. Context-dependence of long-term responses of terrestrial gastropod populations to large-scale disturbance. Journal of Tropical Ecology 22: 111-122.

Boyd, R. 1999. Indians, fire and the land in the Pacific Northwest. Oregon State University Press, Corvallis, Oregon. 313 pp.

Brady, J.K. and T.A. Pearce. 2007. Terrestrial Slugs in Strip Mined and Unmined Forested Land, Tuscarawas County, Ohio, U.S.A. Proceedings of the Academy of Natural Sciences of Philadelphia 156:117-122.

Bros, V., Moreno-Rueda, G., and X. Santos. 2011. Does postfire management affect the recovery of Mediterranean communities? The case study of terrestrial gastropods. Forest Ecology and Management 261(3): 611-619.

Burke, T.E. 1999. Management recommendations for terrestrial mollusk species. *Cryptomastix devia*, the Puget Oregonian Snail. V. 2.0. Prepared for the Oregon Bureau of Land Management. 33 pp. Available at: http://www.blm.gov/or/plans/surveyandmanage/MR/TM4Species/2000-015_1.pdf (Accessed 20 May 2011).

Caldwell, R.S. 1993. Macroinvertebrates and their relationship to coarse woody debris: with special reference to land snails. Pp. 49-54 in: J.W. McMinn, D.A. Crossley (eds.) Biodiversity and Coarse Woody Debris in Southern Forests. Proceedings of the workshop on coarse woody debris in southern forests: effects on biodiversity. USDA Forest Service General Technical Report SE-GTR-94. These pages can be previewed at: http://books.google.com/books?id=9B3980OPKJIC&printsec=frontcover#v=onepage&q&f=false (Accessed 25 Oct. 2011).

Cameron, R.A, Down, D.K., and D.J. Pannett. 1980. Historical and environmental influences on hedgerow snail faunas. Biological Journal of the Linnean Society 13: 75-87.

Chen, J.Q, Franklin, J.F. 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.

Churchfield, S. 1984. Dietary separation in three species of shrew inhabiting water-cress beds. Journal of Zoology 204: 211–228.

Curry, T., Greenwald, N., and A. Garty. 2008. Petition to list 32 mollusk species from freshwater and terrestrial ecosystems of the northwestern United States as Threatened or Endangered under the Endangered Species Act.

Duffey, E. 1975. The effects of human trampling on the fauna of grassland litter. Biological Conservation 7: 255-274.

Dunk J.R., Zielinski, W.J., and H.K. Preisler. 2004. Predicting the occurrence of rare mollusks in Northern California forests. Ecological Applications 14(3): 713–729.

Forman, R.T.T. and L.E. Alexander. 1998. Roads and their major ecological effects. Annual Review of Ecology and Systematics 29: 207-231.

France, R.L. 1997. Macroinvertebrate colonization of woody debris in Canadian shield lakes following riparian clearcutting. Conservation Biology 11:513–521.

Frest, T.J. 2002. Native snails: Indicators of Ecosystem Health. p. 211-215, in: Welfare Ranching, G. Wuerthner and M. Matteson (Eds.). Island Press, Sausalito, California.

Frest, T.J. and E.J. Johannes. 1995. Interior Columbia Basin mollusk species of special concern. Deixis Consultants, Seattle, WA. Prepared for the U.S. Department of Agriculture, Forest Service; U.S. Department of the Interior, Bureau of Land Management, Upper Columbia River Basin Ecosystem Management Project. 274 pp. + appendices.

Gärdenfors, U., Waldén, H.W. and I. Wäreborn. 1995. Effects of soil acidification on forest land snails. Ecological Bulletins 44: 259-270.

Gervais, J. A., Taveset, A., and M.F. Willson. 1998. The potential for seed dispersal by the banana slug (*Ariolimax columbianus*). American Midland Naturalist 140:103–110.

Götmark, F., von Proschwitz, T., and N. Franc. 2008. Are small sedentary species affected by habitat fragmentation? Local vs. landscape factors predicting species richness and composition of land mollusks in Swedish conservation forests. Journal of Biogeography 35(6): 1062-1076.

Graveland, J., van der Wal, R., van Balen, J.H., and A.J. van Noordwijk. 1994. Poor reproduction in forest passerines from decline of snail abundance on acidified soils. Nature 368: 446–448.

Graveland, J., and R. van der Wal. 1996. Decline in snail abundance due to soil acidification causes eggshell defects in forest passerines. Oecologia 105: 351–360.

Halpern, C.B. and T.A. Spies. 1995. Plant species diversity in natural and managed forest of the Pacific Northwest. Ecological Applications 5: 913-934.

Hartley, M.K., Rogers, W.E., Siemann, E., and J. Grace. 2007. Responses of prairie arthropod communities to fire and fertilizer: balancing plant and arthropod conservation. American Midland Naturalist 157: 92-105.

Hawkins, J.W., Lankester, M.W., Lautenschlager, R.A., and F.W. Bell. 1997a. Length-biomass and energy relationships of terrestrial gastropods in northern forest ecosystems. Canadian Journal of Zoology 75: 501–505.

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

Huggard, D.J., Kremsater, L.L., and F.L. Bunnell. *In press*. Learning from Organisms. Chapter 11 *in* Forestry and biodiversity learning how to sustain biodiversity in managed forests. Ed. F. L. Bunnell and G. B. Dunsworth.

Huggard, D.J. and A. Vyse. 2002. Comparing clearcutting and alternatives in a high elevation forest: early results from the Sicamous Creek Project. British Columbia Ministry of Forests Research Program Extension Note 63: 1-10.

Hylander K., Nilsson, C., and T. Göthner. 2004. Effects of buffer-strip retention and clearcutting on land snails in boreal riparian forests. Conservation Biology 18(4): 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(11): 1811-1819.

Jacot, A.P. 1935. Molluscan populations of old growth forests and rewooded fields in the Asheville Basin of North Carolina. Ecology 16(4): 603-605.

Jennings, T.J. and J.P. Barkham. 1979. Litter decomposition by slugs in mixed deciduous woodland. Holarctic Ecology 2(1): 21-29.

Jones, J.A., Swanson, F.J., Wemple, B.C., and K.U. Snyder. 2000. Effects of roads on hydrology, geomorphology, and disturbance patches in stream networks. Conservation Biology 14(1): 76-85.

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

Kappes, H. 2005. Influence of coarse woody debris on the gastropod community of a managed calcareous beech forest in Western Europe. Journal of Molluscan Studies 71(2): 85-91.

Karlin, E.J. 1961. Ecological relationships between vegetation and the distribution of land snails in Montana, Colorado and New Mexico. American Midland Naturalist 65: 60–66.

Kiss, L. and F. Magnin. 2006. High resilience of Mediterranean land snail communities to wildfires. Biodiversity and Conservation 15: 2925–2944.

Kiss, L., Magnin, F., and F. Torre. 2004. The role of landscape history and persistent biogeographical patterns in shaping the responses of Mediterranean land snail communities to recent fire disturbances. Journal of Biogeography 31(1): 145-157.

Kiss, L. and F. Magnin. 2003. The impact of fire on some Mediterranean land snail communities and patterns of post-fire recolonization. Journal of Molluscan Studies 69:43-53.

Kralka, R.A. 1986. Population characteristics of terrestrial gastropods in boreal forest habitats. American Midland Naturalist 115:156–164.

Livshits, G.M. 1983. Ecology of the terrestrial snail (*Brephulopsis bidens*): age composition, population density and spatial distribution of individuals. Journal of Zoology 199: 433–446.

Locasciulli, O. and D.A. Boag. 1987. Microdistribution of terrestrial snails (Stylommatophora) in forest litter. The Canadian Field-Naturalist 101: 76-81.

Martin, S.M. 2000. Terrestrial snails and slugs (Mollusca: Gastropoda) of Maine. Northeastern Naturalist 7(1): 33–88.

Mason, C.F. 1970a. Food, feeding rates and assimilation in woodland snails. Oecologia 4: 358–373.

Mason, C.F. 1970b. Snail populations, beech litter production, and the role of snails in litter decomposition. Oecologia 5: 215–239.

McDade, K. 2002. Habitat relationships of small terrestrial vertebrates and invertebrates in managed forests in the southern Oregon Cascades. M.S. Thesis. Corvallis, OR: Oregon State University. 212 pp.

Meadows, D.W. 2002. The effect of roads and trails on movement of the Ogden Rocky Mountain snail (*Oreohelix peripherica wasatchensis*). Western North American Naturalist 62: 377-380.

Moning, C. and J. Müller. 2009. Critical forest age thresholds for the diversity of lichens, molluscs and birds in beech (*Fagus sylvatica* L.) dominated forests. Ecological Indicators 9(5): 922-932.

Moore, J.D., Ouimet, R., Camiré, C. and D. Houle. 2002. Effects of two silvicultural practices on soil fauna abundance in a northern hardwood forest, Québec, Canada. Canadian Journal of Soil Science 82: 105–113.

Müller, J., Strätz, C., and T. Hothorn. 2005. Habitat factors for land snails in European beech forests with a special focus on coarse woody debris. European Journal of Forest Research 124: 233-242.

Nekola, J.C. 2002. Effects of fire management on the richness and abundance of central North American grassland land snail faunas. Animal Biodiversity and Conservation 25: 53-66.

Niemelä, J., 1997. Invertebrates and boreal forest management. Conservation Biology 11: 601–610.

Nyffeler, M. & W.O.P. Symondson. 2001. Spiders and harvestmen as gastropod predators. Ecological Entomology 26: 617-628.

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 Report prepared by Biolinx Environmental Research Ltd., Sidney, BC.

Page, H., Rupp, L., Wiebner, S. and J.G. Goldammer. 2000. Feuerokologie und feuer-management auf augsgewahlten rebboschungen in Kaiserstuhl, Abschulussbericht zur vorlage an das Ministerium Landlicher Raum Baden-Wurttemberg. [Fire ecology and fire management at selected vinyard slopes in the Kaiserstuhl, Final Report to the Baden Wurttemberg Ministry of Agriculture]. University of Freiburg, Germany.

Page, H. and J.G. Goldammer. 2004. Prescribed Burning in Landscape Management and Nature Conservation: The First Long-Term Pilot Project in Germany in the Kaiserstuhl Viticulture Area, Baden-Württemberg, Germany. International Forest Fire News (IFFN) 30: 49-58.

Prezio, J.R., Lankester, M.W., Lautenschlager, R.A., 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.

Reinink, K. 1979. Observations on the distribution of land snails in the woods of the Ilsselmeer polders. Basteria 43: 33-45.

Richter, K.O. 1979. Aspects of nutrient cycling by *Ariolimax columbianus* (Mollusca: Arionidae) in Pacific Northwest coniferous forests. Pedobiologia 19: 60–74.

Rosenvald, R. and A. Lõhmus. 2007. For what, when, and where is green-tree retention better than clear-cutting? A review of the biodiversity aspects. Forest Ecology and Management 255: 1-15.

Roth, B. and P.H. Pressley. 1986. Observations on the range and natural history of *Monadenia setosa* (Gastropoda: Pulmonata) in the Klamath Mountains, California, and the taxonomy of some related species. Veliger 29: 169–182.

Rykken, J.J., Moldenke, A.R., and D.H. Olson. 2007. Headwater riparian forest-floor invertebrate communities associated with alternative forest management practice. Ecological Applications 17(4): 1168-1183.

Sarma, K., Tandon R., Shivanna K.R., and H.Y. Mohan Ram. 2007. Snail-pollination in *Volvulopsis nummularium*. Current Science. 93: 826-831.

Shaffer, M.L. 1981. Minimum population sizes for species conservation. BioScience 31(2): 131-134.

South, A., 1980. A technique for the assessment of predation by birds and mammals on the slug *Deroceras reticulatum* (Muller) (Pulmonata: Limacidae). Journal of Conchology 30: 229–234.

Stiven, A.E. 1989. Population biology of two land snails (*Mesomphix* spp.): variation among six southern Appalachian sites with differing disturbance histories. Oecologia 79(3): 372-382.

Strayer, D., Pletscher, D.H., Hamburg, S.P., 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.

Ström, L. 2004. Long-term effects of riparian clear-cutting- richer land snail communities in regenerating forests. M.S. Thesis. Umeå, Sweden: Umeå University. 23 pp.

Ström, L., K. Hylander, and D. Mats. 2009. Different long-term and short-term responses of land snails to clear-cutting of boreal stream-side forests. Biological Conservation 142(8): 1580-1587.

Swengel, A.B. 2001. A literature review of insect responses to fire, compared to other conservation managements of open habitat. Biodiversity and Conservation 10:1141–1169.

Underhill, J.E. and P.G. Angold. 2000. Effects of roads on wildlife in an intensively modified landscape. Environmental Reviews 8: 21–39.

Wäreborn, I. 1979. Reproductive success of two species of land snails in relation to calcium salts in forest litter. Malacologia 18, 177–180.

Wessell, S.J. 2005. Biodiversity in Managed Forests of Western Oregon: Species Assemblages in Leave Islands, Thinned, and Unthinned Forests. M.S. Thesis. Corvallis, OR: Oregon State University. 74 pp.

Werner, S.M. and K.F. Raffa. 2000. Effects of forest management practices on the diversity of ground-occurring beetles in mixed northern hardwood forests of the Great Lakes Region. Forest Ecology and Management 139: 135-155.

Wirth, T., Oggier, P., and B. Baur. 1999. Effect of road width on dispersal and population genetic structure in the land snail *Helicella itala*. Journal of Nature Conservation 8: 23-29.

Section Two: Citations by Topic

ECOSYSTEM FUNCTIONS OF TERRESTRIAL MOLLUSKS

Ball, M.C., Lankester, M.W., and S.P. Mahoney. 2001. Factors affecting the distribution and transmission of *Elaphostrongylus rangiferi* (Protostrongylidae) in caribou (*Rangifer tarandus caribou*) of Newfoundland, Canada. Canadian Journal of Zoology 79:1265–1277.

Burke, T.E. 1999. Management recommendations for terrestrial mollusk species. *Cryptomastix devia*, the Puget Oregonian Snail. V. 2.0. Prepared for the Oregon

Bureau of Land Management. 33 pp. Available at: http://www.blm.gov/or/plans/surveyandmanage/MR/TM4Species/2000-015_1.pdf (Accessed 20 May 2011).

Caldwell, R.S. 1993. Macroinvertebrates and their relationship to coarse woody debris: with special reference to land snails. Pp. 49-54 in: J.W. McMinn, D.A. Crossley (eds.) Biodiversity and Coarse Woody Debris in Southern Forests. Proceedings of the workshop on coarse woody debris in southern forests: effects on biodiversity. USDA Forest Service General Technical Report SE-GTR-94. These pages can be previewed at: http://books.google.com/books?id=9B3980OPKJIC&printsec=frontcover#v=onepage&q&f=false (Accessed 25 Oct. 2011).

Churchfield, S. 1984. Dietary separation in three species of shrew inhabiting water-cress beds. Journal of Zoology 204: 211–228.

Frest, T.J. and E.J. Johannes. 1995. Interior Columbia Basin mollusk species of special concern. Deixis Consultants, Seattle, WA. Prepared for the U.S. Department of Agriculture, Forest Service; U.S. Department of the Interior, Bureau of Land Management, Upper Columbia River Basin Ecosystem Management Project. 274 pp. + appendices.

Gervais, J. A., Taveset, A., and M.F. Willson. 1998. The potential for seed dispersal by the banana slug (*Ariolimax columbianus*). American Midland Naturalist 140:103–110.

Graveland, J., van der Wal, R., van Balen, J.H., and A.J. van Noordwijk. 1994. Poor reproduction in forest passerines from decline of snail abundance on acidified soils. Nature 368: 446–448.

Graveland, J., and R. van der Wal. 1996. Decline in snail abundance due to soil acidification causes eggshell defects in forest passerines. Oecologia 105: 351–360.

Hawkins, J.W., Lankester, M.W., Lautenschlager, R.A., and F.W. Bell. 1997a. Length-biomass and energy relationships of terrestrial gastropods in northern forest ecosystems. Canadian Journal of Zoology 75: 501–505.

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

Jennings, T.J. and J.P. Barkham. 1979. Litter decomposition by slugs in mixed deciduous woodland. Holarctic Ecology 2(1): 21-29.

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

Martin, S.M. 2000. Terrestrial snails and slugs (Mollusca: Gastropoda) of Maine. Northeastern Naturalist 7(1): 33–88.

Mason, C.F. 1970a. Food, feeding rates and assimilation in woodland snails. Oecologia 4: 358–373.

Mason, C.F. 1970b. Snail populations, beech litter production, and the role of snails in litter decomposition. Oecologia 5: 215–239.

Nyffeler, M. & W.O.P. Symondson. 2001. Spiders and harvestmen as gastropod predators. Ecological Entomology 26: 617-628.

Richter, K.O. 1979. Aspects of nutrient cycling by *Ariolimax columbianus* (Mollusca: Arionidae) in Pacific Northwest coniferous forests. Pedobiologia 19: 60–74.

Sarma, K., Tandon R., Shivanna K.R., and H.Y. Mohan Ram. 2007. Snail-pollination in *Volvulopsis nummularium*. Current Science. 93: 826-831.

South, A., 1980. A technique for the assessment of predation by birds and mammals on the slug *Deroceras reticulatum* (Muller) (Pulmonata: Limacidae). Journal of Conchology 30: 229–234.

Strayer, D., Pletscher, D.H., Hamburg, S.P., 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.

HABITAT CHARACTERISTICS OF TERRESTRIAL MOLLUSKS

Abele, S.E. 2010. Gastropod diversity in the boreal mixedwood forest of northern Alberta – variation among forest types and response to partial harvesting. M.S. Thesis. Edmonton, Alberta: University of Alberta. 107 pp.

Addison, J.A. and K.N. Barber. 1997. Response of soil invertebrates to clearcutting and partial cutting in a boreal mixedwood forest in Northern Ontario. Natural Resources Canada, Canadian Forest Service, Great Lakes Forestry Centre. Information Report GLC-X-1. 23 pp. Available at http://cfs.nrcan.gc.ca/pubwarehouse/pdfs/9135.pdf (Accessed 20 May 2011).

Anderson, T. 2004. Callused Vertigo (*Vertigo authuri*): a technical conservation assessment. USDA Forest Service, Rocky Mountain Region. Available at: http://www.fs.fed.us/r2/projects/scp/assessments/callusedvertigo.pdf (Accessed 27 June 2011).

Asami, T. 1993. Interspecific differences in desiccation tolerance of juvenile land snails. Functional Ecology 7: 571-577.

Baur, A. and B. Baur. 1993. Daily movement patterns and dispersal in the land snail *Arianta arbustorum*. Malacologia 35: 89–98.

Brady, J.K. and T.A. Pearce. 2007. Terrestrial Slugs in Strip Mined and Unmined Forested Land, Tuscarawas County, Ohio, U.S.A. Proceedings of the Academy of Natural Sciences of Philadelphia 156:117-122.

Bros, V., Moreno-Rueda, G., and X. Santos. 2011. Does postfire management affect the recovery of Mediterranean communities? The case study of terrestrial gastropods. Forest Ecology and Management 261(3): 611-619.

Caldwell, R.S. 1993. Macroinvertebrates and their relationship to coarse woody debris: with special reference to land snails. Pp. 49-54 in: J.W. McMinn, D.A. Crossley (eds.) Biodiversity and Coarse Woody Debris in Southern Forests. Proceedings of the workshop on coarse woody debris in southern forests: effects on biodiversity. USDA Forest Service General Technical Report SE-GTR-94. These pages can be previewed at: http://books.google.com/books?id=9B398OOPKJIC&printsec=frontcover#v=onepage&q&f=false (Accessed 25 Oct. 2011).

Cameron, R.A, Down, D.K., and D.J. Pannett. 1980. Historical and environmental influences on hedgerow snail faunas. Biological Journal of the Linnean Society 13: 75-87.

Chen, J.Q, Franklin, J.F. 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.

Frest, T.J. and E.J. Johannes. 1995. Interior Columbia Basin mollusk species of special concern. Deixis Consultants, Seattle, WA. Prepared for the U.S. Department of Agriculture, Forest Service; U.S. Department of the Interior, Bureau of Land Management, Upper Columbia River Basin Ecosystem Management Project. 274 pp. + appendices.

Gärdenfors, U., Waldén, H.W. and I. Wäreborn. 1995. Effects of soil acidification on forest land snails. Ecological Bulletins 44: 259-270.

Gervais, J. A., Taveset, A., and M.F. Willson. 1998. The potential for seed dispersal by the banana slug (*Ariolimax columbianus*). American Midland Naturalist 140:103–110.

Götmark, F., von Proschwitz, T., and N. Franc. 2008. Are small sedentary species affected by habitat fragmentation? Local vs. landscape factors predicting species richness and composition of land mollusks in Swedish conservation forests. Journal of Biogeography 35(6): 1062-1076.

Graveland, J., van der Wal, R., van Balen, J.H., and A.J. van Noordwijk. 1994. Poor reproduction in forest passerines from decline of snail abundance on acidified soils. Nature 368: 446–448.

Graveland, J., and R. van der Wal. 1996. Decline in snail abundance due to soil acidification causes eggshell defects in forest passerines. Oecologia 105: 351–360.

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

Hylander K., Nilsson, C., and T. Göthner. 2004. Effects of buffer-strip retention and clearcutting on land snails in boreal riparian forests. Conservation Biology 18(4): 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(11): 1811-1819.

Jacot, A.P. 1935. Molluscan populations of old growth forests and rewooded fields in the Asheville Basin of North Carolina. Ecology 16(4): 603-605.

Kappes, H. 2005. Influence of coarse woody debris on the gastropod community of a managed calcareous beech forest in Western Europe. Journal of Molluscan Studies 71(2): 85-91.

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

Karlin, E.J. 1961. Ecological relationships between vegetation and the distribution of land snails in Montana, Colorado and New Mexico. American Midland Naturalist 65: 60–66.

Kiss, L. and F. Magnin. 2006. High resilience of Mediterranean land snail communities to wildfires. Biodiversity and Conservation 15: 2925–2944.

Kralka, R.A. 1986. Population characteristics of terrestrial gastropods in boreal forest habitats. American Midland Naturalist 115:156–164.

Livshits, G.M. 1983. Ecology of the terrestrial snail (*Brephulopsis bidens*): age composition, population density and spatial distribution of individuals. Journal of Zoology 199: 433–446.

Locasciulli, O. and D.A. Boag. 1987. Microdistribution of terrestrial snails (Stylommatophora) in forest litter. The Canadian Field-Naturalist 101: 76-81.

Moning, C. and J. Müller. 2009. Critical forest age thresholds for the diversity of lichens, molluscs and birds in beech (*Fagus sylvatica* L.) dominated forests. Ecological Indicators 9(5): 922-932.

Müller, J., Strätz, C., and T. Hothorn. 2005. Habitat factors for land snails in European beech forests with a special focus on coarse woody debris. European Journal of Forest Research 124: 233-242.

Niemelä, J., 1997. Invertebrates and boreal forest management. Conservation Biology 11: 601–610.

Prezio, J.R., Lankester, M.W., Lautenschlager, R.A., 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.

Reinink, K. 1979. Observations on the distribution of land snails in the woods of the Ilsselmeer polders. Basteria 43: 33-45.

Sarma, K., Tandon R., Shivanna K.R., and H.Y. Mohan Ram. 2007. Snail-pollination in *Volvulopsis nummularium*. Current Science. 93: 826-831.

Strayer, D., Pletscher, D.H., Hamburg, S.P., 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.

Ström, L. 2004. Long-term effects of riparian clear-cutting- richer land snail communities in regenerating forests. M.S. Thesis. Umeå, Sweden: Umeå University. 23 pp.

Ström, L., K. Hylander, and D. Mats. 2009. Different long-term and short-term responses of land snails to clear-cutting of boreal stream-side forests. Biological Conservation 142(8): 1580-1587.

Wäreborn, I. 1979. Reproductive success of two species of land snails in relation to calcium salts in forest litter. Malacologia 18, 177–180.

GASTROPOD RESPONSE TO SILVICULTURE PRACTICES

Abele, S.E. 2010. Gastropod diversity in the boreal mixedwood forest of northern Alberta – variation among forest types and response to partial harvesting. M.S. Thesis. Edmonton, Alberta: University of Alberta. 107 pp.

Asami, T. 1993. Interspecific differences in desiccation tolerance of juvenile land snails. Functional Ecology 7: 571-577.

Aubry, K.B., Halpern, C.B., and C.E. Peterson. 2009. Variable-retention harvests in the Pacific Northwest: a review of short-term findings from the DEMO study. *Forest Ecology and Management* 258: 398-408.

Battles*,* J.J.*,* Shlisky, A.J., Barrett, R.H., Heald, R.C., and B.H. Allen-Diaz. 2001. The effects of forest management on plant species diversity in a Sierran conifer forest*. Forest* Ecology and Management 146(1-3): 211-222.

Baur, A. and B. Baur. 1993. Daily movement patterns and dispersal in the land snail *Arianta arbustorum*. Malacologia 35: 89–98.

Baur, B. 1993. Population structure, density, dispersal and neighbourhood size in *Arianta arbustorum* (Linnaeus, 1758) (Pulmonata: Helicidae). Annalen des Naturhistorischen Museums Wien 94/95B: 307–321.

Bloch, C.P. and M.R. Willig. 2006. Context-dependence of long-term responses of terrestrial gastropod populations to large-scale disturbance. Journal of Tropical Ecology 22: 111-122.

Chen, J.Q, Franklin, J.F. 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.

Duffey, E. 1975. The effects of human trampling on the fauna of grassland litter. Biological Conservation 7: 255-274.

France, R.L. 1997. Macroinvertebrate colonization of woody debris in Canadian shield lakes following riparian clearcutting. Conservation Biology 11:513–521.

Halpern, C.B. and T.A. Spies. 1995. Plant species diversity in natural and managed forest of the Pacific Northwest. Ecological Applications 5: 913-934.

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

Huggard, D.J., Kremsater, L.L., and F.L. Bunnell. *In press*. Learning from Organisms. Chapter 11 *in* Forestry and biodiversity learning how to sustain biodiversity in managed forests. Ed. F. L. Bunnell and G. B. Dunsworth.

Huggard, D.J. and A. Vyse. 2002. Comparing clearcutting and alternatives in a high elevation forest: early results from the Sicamous Creek Project. British Columbia Ministry of Forests Research Program Extension Note 63: 1-10.

Hylander K., Nilsson, C., and T. Göthner. 2004. Effects of buffer-strip retention and clearcutting on land snails in boreal riparian forests. Conservation Biology 18(4): 1052-1062.

Kappes, H. 2005. Influence of coarse woody debris on the gastropod community of a managed calcareous beech forest in Western Europe. Journal of Molluscan Studies 71(2): 85-91.

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

Kralka, R.A. 1986. Population characteristics of terrestrial gastropods in boreal forest habitats. American Midland Naturalist 115:156–164.

McDade, K. 2002. Habitat relationships of small terrestrial vertebrates and invertebrates in managed forests in the southern Oregon Cascades. M.S. Thesis. Corvallis, OR: Oregon State University. 212 pp.

Moning, C. and J. Müller. 2009. Critical forest age thresholds for the diversity of lichens, molluscs and birds in beech (*Fagus sylvatica* L.) dominated forests. Ecological Indicators 9(5): 922-932.

Moore, J.D., Ouimet, R., Camiré, C. and D. Houle. 2002. Effects of two silvicultural practices on soil fauna abundance in a northern hardwood forest, Québec, Canada. Canadian Journal of Soil Science 82: 105–113.

Müller, J., Strätz, C., and T. Hothorn. 2005. Habitat factors for land snails in European beech forests with a special focus on coarse woody debris. European Journal of Forest Research 124: 233-242.

Niemelä, J., 1997. Invertebrates and boreal forest management. Conservation Biology 11: 601–610.

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 Report prepared by Biolinx Environmental Research Ltd., Sidney, BC.

Prezio, J.R., Lankester, M.W., Lautenschlager, R.A., 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.

Rosenvald, R. and A. Lõhmus. 2007. For what, when, and where is green-tree retention better than clear-cutting? A review of the biodiversity aspects. Forest Ecology and Management 255: 1-15.

Shaffer, M.L. 1981. Minimum population sizes for species conservation. BioScience 31(2): 131-134.

Stiven, A.E. 1989. Population biology of two land snails (*Mesomphix* spp.): variation among six southern Appalachian sites with differing disturbance histories. Oecologia 79(3): 372-382.

Underhill, J.E. and P.G. Angold. 2000. Effects of roads on wildlife in an intensively modified landscape. Environmental Reviews 8: 21–39.

Wessell, S.J. 2005. Biodiversity in Managed Forests of Western Oregon: Species Assemblages in Leave Islands, Thinned, and Unthinned Forests. M.S. Thesis. Corvallis, OR: Oregon State University. 74 pp.

IMPACTS OF ROADS ON GASTROPOD DISPERSAL AND POPULATION GENETICS

Akcakaya, H.R. and B. Baur. 1996. Effects of population subdivision and catastrophes on the persistence of a land snail metapopulation. Oecologia 105: 475–483.

Arnaud, J.F., Madec, L., Bellido, A. and A. Guiller. 1999. Microspatial genetic structure in the land snail *Helix aspersa* (Gastropoda: Helicidae). Heredity 83: 110–119.

Arnaud, J.F., 2003. Metapopulation genetic structure and migration pathways in the land snail *Helix aspersa*: influence of landscape heterogeneity. Landscape Ecology 18: 333–346.

Baur, A. and B. Baur. 1990. Are roads barriers to dispersal in the land snail *Arianta arbustorum*? Canadian Journal of Zoology 68: 613–617.

Baur, A. and B. Baur. 1992. Effect of corridor width on animal dispersal: a simulation study. Global Ecology and Biogeography 2: 52–56.

Baur, A. and B. Baur. 1993. Daily movement patterns and dispersal in the land snail *Arianta arbustorum*. Malacologia 35: 89–98.

Baur, B. 1993. Population structure, density, dispersal and neighbourhood size in *Arianta arbustorum* (Linnaeus, 1758) (Pulmonata: Helicidae). Annalen des Naturhistorischen Museums Wien 94/95B: 307–321.

Forman, R.T.T. and L.E. Alexander. 1998. Roads and their major ecological effects. Annual Review of Ecology and Systematics 29: 207-231.

Frest, T.J. 2002. Native snails: Indicators of Ecosystem Health. p. 211-215, in: Welfare Ranching, G. Wuerthner and M. Matteson (Eds.). Island Press, Sausalito, California.

Jones, J.A., Swanson, F.J., Wemple, B.C., and K.U. Snyder. 2000. Effects of roads on hydrology, geomorphology, and disturbance patches in stream networks. Conservation Biology 14(1): 76-85.

Meadows, D.W. 2002. The effect of roads and trails on movement of the Ogden Rocky Mountain snail (*Oreohelix peripherica wasatchensis*). Western North American Naturalist 62: 377-380.

Wirth, T., Oggier, P., and B. Baur. 1999. Effect of road width on dispersal and population genetic structure in the land snail *Helicella itala*. Journal of Nature Conservation 8: 23-29.

GASTROPOD RESPONSE TO FIRE

Agee, J.K. 1993. Fire Ecology of the Pacific Northwest. Island Press, Washington, D.C., 493 pp.

Agee, J.K. 2001. GOBIG2K: an analysis of fire and mollusk species in California National Forests covered by the Northwest Forest Plan. Final Report, USDA Forest Service, Klamath National Forest. Yreka, California, USA.

Anderson, T. 2004. Callused Vertigo (*Vertigo authuri*): a technical conservation assessment. USDA Forest Service, Rocky Mountain Region. Available at: http://www.fs.fed.us/r2/projects/scp/assessments/callusedvertigo.pdf (Accessed 27 June 2011).

Beetle, D.E. 1997. Recolonization of burned aspen groves by land snails. Yellowstone Science 5(3): 6-8.

Boyd, R. 1999. Indians, fire and the land in the Pacific Northwest. Oregon State University Press, Corvallis, Oregon. 313 pp.

Bros, V., Moreno-Rueda, G., and X. Santos. 2011. Does postfire management affect the recovery of Mediterranean communities? The case study of terrestrial gastropods. Forest Ecology and Management 261(3): 611-619.

Burke, T.E. 1999. Management recommendations for terrestrial mollusk species. *Cryptomastix devia*, the Puget Oregonian Snail. V. 2.0. Prepared for the Oregon Bureau of Land Management. 33 pp. Available at: http://www.blm.gov/or/plans/surveyandmanage/MR/TM4Species/2000-015_1.pdf (Accessed 20 May 2011).

Hartley, M.K., Rogers, W.E., Siemann, E., and J. Grace. 2007. Responses of prairie arthropod communities to fire and fertilizer: balancing plant and arthropod conservation. American Midland Naturalist 157: 92-105.

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

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(11): 1811-1819.

Karlin, E.J. 1961. Ecological relationships between vegetation and the distribution of land snails in Montana, Colorado and New Mexico. American Midland Naturalist 65: 60–66.

Kiss, L. and F. Magnin. 2006. High resilience of Mediterranean land snail communities to wildfires. Biodiversity and Conservation 15: 2925–2944.

Kiss, L., Magnin, F., and F. Torre. 2004. The role of landscape history and persistent biogeographical patterns in shaping the responses of Mediterranean land snail communities to recent fire disturbances. Journal of Biogeography 31(1): 145-157.

Kiss, L. and F. Magnin. 2003. The impact of fire on some Mediterranean land snail communities and patterns of post-fire recolonization. Journal of Molluscan Studies 69:43-53.

Nekola, J.C. 2002. Effects of fire management on the richness and abundance of central North American grassland land snail faunas. Animal Biodiversity and Conservation 25: 53-66.

Page, H., Rupp, L., Wiebner, S. and J.G. Goldammer. 2000. Feuerokologie und feuer-management auf augsgewahlten rebboschungen in Kaiserstuhl, Abschulussbericht zur vorlage an das Ministerium Landlicher Raum Baden-Wurttemberg. [Fire ecology and fire management at selected vinyard slopes in the Kaiserstuhl, Final Report to the Baden Wurttemberg Ministry of Agriculture]. University of Freiburg, Germany.

Page, H. and J.G. Goldammer. 2004. Prescribed Burning in Landscape Management and Nature Conservation: The First Long-Term Pilot Project in Germany in the Kaiserstuhl Viticulture Area, Baden-Württemberg, Germany. International Forest Fire News (IFFN) 30: 49-58.

Strayer, D., Pletscher, D.H., Hamburg, S.P., 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.

Section Three: Summaries of Relevant Research Papers

Note: This bibliography covers the impact of forestry practices (logging, roads, and fire) on terrestrial gastropods (snails and slugs). Papers regarding gastropod response to mining, grazing, agriculture, acid rain, and other activities are, for the most part, not reviewed. Bulleted content is paraphrased unless indicated by quotation marks. Citation codes: RS= research study, MP= modeling paper, RP= review paper or book, PR= peer-reviewed.

Abele, S.E. 2010. Gastropod diversity in the boreal mixedwood forest of northern Alberta – variation among forest types and response to partial harvesting. M.S. Thesis. Edmonton, Alberta: University of Alberta. 107 pp. RS.

- This study examined gastropod assemblages in relation to forest cover type and in response to variable retention harvesting in mixed-wood boreal forests of northwestern Alberta. The experimental site consisted of 100 10-hectare plots, treated according to a two factorial design, replicated 3 times. The two factors included in the experiment were cover type (four types, representing a gradient from deciduous- to coniferous-dominated) and harvest treatment (seven types, consisting of variable levels of dispersed green tree retention as a proportion of original stand stem density: clear cut (with 1-2 % retention), 10% retention, 20% retention, 50% retention, 75% retention, and unharvested controls (100% retention)). Forest stands ranged in age from 62-124 years.
- In the retention study, sampling was conducted 9 years post-harvest. Board trap sampling techniques yielded a total of nine species. In the forest-cover study, sampling was conducted using both board traps and soil samples, yielding a total of 15 species.
- Gastropod assemblages were strongly influenced by canopy composition, with most gastropods showing a strong affinity for broadleaf dominated forests. Deciduous dominated forests stood apart from the other forest types as having higher gastropod abundance and species richness. Tree species mixture influenced gastropod distribution; basal tree area of either conifer or broadleaf trees was generally associated with gastropod distribution within a stand. Herb and shrub cover in the understory also had an influence on gastropod distributions. Litter depth influenced gastropod composition in the deciduous dominated forest types, with most species associated with deeper litter. Species-level responses to coarse woody debris cover was more variable.

- With regard to dispersed retention, increases in retention levels had no observable effect on gastropod species richness nine years post-harvest. Moreover, rather than reducing gastropod abundance, increased harvest intensity was associated with increased abundance of many species, although abundance declined for other species. For example, the slug *Deroceras laeve* was the second most dominant gastropod in unharvested treatments, but exhibited notable declines in response to any harvesting. The snail *Discus shimekii* showed a decline in abundance with increasing harvest intensity, and was uncommon or absent in sites with the lowest retention levels.
- The authors note that although increases in harvesting intensity generated increases in overall gastropod abundances in this study, such increases are not necessarily optimal for ecosystem function. It is concluded that harvesting with retention helps to maintain pre-harvest boreal gastropod assemblages and will likely conserve boreal gastropod assemblages if used as a tool for biodiversity management.

Addison, J.A. and K.N. Barber. 1997. Response of soil invertebrates to clearcutting and partial cutting in a boreal mixedwood forest in Northern Ontario. Natural Resources Canada, Canadian Forest Service, Great Lakes Forestry Centre. Information Report GLC-X-1. 23 pp. Available at http://cfs.nrcan.gc.ca/pubwarehouse/pdfs/9135.pdf (Accessed 20 May 2011). RS, PR.

- This study examined the short-term effects (two years) of different harvesting methods (clearcutting and partial cutting) on soil invertebrates (carabid beetles, Collembola, mites, and fly larvae) in a boreal mixed wood forest in northern Ontario. Land snail responses were not investigated in this study, but results may be applicable.
- Overall, soil invertebrates were significantly affected by harvesting practices, as reflected in post-disturbance abundance declines of some taxonomic groups (mites and flies) and community structure changes in other groups (ground beetles and Collembola).
- Management implications developed in the course of this research are as follows:
    - Use harvesting techniques that minimize soil compaction and damage to (or removal of) the organic layer where most nutrients and soil fauna are found. In the present study, use of the Timberjack appeared to cause little (if any) damage to the organic mat or its resident invertebrate populations, while use of the feller-buncher and grapple skidder or single-grip harvester and grapple skidder both resulted in adverse effects on microarthropod abundances.
    - Avoid creating situations of microclimatic extremes. While some level of changes in the physical environment can be tolerated, many soil invertebrates are extremely sensitive to temperature and moisture extremes. Limiting the size of clear-cuts (e.g. less than 10 ha), or the use of partial cuts reduces microclimatic extremes. In general in this study, microclimate and biological variables (e.g., diversity indices) for the partial cuts were intermediate between values obtained for the uncut forests and the clear-cuts.
    - Regenerate boreal forests as mixed woods. Although traditional forestry practices often favor the establishment of simple stand structures that produce coniferous wood, there is growing scientific support for managing the boreal mixedwood resource as mixed species forests. Benefits include higher nutrient

content in soil and improved control of fungal diseases as a result of the feeding activities of soil invertebrate communities associated with multispecies forests.
    - Provide refugia from which re-colonization of cut areas can occur. This is particularly important for small, fragile invertebrates which lack well developed dispersal capabilities (e.g., land snails). Refugia should include tracts of uncut forest (at the landscape level) and coarse woody debris and areas of intact forest floor (at the microsite scale). Woody debris provides islands of habitat, food, and protection from microclimatic extremes, increasing species' tolerance of temporarily inhospitable environments. In the clear-cuts examined in this study, the presence of decomposing woody debris on logging trails appeared to mitigate the adverse effects of the harvesting machinery on soil invertebrate populations.

Agee, J.K. 1993. Fire Ecology of the Pacific Northwest. Island Press, Washington, D.C., 493 pp. RP, PR.

- This book highlights wildfire as a major natural disturbance in western ecosystems, and as an important ecological process in shaping community structure and function.

Agee, J.K. 2001. GOBIG2K: an analysis of fire and mollusk species in California National Forests covered by the Northwest Forest Plan. Final Report, USDA Forest Service, Klamath National Forest. Yreka, California, USA. RS.

- Prior to this study, research on Klamath National Forest suggested a positive relationship between past occurrence of fire and mollusk presence. This study continued to investigate this same relationship, but with a larger study area across four National Forests.
- Both positive and negative relationships between fire evidence and mollusk presence were evident. Survey and Manage species as a group exhibited higher occurrence at sites with less fire evidence (e.g., no fire or fire in the distant past) when compared with sites exhibiting more recent evidence of fire. At the species level, *Monadenia churchi* followed this same pattern, while *Helminthoglypta talmadgei* had higher proportions of occurrence in more recently burned sites.
- The author makes several recommendations for fire management with regard to rare mollusk species, including leaving a minimum time of 3+ years between reburns, leaving greater than 20% of an individual burn unit untouched by fire, and rotating spring and fall burns.
- In dry, fire-prone forests impacted by long periods of fire exclusion, rare species protection may require restoration of firesafe conditions to forests. It is recommended that fuel treatments be designed to create firesafe forests by applying the following criteria: surface fuel reduction should result in lower flame length; ladder fuel should be reduced, increasing the height to live crown; and crowns should be thinned to reduce chances of independent crown fires.

Akcakaya, H.R. and B. Baur. 1996. Effects of population subdivision and catastrophes on the persistence of a land snail metapopulation. Oecologia 105: 475–483. MS, PR.

- The objectives of this study were to investigate the effect of population subdivision on the persistence of a land snail metapopulation and to analyze the interaction between spatial factors, population subdivision, and catastrophes. The dynamics of a metapopulation of the land snail *Arianta arbustorum* in north-eastern Switzerland was modeled. The metapopulation was spread over an area approximately 200 m by 250 m, with about 15,000 adult snails distributed into 17 populations (150-4,000 adults in each population), and with an average snail density at 3.34 m^2.
- A spatially structured, stochastic, age-structured metapopulation model was developed using field data from previous studies on the metapopulation and incorporating distance-dependent dispersal through stream banks, correlated environmental fluctuations, and catastrophes resulting from heavy rains.
- The modeling results highlight various complex interactions among factors involved in meta-population dynamics. For example, in most cases population subdivision may increase the risk of extinction caused by increased susceptibility to factors such as edge effects and demographic stochasticity, however, in other cases, population subdivision may act as a way to decrease threats from environmental fluctuations and catastrophes, if such threats are distributed unevenly over the landscape.

Anderson, T. 2004. Callused Vertigo (*Vertigo authuri*): a technical conservation assessment. USDA Forest Service, Rocky Mountain Region. Available at: http://www.fs.fed.us/r2/projects/scp/assessments/callusedvertigo.pdf (Accessed 27 June 2011). RP.

- This paper reviews threats to *Vertico authuri,* including fire, roads, and timber harvest. While emphasis is placed on *V. authuri*, general land snail information is also reviewed.
- With regard to fire, it is reported that the burning of sites with known *V. authuri* populations resulted in no live snails of any species 1 and 2 years post-burn. The long-term effects of these fires are unclear.

Arnaud, J.F., Madec, L., Bellido, A. and A. Guiller. 1999. Microspatial genetic structure in the land snail *Helix aspersa* (Gastropoda: Helicidae). Heredity 83: 110–119. RS, PR.

- The microspatial genetic structure of allele frequencies at seven isozyme loci was examined for 15 populations of the land snail *Helix aspersa* sampled in north-western France.
- Analyses of gene flow and genetic distances failed to reveal a significant relationship with geographical distance, probably because of the complexity of environmental heterogeneity. However, matrix comparisons between genetic distances and connectivity networks among adjacent colonies yielded a significant correlation in every case, indicating a `step-by-step' relationship between neighboring localities.
- With regard to roads, genetic structure did not show the clear pattern expected if roads acted as barriers to individual dispersal.

Arnaud, J.F., 2003. Metapopulation genetic structure and migration pathways in the land

snail *Helix aspersa*: influence of landscape heterogeneity. Landscape Ecology 18: 333–346. RS, PR.

- The spatial genetic structuring of a metapopulation (32 colonies) of the land snail *Helix aspersa* was investigated in an intensive agricultural area in France. The identification of extrinsic barriers to migration and their impact on the genetic distribution was addressed by genotyping 580 individuals. Both the distance as well as the direction over which the spatial genetic arrangement occurs were evaluated, and different connectivity networks and geographical distances based on landscape features were constructed to evaluate the effect of environmental heterogeneity and to test the adequacy of an isolation by distance model on the distribution of the genetic variability. For example, cultivated fields and irrigation canals were considered insurmountable obstacles for snails, while roads were treated as passable, since previous research of genetic variation between opposite road populations of this species suggested no barrier effects on dispersal.
- "Genetic distances based only on genetic drift yielded the most plausible biologically meaningful interpretation of the observed spatial structure. Applying a landscape-based geographical distance which postulates that migration arises along roadside verges, hedges or irrigation canal embankments gave a better fit to an isolation by distance model than did a simple Euclidean distance. The progressive decline of genetic similarity with physical distance appeared to be environmentally induced, leading to functional migration pathways".
- Results suggest that in highly fragmented habitats, hospitable corridors like roadsides, ditches or hedges may impose a directionality in genetic exchanges between local colonies of some snail species, allowing for moderate but effective genetic connectivity.

Asami, T. 1993. Interspecific differences in desiccation tolerance of juvenile land snails. Functional Ecology 7: 571-577. RS, PR.

- This study examined the survival of two snail species under well-lit, 20 and 30 degree C treatments for 4 to 22 days. Despite the two species' close similarity in shell structure, young juveniles of one species (*Triodopsis albolabris*) were found to be much superior to the other (*Mesodon normalis*) in body water retention and in survival in low humidity.
- These differences are attributed to evolutionary divergence in physiological tolerance of desiccation, and have resulted in contrasting patterns of geographical distribution. Snails with geographic distribution in arid habitats where the forest litter often dries up and daytime temperatures are relatively high were more tolerant of desiccation in the laboratory than snails distributed in less arid, upland habitats.
- Results indicate genetic variation and heritability of desiccation tolerance in some species, since juveniles of *M. normalis* differed in survival and dehydration rate in low humidity depending on their parents.

Atlegrim, O. and K. Sjöberg. 1995. Effects of clear-cutting and selective felling in Swedish Boreal coniferous forest: response of invertebrate taxa eaten by birds. Entomologica Fennica 6: 79–90. RS, PR.

- This study analyzed the short-term effects (0-4 years) of selective cutting and clear-cutting on the invertebrate food resources of insectivorous birds in Swedish boreal coniferous forests. In the selective cutting treatment, approximately 30% of the individual trees were removed (45-50% of the tree volume), with the cutting distributed over all age classes. In the clearcut treatment, the whole tree layer was removed, followed by scarification.
- Comparisons between selective fellings, clear-cuttings, and uncut controls showed considerable effects of clear-cutting on terricolous and field layer invertebrates including spiders (Araneae) and herbivorous larvae of Lepidoptera and Hymenoptera: Symphyta. Clear-cutting had significantly lower invertebrate abundance and biomass and a different community composition relative to controls. In contrast, selective felling did not differ from controls in the occurrence of invertebrates.
- Although snails were not examined in this study, the direct and indirect effects of clear-cutting (e.g., increased temperature range, increased sun exposure, changes in resource availability) may impact this group similarly.

Aubry, K.B., Halpern, C.B., and C.E. Peterson. 2009. Variable-retention harvests in the Pacific Northwest: a review of short-term findings from the DEMO study. Forest Ecology and Management 258: 398-408. RS/RP, PR.

- This paper provides a comprehensive review of the short-term (1-7 years) results of Demonstration of Ecosystem Management Options (DEMO) studies, a series of studies in the Pacific Northwest addressing the ecological benefits of green tree retention under varying levels of retention and patterns of retained trees. The DEMO experimental design consisted of six treatments, each 13 ha in size, replicated at six locations (blocks) in western Washington and Oregon. Treatments represent strong contrasts in retention level (15-100% of original basal area) and pattern (trees dispersed vs. aggregated in 1-ha patches) in mature Douglas-fir (*Pseudotsuga menziesii*) forests.
- The level of retention was found to have a strong effect on many responses; at 15% retention, regardless of pattern, microclimate, ecological responses, and public perceptions of visual quality did not differ from those measured in the “clearcut” areas of aggregated treatments.
- Group retention in 1-ha aggregates was more beneficial than dispersed retention for a wide variety of response variables. Aggregates greatly reduced damage to and mortality of residual trees (particularly at lower levels of retention) and provided short-term refugia for forest organisms sensitive to disturbance or environmental stress.
- Overall, study results suggest that retention levels >15% are needed to effectively retain sensitive plants and animals, ameliorate harsh microclimatic conditions, and gain public acceptance of retention harvests in these forests.

Ball, M.C., Lankester, M.W., and S.P. Mahoney. 2001. Factors affecting the distribution and transmission of *Elaphostrongylus rangiferi* (Protostrongylidae) in caribou (*Rangifer tarandus caribou*) of Newfoundland, Canada. Canadian Journal of Zoology 79:1265–1277. RS, PR.

- This study reports the relationship between the parasitic nematode *Elaphostrongylus rangiferi* and gastropods (intermediate hosts).

Battles, J.J., Shlisky, A.J., Barrett, R.H., Heald, R.C., and B.H. Allen-Diaz. 2001. The effects of forest management on plant species diversity in a Sierran conifer forest. Forest Ecology and Management 146(1-3): 211-222. RS, PR.

- This study highlights the influence of logging practices on vascular plant diversity in a mixed conifer forest in the Sierra Nevada of California.

Baur, A. and B. Baur. 1990. Are roads barriers to dispersal in the land snail *Arianta arbustorum*? Canadian Journal of Zoology 68: 613–617. RS, PR.

- The effect of road width/type on dispersal in the land snail *Arianta arbustorum* was examined by recording displacements of marked individuals during one activity season (3 months) at three sites in central Sweden: a paved road (8 m wide, low traffic density) and an unpaved track (3 m wide), and an overgrown path (0.3 m wide).
- The average displacements ranged from 1.5 to 4.9 m at different sites; the maximum recorded displacement was 14 m. Displacements were largest in early summer, the period of maximum mating and feeding activities.
- At the paved road and unpaved track, the snails' movements were largely confined to roadside vegetation belts. After 3 months, only one (0.6%) of the 168 recaptured snails crossed the paved road, despite the fact that seven snails (4.1%) moved at least 8 m along the verges, a distance corresponding to the width of the paved road. Likewise, only two snails (4.3%) crossed the track, even though 23 individuals (49.0%) moved a distance longer than the track width (3 m).
- These findings indicate that both the road and track acted as dispersal barriers to snails. By contrast, the overgrown path did not influence the snails' movement.
- Multiple factors may influence the degree of dispersal restriction due to roads, including road width and traffic density. In this study, even on roads with low traffic density, numerous crushed snails were found along the road and the track verges.
- Direct monitoring of snail movements using recapture techniques has many challenges. In this study, data about the most- and the least-mobile snails may be underrepresented since the most mobile individuals may have left the study area and the least mobile ones may have buried themselves in the soil. Additionally, while accurate recording of marked individuals requires fine mapping of the study area and frequent observations, this extensive searching procedure can damage the vegetation and change the microclimate, which in turn may alter the snails' behavior and influence the recapture frequency of marked snails.
- In summary, results suggest that roads act as barriers to dispersal between snail populations, and populations separated by paved roads with high traffic densities may be isolated from each other. Snail dispersal across roads is limited by mortality caused by both traffic and desiccation in the artificial habitat.

Baur, A. and B. Baur. 1992. Effect of corridor width on animal dispersal: a simulation study. Global Ecology and Biogeography 2: 52–56. MS, PR.

- The effect of corridor width on dispersal speed was examined in the land snail, *Arianta arbustorum*, an animal repelled by unfavorable habitat at the corridor's edges. Using data on the movement pattern of this species in a natural population, snail dispersal was simulated in an unlimited plane and in corridors of different widths over periods of 120 days.
- The simulations showed that corridor width affects dispersal speed in land snails. Snail dispersal decreased with decreasing corridor width and never reached distances recorded in unlimited planes. Simulation results are supported by field data and are consistent with reports in the literature that snails disperse more rapidly in extensive, two-dimensional habitats than in corridors such as roadside verges, river embankments, and hedges.
- The reduced dispersal of snails in corridors may be a result of their behavior at the edges. While some species (e.g., carabid beetles and rodents) use the edges of corridors as guiding lines and exhibit more directed movements and rapid dispersal along corriders than in unlimited planes, other animals (e.g., land snails) are repelled by corridor edges and rather than following the edge continue their movement in a new direction, thus dispersing more slowly than in unlimited habitats. Individuals reaching the edge of the vegetation belt generally do not enter the suboptimal surroundings, but instead enter the favorable habitat. For these animals, it follows that in narrow corridors, a high proportion of animals will frequently reach the corridor edges, reducing the dispersal speed and implying both a decreased number of migrants, and lowered gene flow among populations. For rare or narrowly distributed species, this, in turn, may lead to an increased probability of local extinction.

Baur, A. and B. Baur. 1993. Daily movement patterns and dispersal in the land snail *Arianta arbustorum*. Malacologia 35: 89–98. RS, PR.

- This study used mark and recapture techniques to examine the relationship between daily movements of the land snail *Arianta arubstorum* and the snails’ dispersal over longer periods.
- The snails showed no preference in direction of movement, and the directions chosen by an individual on consecutive days were independent from each other, consistent with the assumptions of a random movement model.
- The snails’ movements were confined to favorable vegetation; in a 1-m wide belt of tall grass and forbs, individuals did not enter into drier surroundings (mowed meadow) but continued to move in a new direction within the belt.
- Dispersal simulations and a review of the literature showed that snails disperse significantly longer distances in two-dimensional habitats than in linear habitats of 1 and 8 m width.

Baur, B. 1993. Population structure, density, dispersal and neighbourhood size in *Arianta arbustorum* (Linnaeus, 1758) (Pulmonata: Helicidae). Annalen des Naturhistorischen Museums Wien 94/95B: 307–321. RP, PR.

- This paper reviews field studies on the ecology of a helicid land snail, *Arianta arbustorum*, in the Alps and Scandinavia. Emphasis is placed on the spatial distribution of individuals, population structure, population density and dispersal.
- The spatial distribution of this species was found to be influenced by the heterogeneity of the landscape, including moisture of the microhabitat, calcium content of the soil, type and height of the vegetation, availability of food plants, oviposition sites and resting sites.
- Daily movement distances ranged from 0 to 4.44 m (median value: 0.58 m). The snails showed no preference in direction of movement; the directions chosen on consecutive days were independent, and the snails moved similar distances in all directions.

Baur, A. and B. Baur. 1995. Habitat-related dispersal in the rock-dwelling land snail *Chondrina clienta.* Ecography 18(2): 123-130. RS, PR.

- This study used mark and recapture techniques to examine dispersal of a rock-dwelling land snail, *Chondrina clienta,* in four habitat types (limestone pavement, vertical rock walls, a pile of stones, and a stone wall) over a 3 year period.
- Habitat type was found to have a significant influence on the dispersal distances of this species. The largest dispersal distances were recorded in the limestone pavement (264 cm/yr) and vertical rock walls (96 cm/yr), both simple habitats for travelling snails. Dispersal was less in the stone pile (68 cm/yr) and on the stone wall (88 cm/yr), more complex habitats with multiple layers of stone pieces.

Beetle, D.E. 1997. Recolonization of burned aspen groves by land snails. Yellowstone Science 5(3): 6-8. RS.

- This five-year study examined the survival of mollusks in burned aspen groves following the fires of 1988 in Yellowstone National Park. Since no preburn data existed, snail populations in both burned and unburned aspen groves were examined. Sampling of 18 sites was done one year after the fire and eight selected sites were re-examined three more times over the five year period to determine survival and population regrowth. One site was contiguous to unburned aspen from which migration might occur.
- Overall, fires were found to have a major impact on snails in Yellowstone National Park. The first year following the fires, fewer individual snails and fewer species were encountered in the burned areas than in the unburned areas (specific numbers or results of significance tests are not provided). The number of species found in the burned areas continued to decline in subsequent years.
- One severely burned site had only burned shells in 1989, and continued to support no live snails after five years. Other burned sites initially had a few species, but after five years (including two dry years) live snails were no longer present. Two lightly burned sites with hospitable conditions (e.g., damp habitat, abundant litter, uncharred/charred

rotten logs) maintained snail populations over the five year period, but species richness did not increase over that time.

- No evidence of migration into burned groves was found. It is noted that aspen groves in Yellowstone are fairly isolated, which makes recolonization difficult.

Bloch, C.P. and M.R. Willig. 2006. Context-dependence of long-term responses of terrestrial gastropod populations to large-scale disturbance. Journal of Tropical Ecology 22: 111-122. RS, PR.

- This study examined the long-term (up to 14 year) population trends of 17 species of terrestrial gastropods following two major disturbances (hurricanes) in an effort to determine whether gastropods respond to major disturbances in a consistent fashion, or whether differences in disturbance intensity or disturbance history result in disparate population-level responses.
- Gastropod species in this study responded to disturbance in a species-specific manner. Some species increased, some decreased, and some exhibited no simple trend in population density or spatial variability following disturbance. In the case of hurricanes, population responses probably hinge on trade-offs between sensitivity to microclimatic changes and resource availability resulting from the relocation of biomass from the canopy to the forest floor. (This differs from silviculture methods in which a significant amount of biomass is removed from the forest.). Additionally, the historical context within which a disturbance occurs may be as important, or more so, than the disturbance intensity.
- While hurricanes were the disturbance type investigated in this study, results may be relevant for understanding gastropod responses to other types of disturbance (e.g., tree harvest) that generate large, widespread openings in the forest canopy.

Boyd, R. 1999. Indians, fire and the land in the Pacific Northwest. Oregon State University Press, Corvallis, Oregon. 313 pp. RP, RR.

- This book addresses the role of anthropogenic fire in shaping forest ecosystems in the Pacific Northwest.

Brady, J.K. and T.A. Pearce. 2007. Terrestrial Slugs in Strip Mined and Unmined Forested Land, Tuscarawas County, Ohio, U.S.A. Proceedings of the Academy of Natural Sciences of Philadelphia 156:117-122. RS, PR.

- This paper reports results from an Ohio study on the influence of forest patch size, proximity to forest edge, and strip mining history on slug diversity. Of the seven forested localities three were former strip mines.
- Slug species richness did not correlate significantly with mining history, proximity of the traps to the forest edge, or with forest patch size, although there was a non-significant trend for greater slug diversity at larger forest patches, and species richness of slugs was greater in forests containing *Quercus* (oak).
- The use of pitfall traps containing propylene glycol is discussed as promising method for collecting slug species.

Bros, V., Moreno-Rueda, G., and X. Santos. 2011. Does postfire management affect the recovery of Mediterranean communities? The case study of terrestrial gastropods. Forest Ecology and Management 261(3): 611-619. RS, PR.

- This study examined the taxonomic and functional response of a Mediterranean snail community to fire and post-fire management. Burned and adjacent unburned sites with the same dominant tree species were compared, and four different post-fire management strategies were implemented and replicated: post-fire logging with complete tree removal (trunks and branches); post-fire logging with trunk removal only (branches spread on ground); post fire trunk removal and subsoiling (later replanted); and no post-fire management.
- A total of 666 snails were collected, representing 32 species. Fire exerted a major impact on the snail community, strongly reducing diversity and species richness, particularly for forest species living in the humus. All but five of the 32 species examined were associated with unburned habitat, and fire resulted in population declines and extirpations of 25 species. However, the total number of snails encountered per site showed no differences among treatments, suggesting that, although the fire drastically reduced diversity, some species took advantage of new habitats and expanded their populations, resulting in similar total numbers of snail individuals in burnt and unburnt treatments. Since wildfires lead to a simplification of the vegetation structure, often dominated by grasses, post-fire habitat favors snail species characteristic of habitats with grassy vegetation. In this study, four such species were found to increase their abundance at burnt sites.
- Only slight differences were found within the post-fire practices, presumably because of the strong initial impact of fire and subsequent xerophilous postfire conditions. However, the area with only trunk removal showed a positive response of generalist snail species, probably due to moist microhabitats provided by the accumulation of wood debris on the ground.

Burke, T.E. 1999. Management recommendations for terrestrial mollusk species. *Cryptomastix devia*, the Puget Oregonian Snail. V. 2.0. Prepared for the Oregon Bureau of Land Management. 33 pp. Available at: http://www.blm.gov/or/plans/surveyandmanage/MR/TM4Species/2000-015_1.pdf (Accessed 20 May 2011). RP.

- This paper describes habitat needs, threats, and management recommendations for *Cryptomastix devia*, a terrestrial snail species. Although much of the report is highly species-specific, some general gastropod material, including a review on fire impacts, is provided.
- With regard to fire, it is reported that the impact of fire depends on several variables, including intensity, season and relationship to the life cycle of the species. Intense fire events can be very destructive to snails and slugs, both by direct mortality and destruction of critical habitat, resulting in the persistence of only a small fraction of mollusk fauna for many years (possibly a century or more). Less-severe fires leaving numerous large, minimally charred logs in the stand result in a greater portion of mollusk survival. Zero to two or rarely three species may be expected in burned stands

without abundant logs remaining, while five to seven species may be expected to be found in stands similarly treated but with the logs remaining, and 13 to 20 or more species may be found in unburned stands. Whether gastropods remain through the burn, protected by the abundant logs, or are able to more rapidly disperse back into the stand because of the cover provided by the logs has not been determined.
- Once extirpated from a site, populations of most gastropod species are slow to recover. Sites that appear to be suitable snail and slug habitat, but which have been burned in the past, are reported to support few if any species or individuals even after 50 years and longer. Even abundant, larger species (e.g., *Haplotrema* and *Vespericola*) may take several years to repopulate burned sites once habitat is restored.

Caldwell, R.S. 1993. Macroinvertebrates and their relationship to coarse woody debris: with special reference to land snails. Pp. 49-54 in: J.W. McMinn, D.A. Crossley (eds.) Biodiversity and Coarse Woody Debris in Southern Forests. Proceedings of the workshop on coarse woody debris in southern forests: effects on biodiversity. USDA Forest Service General Technical Report SE-GTR-94. These pages can be previewed at: http://books.google.com/books?id=9B3980OPKJIC&printsec=frontcover#v=onepage&q&f=false (Accessed 25 Oct. 2011). RP, PR.
- This paper reviews the relationship between coarse woody debris and land snails.
- Land snail feeding groups include detritivores, fungivores, herbivores, carnivores, and combinations thereof. Land snails have important role in storing, releasing, and cycling calcium in the ecosystems they inhabit.
- The higher abundance of snails in woodlands is probably due to greater habitat diversity. Coarse woody debris is important to a large percentage of land snails, although the nature of this dependence is not well-understood and deserves further attention.

Cameron, R.A, Down, D.K., and D.J. Pannett. 1980. Historical and environmental influences on hedgerow snail faunas. Biological Journal of the Linnean Society 13: 75-87. RS, PR.
- This study in the English Midlands reports a positive relationship between snail diversity and age of hedge habitat. It is suggested that these differences are primarily due to the poor dispersal of snails rather than to existing environmental differences between hedges of differing age.

Chen, J.Q, Franklin, J.F. 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. RS, PR.
- This study measured microclimatic conditions of a recent clearcut (10 to 15 years old), edge, and adjacent interior old-growth Douglas-fir forest in Washington, over two growing seasons.
- Over the growing season, daily averages of air and soil temperatures, wind velocity, and short-wave radiation were consistently lower, and soil and air moisture higher, in the remnant old-growth forest than in the clearcut or edge environments. Daily differences

(*i.e.,* maximums minus minimums) of all variables were consistently lower in the old-growth forest. The highest variability in microclimate was found at the edge, rather than in either clearcut or interior forest, primarily because of the influence related to edge orientation. Edge microclimates were intermediate between clearcut and interior forest for wind velocity and solar radiation, but not for temperature and moisture.

Churchfield, S. 1984. Dietary separation in three species of shrew inhabiting water-cress beds. Journal of Zoology 204: 211–228. RS, PR.

- This study addresses gastropods as a food source for shrews.

Curry, T., Greenwald, N., and A. Garty. 2008. Petition to list 32 mollusk species from freshwater and terrestrial ecosystems of the northwestern United States as Threatened or Endangered under the Endangered Species Act. RP.

- This petition identifies 32 mollusks in the Pacific Northwest as in danger of extinction.

Duffey, E. 1975. The effects of human trampling on the fauna of grassland litter. Biological Conservation 7: 255-274. RS, PR.

- This study measured the effects of human trampling on the invertebrate fauna of leaf litter. Sterilized hay in nylon mesh bags was placed in a grassy meadow for a 12 month period and exposed to different levels of treading intensity: 0 (control), 5 treads per month (light), and 10 treads per month (heavy). Treading was carried out by a 182 lb person wearing rubber boots.
- Changes in litter structure, decreases in litter depth and volume, decreases in air space, penetration of soil into the litter, and physical impacts of treading all combined to cause a rapid fall in the abundance of most animals recorded. Both snails and slugs exhibited drastic declines (generally over 50%) in the treaded treatments, although differences between heavy and light treatments were small and not significant.
- Results are consistent with other findings in which changes due to human or cattle trampling are evident in the invertebrate community associated with leaf litter and vegetation long before the effects on plants (e.g., damaged plants, bare patches of soil) become apparent. Mechanisms by which invertebrates are impacted by treading include direct destruction of individual animals by foot contact, and (more significantly) changes in microhabitat structure, such as rapid loss of leaf litter by dispersal and fragmentation, and decrease in the height of living vegetation.

Duguay, J.P., Wood, P.B., and G.W. Miller. 2000. Effects of timber harvests on invertebrate biomass and avian nest success. Wildlife Society Bulletin 28: 1123-1131. RS, PR.

- Among other bird-related topics, this study examined invertebrate response to clearcutting (removal of an entire stand in one cutting) and two-age management (37-49 mature trees/ha remaining, similar to seed-tree methods except that residual trees are not harvested when the regenerated stand becomes established, but rather remain until the new stand reaches rotation age) in deciduous forests in West Virginia. Two-age stands were harvested ~9 to 17 years prior to the study, and clearcut stands were

harvested ~14 to 16 years prior to the study. The unharvested stands were 75 to 85 years old.

- Of the three treatments, clearcuts had the lowest biomass of litter-dwelling invertebrates, particularly in summer when the difference between unharvested and clearcut treatments were significant. No significant differences were detected between unharvested and two-age management.
- It is unclear from the paper whether snails were collected in the study and included in the analyses; inclusion is likely since the focus was on invertebrates palatable to birds.

Dunk, J.R., Zielinski, W.J., West, K., Schmidt, K., Baldwin, J., Perrochet, J., Schlick, K., and J. Ford. 2002. Distributions of rare mollusks relative to reserved lands in northern California. Northwest Science 76: 249–256. RS, PR.

- This study took place in four National Forests in northern California. Because of their protection under the North West Forest Plan (NWFP), nine terrestrial "Survey and Manage" mollusks were selected for surveys.
- Mollusks occurred more frequently than expected in Riparian Reserves, but didn't differ in occurrence between other types of reserved and non-reserved lands. The authors state that it is premature to draw any conclusions about the need for more or less protection, or about the importance of any habitat feature for this group, noting the need for species-by-species habitat analyses before a more complete picture of habitat associations and conservation need is possible.

Dunk J.R., Zielinski, W.J., and H.K. Preisler. 2004. Predicting the occurrence of rare mollusks in Northern California forests. Ecological Applications 14(3): 713–729. RS, PR.

- Five terrestrial mollusks in northern California that were assumed to be sensitive to land management activities were sampled from 308 plots randomly selected from a grid of points across a 2.2 million-ha study area.
- Generalized Additive Models were used to estimate each mollusk's geographic range and to develop predictive habitat models within their ranges. Models were developed at one microscale (1 ha) and six mesoscales (ranging from 12.5 to 1250 ha) using vegetation, physical, climatic, and spatial location covariates.
- Predictive habitat models explained from 40.8% to 94.5% of the deviance in models describing the species' occurrences. Models at the 1-ha scale were generally better than models at larger spatial scales, and spatial location and climatic variables contributed significantly to the predictions of occurrence for most species.
- One species was more frequently associated with late-successional forests, another was found to be a habitat generalist, and the remaining three species were not detected enough for strong conclusions to be made about their habitat associations.
- Predictive habitat models may provide guidance to land managers by determining where surveys may or may not be necessary, or what effects a project may have on habitat in the project area or across the range of a species.

Dunk J.R., Zielinski, W.J., and H.H. Welsh, Jr. 2006. Evaluating reserves for species richness and

representation in northern California. Diversity and Distributions 12: 434–442. RS, PR.

- Field data from a random sampling design was used to map the distribution of local and regional richness of terrestrial mollusks within northern California's portion of the Klamath-Siskiyou region, and to evaluate the protection afforded by reserves established for varying reasons (e.g. for inspiration and recreation for people vs. species conservation) to hotspots of species richness and species representation of these taxa.
- When species richness hotspots were defined as including the richest 25% of the area, reserves were found to include disproportionately greater areas of hotspots for mollusks, whereas non-reserved lands contained greater than expected areas with lower species richness.
- Results suggest that conservation plans designed around umbrella species (in this case, the northern spotted owl) can be effective at promoting diversity in other lesser-known species groups.
- Further evaluation of the biotic and abiotic factors associated with local and regional hotspots could provide land managers a template of desired conditions to maintain or encourage for mollusks.

Forman, R.T.T. and L.E. Alexander. 1998. Roads and their major ecological effects. Annual Review of Ecology and Systematics 29: 207-231. RP, PR.

- This review identifies the major ecological effects of roads. Among other effects, roads are found to accumulate a variety of contaminants, and increase introductions of nonnative and/or noxious plant and animal species.

France, R.L. 1997. Macroinvertebrate colonization of woody debris in Canadian shield lakes following riparian clearcutting. Conservation Biology 11:513–521. RS, PR.

- This study found that riparian clearcut logging resulted in a dramatic shift from once dominant conifers to regrowth composed largely of deciduous trees, thus altering the composition and abundance of forest litter 4 to 10 years post-harvest.

Frest, T.J. 2002. Native snails: Indicators of Ecosystem Health. p. 211-215, in: Welfare Ranching, G. Wuerthner and M. Matteson (Eds.). Island Press, Sausalito, California. RP, PR.

- Among other topics, this book chapter reviews the impacts of roadways on mollusks.
- "The direct effect [of road building] on an existing colony [of mollusks] is extirpation in the roadway proper; site preparation often extends the effects. Road building also increases human traffic, including foot traffic; increases exposure, insolation, and effective ground temperature; changes the local plant community; often leads to the introduction of disturbance plants and nonnative and noxious plants and animal species; and initiates damaging side effects, such as herbicide spraying. Even for larger animals, roads may be impassable migration barriers; they are even more so for smaller and soft-bodied animals like snails."

Frest, T.J. and E.J. Johannes. 1995. Interior Columbia Basin mollusk species of special concern. Deixis Consultants, Seattle, WA. Prepared for the U.S. Department of Agriculture, Forest

Service; U.S. Department of the Interior, Bureau of Land Management, Upper Columbia River Basin Ecosystem Management Project. 274 pp. + appendices. RP.

- Among other topics, this report reviews the ecological significance of mollusks.
- Snails and slugs provide food to many small mammals (e.g., shrews, voles, shrew moles), amphibians, and a number of birds. Various insects, including certain beetle, fly, and wasp families, either prey upon snails directly or parasitize them (by laying eggs inside them).
- Empty snail shells are used for shelter, domiciles, or oviposition sites by a variety of invertebrates.

Gärdenfors, U., Waldén, H.W. and I. Wäreborn. 1995. Effects of soil acidification on forest land snails. Ecological Bulletins 44: 259-270. RS, PR.

- Snails need calcium for shell construction, reproduction, and various physiological processes and are thus suspected of being susceptible to acidification in terrestrial habitats. This study investigated the effect of on-going acidification in Sweden on forest land snail populations, and the relationships between snail density and calcium levels. Methods included re-inventories of snail populations in 57 forest sites originally investigated 14 and 46 years earlier, experimental liming in forests, and examination of elemental composition in snail shells from different environmental situations.
- In general, snail density clearly decreased between the sampling periods, particularly at localities with low base saturation and low pH; parallel to this a decrease in calcium concentration in litter occurred. Experimental liming in beech forests resulted in an increase of snail density by a factor of 10-90, indicating that liming can counteract reductions in snail populations caused by soil acidification. Highly significant correlations between snail density and calcium concentration, pH, base saturation and base cation concentration of the litter were found. Analyses of shell elemental composition indicated that concentrations of certain elements were dependent on acidity in the environment in which the snails lived, suggesting that shells from different localities and time periods can be used as bio-indicators and environmental archives.

Gervais, J. A., Taveset, A., and M.F. Willson. 1998. The potential for seed dispersal by the banana slug (*Ariolimax columbianus*). American Midland Naturalist 140:103–110. RS, PR.

- This study tested the hypothesis that the banana slug (*Ariolimax columbianus*) defecates viable seeds and may thus act as a seed disperser. Previous observations confirmed that these slugs eat the fruits of many wild plants. Captive slugs were fed the fruits of six forest plants, and defecated seeds were wiped clean and planted along with control seeds from ripe fruits to determine the effects of slug ingestion on seed germination.
- At least some seeds of each species germinated after the fruits were consumed by the slugs, but the effects on germination were species-specific. Seeds of *Rubus spectabilis* were less likely to germinate after passage through the guts of slugs, while seeds of *Disporum smithii* seeds appeared to have germination enhancement following rasping of the seeds by slugs, although this was not statistically significant.

- “Despite the short distances slugs are likely to disperse seeds, their generalist habits and ubiquity suggest that they may have complex and ecologically significant effects on seed dispersal in Pacific Northwest forests”.

Götmark, F., von Proschwitz, T., and N. Franc. 2008. Are small sedentary species affected by habitat fragmentation? Local vs. landscape factors predicting species richness and composition of land mollusks in Swedish conservation forests. Journal of Biogeography 35(6): 1062-1076. RS, PR.

- In landscapes with small, isolated patches of semi-natural habitats, many species that require large habitat areas have disappeared or are threatened. However, for small sedentary taxa that depend on local conditions, such as mollusks, the effect of total habitat area decreases in the landscape is not well-known. The goal of this study was to investigate the relative role of local versus landscape factors for local species diversity of snails and slugs in temperate deciduous forests in southern Sweden.
- 25 small, widely-spaced conservation forests were sampled for mollusks, and factors potentially influencing local diversity of mollusks were also measured.
- The pH of the plant litter was found to be the strongest predictor of both species richness and composition; canopy openness, stony ground and tree species were also important. The area of conservation forest (woodland key habitat) within 10 km of plots was positively associated with species richness and was also related to species composition. Openness of the landscape (agriculture) was negatively associated with species richness, but historical openness seemed to be unimportant. Factors related to climate and topography also predicted species composition of the sites.
- Microhabitat factors are not the sole determiners of local species richness and composition of land mollusks. Although small and sedentary, these organisms seem to be substantially influenced by the surrounding landscape--- an important consideration in conservation and protection of forest biodiversity.

Graveland, J., van der Wal, R., van Balen, J.H., and A.J. van Noordwijk. 1994. Poor reproduction in forest passerines from decline of snail abundance on acidified soils. Nature 368: 446–448. RS, PR.

- This study presents the first experimental evidence that anthropogenic acid deposition over the last two decades has caused a decline of soil calcium in forests with poor soils, resulting in reduced snail density and an increase in eggshell defects in female birds whose primary calcium source is from snails. See comments under Graveland and van der Wal (1996), below.

Graveland, J., and R. van der Wal. 1996. Decline in snail abundance due to soil acidification causes eggshell defects in forest passerines. Oecologia 105: 351–360. RS, PR.

- On poor soils in the Netherlands, an increasing number of great tits, *Parus major*, and of other forest birds produce eggs with defective shells, and have low reproductive success as a result of calcium deficiency. This study investigated whether a decrease in snail abundance could be responsible for the decline in eggshell quality, and if so, what caused this decrease.

- Snail density in forests where tits have eggshell defects was much lower than in forests where tits do not have such defects. Snail density was positively correlated with the calcium content and to a lesser extent with pH of the litter layer. Liming of a calcium-poor forest soil with low snail densities in snail densities comparable to those on calcium-rich soils after 4 years.
- It is concluded that anthropogenic acid deposition over the last two decades has caused a decline of soil calcium in forests with poor soils, resulting in reduced snail density and an increase in eggshell defects in birds.

Halpern, C.B. and T.A. Spies. 1995. Plant species diversity in natural and managed forest of the Pacific Northwest. Ecological Applications 5: 913-934. RS, PR.

- This paper addresses logging-related changes to the diversity, abundance, and composition of forest vegetation over both the short and long-term.

Hartley, M.K., Rogers, W.E., Siemann, E., and J. Grace. 2007. Responses of prairie arthropod communities to fire and fertilizer: balancing plant and arthropod conservation. American Midland Naturalist 157: 92-105. RS, PR.

- This study examined the impact of fire and fertilizer treatments on plant cover and arthropod community structure. Theoretical and realized impacts of fire on invertebrates are discussed.

Hawkins, J.W., Lankester, M.W., Lautenschlager, R.A., and F.W. Bell. 1997a. Length-biomass and energy relationships of terrestrial gastropods in northern forest ecosystems. Canadian Journal of Zoology 75: 501–505. MS, PR.

- The purpose of this study was to develop a length-biomass model as a way to estimate the biomass of terrestrial gastropods in forest systems. The length, width, and wet and dry masses were determined for each of seven gastropod species and used to create a model that adequately predicted biomass on the basis of animal length.
- Based on gastropod densities reported in the literature (2 to $38/m^2$), snails and slugs on the forest floor accounted for 2.5 and 6% of the total animal biomass and energy, respectively, of boreal forest ecosystems. However, because densities of gastropods in both the litter and underlying soil can reach much greater values than on the forest floor (e.g., 80 to $1607/m^2$), published values for animal biomass and caloric energy in boreal forest ecosystems are underestimated. Regardless, terrestrial gastropods clearly make a significant contribution to the animal biomass and energy in boreal forest ecosystems.

Hawkins, J.W., Lankester, M.W., Lautenschlager, R.A., and F.W. Bell. 1997b. Effects of alternative conifer release treatments on terrestrial gastropods in northwestern Ontario. The Forestry Chronicle 73: 91–98. RS, PR.

- This study examined terrestrial gastropod species richness and density in regenerating spruce plantations before and one year after four different conifer release treatments: application of the chemical herbicide Vision® [a.i. glyphosate], application of the chemical herbicide Release® [a.i. triclopyr]), cutting by mechanical means, and motor-manual cutting with brush saws. Differences in gastropod species richness and abundance between a nine year-old spruce plantation and a mature 70-year-old mixedwood forest were also examined.
- Despite marked changes in vegetation structure on the conifer released sites (Bell et al. 1997a), no differences were evident in species richness and density of gastropods following either chemical, mechanical, or motor-manual treatments in the one-year period examined. Although removal of vegetation can cause unfavorable conditions for gastropods (decreased relative humidity and greater extremes in near ground temperatures), it appears that gastropods may respond to such conditions by moving deeper into the soil, resurfacing again as soon as near ground vegetation has regenerated and soil temperature and moisture conditions are restored.
- Species richness of gastropods in the regenerating and uncut forests were similar (20 spp. vs. 18 spp., respectively), while mean density was higher in the regenerating forest than in the uncut forest, primarily due to greater numbers of a few species in the regenerating forest. All of the 18 species of the old forest were also recorded in the plantation. This result may be explained by the greater variety and abundance of near-ground vegetation and deciduous litter in regenerating plantations, which may provide a wider range of suitable microsites for snails and slugs. Additionally, although light intensity and near-ground temperatures are greater on regenerating conifer plantations than in uncut forests, soil moisture remains high in plantations as a result of lower transpiring vegetation.
- Results of this study suggest that within five to eight years of a disturbance such as logging, regenerating areas can be expected to have markedly greater density and somewhat greater richness of gastropod species than occurred in the original mature forests that they replace. However, because much of the literature suggests that gastropods prefer forests with a strong deciduous component, managed conifer plantations would be expected, eventually, to become less suitable over time.

Hawkins, J.W., Lankester, M.W., and R.R.A. Nelson. 1998. Sampling terrestrial gastropods using cardboard sheets. Malacologia 39:1-9. RS, PR.

- This paper evaluates the use of corrugated cardboard sheets as a terrestrial gastropod sampling technique.
- Cardboard sheet sampling is deemed an efficient way to collect large numbers of gastropods and is useful for estimating relative densities and determining species composition of snails and slugs active on the forest floor surface, providing sampling is conducted under appropriate weather conditions (outlined in the paper). Other methods (e.g., soil cores) appear to be more reliable for quantitatively assessing the below-ground component of gastropod communities.

Huggard, D.J., Kremsater, L.L., and F.L. Bunnell. *In press*. Learning from Organisms. Chapter 11 *in* Forestry and biodiversity learning how to sustain biodiversity in managed forests. Ed. F. L. Bunnell and G. B. Dunsworth. RP, PR.

- This book chapter focuses on implementation of programs to monitor organisms as part of adaptive management in forestry.
- "Variable retention is expected to make regenerating stands habitable continually or earlier than regenerating clearcuts, but for many species we do not know at what age a clearcut becomes suitable. If some species are quickly recovered in clearcuts, those species would likely do well in any harvested landscape, and would be less useful as an indicator for monitoring retention"
- With regard to gastropods, it is noted that season variation in gastropod density can be very high, possibly due to species-specific differences in seasonality, or simply seasonal, weather-driven changes in catchability. Also unresolved is whether the seasonality exhibited by different species is itself affected by harvest treatments.

Huggard, D.J. and A. Vyse. 2002. Comparing clearcutting and alternatives in a high elevation forest: early results from the Sicamous Creek Project. British Columbia Ministry of Forests Research Program Extension Note 63: 1-10. RP.

- This paper reviews biotic and abiotic responses to clearcutting and alternatives in a high-elevation coniferous forest in British Columbia.
- With regard to gastropods, the relative abundance of slugs was reduced in treatments with 10 ha clearcuts, 1 ha clearcuts, and 0.1 ha patch cuts with 300 m leave-strips, whereas their abundance was most similar to that in the control in uniform individual tree selection treatment with 80% tree retention.

Hylander K., Nilsson, C., and T. Göthner. 2004. Effects of buffer-strip retention and clearcutting on land snails in boreal riparian forests. Conservation Biology 18(4): 1052-1062. RS, PR.

- This study examined the initial effects of clear-cutting on the litter dwelling snail community in riparian forests along small boreal streams in Sweden. Two different silviculture treatments were applied at each of fifteen sites: clear-cutting across the stream channel, and 10 m-wide buffer strips on each side of the stream. Additionally, 10 unlogged riparian reference sites were examined. Sampling was conducted the summer before and 2.5 years after clear-cutting.
- Clear-cutting radically affected land-snail communities in this study, with most species negatively affected, although there were both species-specific and site-specific differences in sensitivity. After clear-cutting, mean snail abundance and species richness in a 0.5 m^{-2} sample both decreased significantly, from 107 to 87 individuals, and from 9.9 to 7.7 species, respectively. In the uncut reference sites, no significant differences were detected between the years. Snail species most affected by clear-cuts were those with habitat preferences for relatively oligotrophic, shady, moss-rich forests.
- Species richness was less reduced after clear-cutting in areas with high moisture levels in the ground. At the wettest sites with dense bryophyte cover, snails were relatively unaffected by clear-cut conditions, suggesting that wet or moist microsites can serve as

refugia for this group, even at small scales, such as shallow hollows or crevices next to boulders and stumps.
- Differences in the snail community between clear-cuts and buffer strips were also investigated. Buffer strip methods reduced snail abundance but not species diversity, indicating that leaving small groups of intact trees is a good practice for snail conservation in riparian habitats, and can lead to significant increases in the survival of species.
- Overall, an undisturbed bryophyte cover, either by retained trees in the buffer strip or wet conditions at the sites, appear to strongly mitigate the negative effects of clearcutting on this group.

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(11): 1811-1819. RS, PR.

- This study investigated the short-term impacts (2 to 7 years) of forest fires and clear-cutting on forest floor dwelling land snails. Snail fauna were sampled below retained aspen trees in six clear-cuts and surviving aspens in five burnt forests, and compared with samples under scattered aspens in seven adjacent undisturbed forests.
- Burnt sites had a significantly lower abundance of individual snails (11 vs. 30 in 0.5 l sample) and 50% lower species richness (3 vs. 6 species) than undisturbed forests. Burning apparently depleted the snail fauna considerably and some species may be dependent on dispersal and recolonization if they are to recover within the burnt area. Important remaining questions with regard to fire include the difference in response between wildfire and prescribed burning, the effect of fire severity, the temporal pattern of recovery, and possible regional differences.
- Clear-cuts with tree retention had less negative impact than burning on snails, and the snail assemblages (abundances and richness) at clear-cuts did not differ significantly in species composition from adjacent undisturbed forests. Although the above ground micro-climate of clear-cuts is generally drier and fluctuates considerably more than in undisturbed forests, land snails can apparently thrive quite well in the organic layer under retained trees, at least under aspens. “The boreal snail fauna may thus represent a group of organisms that are possible to accommodate quite effectively in a silvicultural landscape under appropriate management practices, in contrast to other species groups that require, for example, recurrent forest fires or very old trees to persist.”
- In this study, pH (or possibly some variable such as calcium content related to pH) was a key factor in explaining species composition in both disturbed and undisturbed sites, with a positive relationship between pH and both species density and abundance in all the stand types.

Jacot, A.P. 1935. Molluscan populations of old growth forests and rewooded fields in the Asheville Basin of North Carolina. Ecology 16(4): 603-605. RS, PR.

- This early North Carolina study examined snail diversity and abundance sampled from eleven forests of different compositions, ages, and with differing disturbance histories.

Two of the sites had been recently burned (<2 years past) by hot fire which consumed all leaf-litter.
- A direct correlation was reported between the drought resistance of species (as indicated by spire length) and their occurrence in more severely disturbed habitat.
- Snail abundance and diversity were not correlated with forest age. However, the proximity of cut forests to old growth stands and the amount of shelter available in a stand both influenced the repopulation of cut sites.
- Fire is reported to have “no serious consequences, probably because… the stratum in which the eggs are laid [was] not seriously affected by the fire.”

Jennings, T.J. and J.P. Barkham. 1979. Litter decomposition by slugs in mixed deciduous woodland. Holarctic Ecology 2(1): 21-29. RS, PR.
- Six slugs given nine test foods were examined for consumption rate, assimilation rate, and faecal production.
- Using regression equations with these results, it is estimated that slugs consume 8.4% of the leaf-litter input each year, and 6.5% of the total available plant litter.
- The role of slugs in decomposition is discussed in relation to other organisms. Although information is limited, results suggest that the high assimilation efficiencies of slugs (>50%) make them a relatively high contributor to the plant decomposition process in forests. Additionally, it is suggested that by physically and chemically altering plant material, slugs may have an important indirect role in promoting fungal and bacterial growth.

Jones, J.A., Swanson, F.J., Wemple, B.C., and K.U. Snyder. 2000. Effects of roads on hydrology, geomorphology, and disturbance patches in stream networks. Conservation Biology 14(1): 76-85. RP, PR.
- Among other topics, this paper addresses the accumulation of contaminants on roadways, and impacts of run-off on the surrounding landscape.

Kappes, H. 2006. Relations between forest management and slug assemblages (Gastropoda) of deciduous regrowth forests. Forest Ecology and Management 237: 450-457. RS, PR.
- This study analyzed the effects of anthropogenic forest disturbances on forest-floor slugs in 68 broad-leaf forests in Western Europe. Anthropogenic disturbances, including dense systems of paths and/or forest roads, past logging, recent logging, open-cast mining, and significant soil degradation/erosion, were scored and added to determine their combined impact on each forest relative to other environmental variables.
- Canonical correspondence analysis with 10 environmental variables showed that although almost all environmental variables were related to the observed slug assemblages, anthropogenic disturbance was the dominant factor structuring the assemblages.
- Diversity was higher in disturbed forests, although the proportion of stenoecious (narrow environmental tolerances) forest species was higher in comparatively undisturbed forests than in forests with high anthropogenic disturbance. Additionally,

the proportion of these species increased with forest age and the amount of woody debris on the forest floor. Slug species richness was highest on soils with pH values between 4 and 5, although soil acidity did not influence abundances. Overall, slug assemblages are more sensitive to forest management than they are to soil acidification.

- Species response curves illustrated that most slugs have defined habitat preferences and may therefore be suitable indicator species.
- This study found that forest slugs with narrow environmental tolerances benefit from older, less-disturbed forests high in coarse woody debris, whereas exotic slug species profit from high anthropogenic disturbance.
- The study stresses the need for nature-oriented management, including increased rotation length, maintenance of groups of old trees and connectivity to aged stands, and enhancement of microhabitat heterogeneity include high levels of coarse woody debris.

Kappes, H. 2005. Influence of coarse woody debris on the gastropod community of a managed calcareous beech forest in Western Europe. Journal of Molluscan Studies 71(2): 85-91. RS, PR.

- The influence of coarse woody debris (CWD) on gastropod fauna of a beech forest was investigated during three seasons (September, March and June), and in two locations (plateau and SW-exposed slope). In each location, sites close to CWD and distant from CWD were distinguished.
- The results clearly revealed a strong influence of CWD on the fauna that was observed in all seasons. A three-way ANOVA with single species revealed a strong influence of CWD, a low influence of location and no influence of season. Two dominant species occurred independent of the three factors analyzed, while seven species clearly preferred CWD sites. Of these, only three species were also significantly influenced by location, of which two preferred the plateau and one preferred the slope. Life-stage analysis of the five most abundant species revealed one species with clear dependence on the sheltered microclimate of CWD sites for reproduction.
- Results of this study highlight the need for management practices favoring the availability of CWD as an important structural component of an array of microhabitats on the forest floor. Such strategies will provide niches for an increased number of individuals and species, thus helping to maintain biodiversity and improving nutrient cycling and other aspects of biological functioning on the forest floor.

Kappes, H., Jordaens, K., Van Houtte, N., Hendrickx, F., Maelfait, J.P., Lens, L., and T. Backeljau. 2009. A land snail's view of a fragmented landscape. Biological Journal of the Linnean Society 98(4): 839-850. RS, PR.

- This study examined the influence of habitat fragmentation on the genetic structure of the low mobility, forest-associated snail *Discus rotundatus* collected from the fragmented landscape of the Lower Rhine Embayment, Germany.
- Both shell morphometric variability (an ecologically relevant character) and sequence variation in a fragment of the mitochondrial 16S rDNA gene were examined.

- The 16S rDNA of this species was highly variable, with a total of 118 haplotypes forming four clades and one unresolved group. However, at the geographic scale considered, fragmentation produced no obvious effect on shell morphometrics and 16S rDNA variation. Instead, the age of the habitat and afforestation/reforestation events appeared to affect shell shape and 16S rDNA in terms of the number of clades per site.
- These results suggest that while populations of non-stenecious species may be relatively stable in a fragmented landscape, events associated with afforestation generate several seemingly persistent peculiarities, such as altered genetic composition and shell characters.

Karlin, E.J. 1961. Ecological relationships between vegetation and the distribution of land snails in Montana, Colorado and New Mexico. American Midland Naturalist 65: 60–66. RS, PR.

- This study explores ecological relationships in terrestrial snails across three states. Thirty-two species and subspecies were collected, with 99% of the individuals associated with some form of deciduous tree, usually aspen. The coniferous forests which were studied exhibited an almost complete absence of snails.
- Results suggest that the availability of calcium (related to vegetation structure) is an important factor affecting snail distribution, and also assert the likelihood of food chain relationships between aspen and land snails.
- The presence of living snails following an apparently recent aspen fire (date unknown) suggests that at least some snail individuals/species are able to survive fire, although the abundance of snails was found to typically decrease following fire. No snails were found in coniferous forests five to seven years after a fire, but snails were present in stands burned 23 years previously that now had pine and aspen trees.
- Chance distribution appears unlikely to be the only method involved in recolonization, and small, permanent populations are suggested to occur. The importance of refugia in snail recolonization potential after a disturbance event is stressed.

Kiss, L. and F. Magnin. 2006. High resilience of Mediterranean land snail communities to wildfires. Biodiversity and Conservation 15: 2925–2944. RS, PR.

- This research examined the short, medium and long-term impact of fire on snail biodiversity in forests in southeastern France. Stratified sampling was conducted on 12 sites according to fire regime (number of fires, fire intervals and age of the last fire) over the past 30 years.
- Despite their poor dispersal abilities, reliance on vegetation, wood, and litter, and sensitivity to environmental extremes, Mediterranean land snail communities were found to be highly resilient to fires.
- Although fire drastically reduced snail abundance in the short-term, species richness and community diversity were preserved, provided that the time lapse between two successive fires was longer than the time required for recovery (around 5 years).
- The observed community resilience was largely attributed to the presence of cryptic refuges within burned areas, allowing land snail survival and persistence after successive fires.

Kiss, L., Magnin, F., and F. Torre. 2004. The role of landscape history and persistent biogeographical patterns in shaping the responses of Mediterranean land snail communities to recent fire disturbances. Journal of Biogeography 31(1): 145-157. RS, PR.

- This Mediterranean study assessed the impact of various fire regimes on land snail communities and analyzed the role of recent landscape history and biogeography in shaping the response patterns of these communities following fire disturbance. A stratified sampling approach was used with regard to fire regime (i.e. number of fires, fire intervals and age of the last fire) occurring over the past 30 years.
- The composition of snail communities was not affected under low intervals of fires, presumably due to the ability of snails to survive in small refuges. At these sites, the overall community composition was more influenced by geography than by fire disturbance. However, in areas where regular disturbance (fire and/or other anthropogenic disturbances that altered the landscape) occurred over decades or centuries, the land snail communities appeared highly modified and shifted to species more specialized to dry areas.

Kiss, L. and F. Magnin. 2003. The impact of fire on some Mediterranean land snail communities and patterns of post-fire recolonization. Journal of Molluscan Studies 69:43-53. RS, PR.

- This study analyzed the immediate and long-term impact of fire on Mediterranean land snail communities, and examined the subsequent patterns of recolonization within these communities. A stratified sampling scheme was conducted according to fire age and distances from the burned/unburned boundaries and from vegetation refuges.
- Although land snail communities decrease in diversity and abundance post-fire, distances from burned/unburned boundaries and vegetation refuges did not significantly influence recolonization patterns in this study, countering the original working hypothesis that land snail recolonization progresses from margins of the burned areas and from vegetation areas spared by the fire.
- In contrast, habitat structure was found to have a strong influence on post-fire community composition, presumably via habitat-related differences in the potential to survive fire. For example, areas with rocks did not burn as intensely as other habitats, and snails at those locations tended to survive in higher numbers. Likewise, areas with deep oak litter apparently promoted survival of certain species.
- Overall, snail communities were found to be relatively resilient to fire perturbation. One year after a fire all ecological groups were represented, suggesting that numerous scattered refuges in disturbed sites lend “a certain permanence” to malacological communities.

Kralka, R.A. 1986. Population characteristics of terrestrial gastropods in boreal forest habitats. American Midland Naturalist 115:156–164. RS, PR.

- This research examined the broad habitat associations of terrestrial gastropod populations in five boreal forest types in Alberta.

- Species composition and abundance varied by habitat type, with most of the 13 species showing a statistical preference for deciduous forests. A few species aggregated in multiple habitat types, one species showed preference for coniferous forests, and one species for logged forests.
- Observed variation in community structure may occur in response to vegetation, moisture, soil chemistry, pH, available food and refugia.

Livshits, G.M. 1983. Ecology of the terrestrial snail (*Brephulopsis bidens*): age composition, population density and spatial distribution of individuals. Journal of Zoology 199: 433–446. RS, PR.

- Among other things, this paper reports that up to 44% of adults and 18% of juvenile gastropods (*Brephulopsis bidens*) died over winter at a mountain site in Russia.
- Pre-adolescent snails exhibited better winter survival than mature adults.

Locasciulli, O. and D.A. Boag. 1987. Microdistribution of terrestrial snails (Stylommatophora) in forest litter. The Canadian Field-Naturalist 101: 76-81. RS, PR.

- The microdistribution of nine litter-dwelling species of small terrestrial snails was studied in three forest habitats over a period of two years in southwestern Alberta.
- Results found snail density to vary among forest habitats; density was highest in a coniferous forest, where litter depth was greatest, intermediate in a deciduous forest, and minimal in a mixed-wood forest where litter depth was least. Snails were clumped both horizontally and vertically, but their microdistribution was unrelated to either the shrub or ground level vegetations. The vertical distribution of snails changed over the period of the study with a general upward movement between May and August.

Martin, S.M. 2000. Terrestrial snails and slugs (Mollusca: Gastropoda) of Maine. Northeastern Naturalist 7(1): 33–88. RP, PR.

- Among other topics, this paper discusses the process of calcium cycling via snails. Decaying shells are noted for returning calcium carbonate to the soil.
- Land mollusks are listed as a foodsource for salamanders, frogs, toads, turtles, snakes, lizards, birds, shrews, voles, moles, rats, mice, chipmunks, and squirrels. Invertebrate predators of terrestrial mollusks include sciomyzid fly larvae, firefly larvae, carabid and staphylinid beetles, and ants.

Mason, C.F. 1970a. Food, feeding rates and assimilation in woodland snails. Oecologia 4: 358–373. RS, PR.

- This study examined the consumption and assimilation of a variety of foods by seven mollusk species in the laboratory. Faecal analyses of litter-dwelling forest snails revealed that all seven species feed predominantly on higher plant material (living or dead). Two species took more chlorophyll-containing plant material than the other species, two species ate significant amounts of animal material, and one species had a significant amount of fungus in its faeces.

- The assimilation efficiency of the molluscs was found to be temperature independent, but ingestion rates and absolute assimilation rates were temperature dependent. Species-specific assimilation efficiencies are reported in the paper.

Mason, C.F. 1970b. Snail populations, beech litter production, and the role of snails in litter decomposition. Oecologia 5: 215–239. RS, PR.

- This study reports the population density and biomass of snails in beech litter, litter production over one year, and the role of snails in litter removal.
- Among other results, the mean annual population density of the 21 snail species recorded on the main sampling site was 489/m^2. The mean annual biomass was 699 mg dry weight/m^2.

McDade, K. 2002. Habitat relationships of small terrestrial vertebrates and invertebrates in managed forests in the southern Oregon Cascades. M.S. Thesis. Corvallis, OR: Oregon State University. 212 pp. RS.

- This study examined forest floor animal abundance and habitat relationships under three different silviculture conditions: clearcuts, commercial thins, and uncut areas in the Umpqua National Forest, Southern Oregon Cascades. Surveys for ground-dwelling fauna yielded a total of 332 gastropods from pitfall traps and transect searches, in addition to a large number of arthropods, amphibians, and small mammals.
- Gastropod captures were similar between thinned and uncut stands, but there were significantly fewer captures in clearcuts than uncut areas. Overall, gastropod species richness and diversity decreased with harvest intensity, and commercial thinning was found to affect forest floor animal populations less severely than clearcut harvesting.
- Multiple linear regression results showed that canopy cover and basal area were important habitat variables for *Haplotrema* snails, suggesting that these animals may be particularly sensitive to tree removal.

Meadows, D.W. 2002. The effect of roads and trails on movement of the Ogden Rocky Mountain snail (*Oreohelix peripherica wasatchensis*). Western North American Naturalist 62: 377-380. RS, PR.

- This study examines road avoidance and its proximate causes in the Ogden Rocky Mountain snail, *Oreohelix peripherica wasatchensis.* Movement preference relative to pathways was assessed in the field, while habitat features causing pathway avoidance were assessed with laboratory choice studies.
- Control site snails had no directional movement preference while road and trail site snails moved away from pathways. In the laboratory, snails preferred natural substrate with leaf litter to road material, but they showed no preference between natural substrate and road material. There was no significant preference for wet vs. dry natural substrate. There was a significant preference for natural substrate with dry leaf litter over natural substrate without litter, as well as for leaf litter on road substrate over natural substrate alone. Natural substrate with artificial leaves was chosen over natural substrate alone.

- Both the field and laboratory experiments revealed that the road avoidance exhibited by this species was due to the absence of leaf litter, which means that even small paths (the smallest measured in this study was 0.7 m [2.3 feet] wide) have an effect on snail movement if no litter is present.
- Movement prevention by roads and paths may hinder the ability of snails to disperse and make recolonization after disturbance events even more difficult. Additionally, fragmentation of populations by roads may result in genetically divergent and less stable subpopulations with a higher probability of extinction.

Moning, C. and J. Müller. 2009. Critical forest age thresholds for the diversity of lichens, molluscs and birds in beech (*Fagus sylvatica* L.) dominated forests. Ecological Indicators 9(5): 922-932. RS, PR.

- This study in southeast Germany examined the impact of forest age on breeding birds, mollusks, and lichens, and identified forest age as a key factor to animal occurrence that may be controlled by forest management. Sampling for mollusks was conducted on 116 plots in sub-montane and montane mixed-beech forests ranging from zero to 400 years.
- In all three taxonomic groups the number of species per plot significantly increased with forest age. Significant forest age threshold ranges for species richness was identified by recursive partitioning methods. The threshold values for mollusks ranged from ~140 to 205 years. Counter to expectations, red-listed mollusks were found to have lower threshold values for forest age than mollusks as a whole.
- Since the identified threshold levels are clearly incompatible with economic reasons for keeping the rotation period in beech stands to less than 140 years to avoid formation of red heartwood, it appears essential to establish a network of trees and stands that are never logged and may thus act as areas for retreat and dispersion for logging-sensitive species.

Moore, J.D., Ouimet, R., Camiré, C. and D. Houle. 2002. Effects of two silvicultural practices on soil fauna abundance in a northern hardwood forest, Québec, Canada. Canadian Journal of Soil Science 82: 105–113. RS, PR.

- This paper reports research into the impact of selective cutting and strip clearcutting on soil fauna abundance in a northern hardwood forest of the Lower Laurentians of Québec.
- Six to twelve years after both selective and strip clearcutting, snails were more abundant in the treated forests than in the adjacent undisturbed forest (control sites). The authors attribute this finding to the post-cutting increase in coarse woody debris, a resource that has been previously established as important to this group. Variance in snail abundance was lower in the control strips compared to the clearcut strips.
- No effect of forest harvest was observed on the abundance of slugs.
- Note that all species in this study were lumped into taxonomic groups (e.g. snails, slugs) and no attempt was made to evaluate effects of tree harvest disturbances at the species level.

Müller, J., Strätz, C., and T. Hothorn. 2005. Habitat factors for land snails in European beech forests with a special focus on coarse woody debris. European Journal of Forest Research 124: 233-242. RS, PR.

- The effects of habitat characteristics on snail density and species richness were examined in acid beech forests in southern Germany. Habitat characteristics were determined and sampling was conducted at 37 plots in one large forest. Significant relationships were found between snail richness and density and the following set of habitat factors: coverage of herbaceous layer, growing stock, mean diameter at breast height of the three largest trees (DBHmax), stand age, total dead wood volume per ha, and advanced decomposed dead wood volume per ha.
- Maximally selected rank statistics were used to estimate cutpoints separating stands with low densities from stands with high snail densities. Cutpoints for a significant higher snail density were defined at a stand age of 187 years, 57 m^3/ha dead wood, 40 m^3/ha advanced decomposed dead wood, 63 cm DBHmax and more than 1% herbaceous layer. For species richness, cutpoints are estimated at 338 m^3/ ha stand volume, 170 years stand age, 50 m^3/ha total dead wood, 15 m^3/ha advanced decomposed dead wood and 56 cm DBHmax. The identified cutpoints are a good base for ecological management decisions in forest management.
- Microhabitat analysis showed a higher pH value and a higher calcium content at the bottom of large snags and under large lying dead wood pieces in comparison to litter, upper mineral soil and at the bottom of vital living trees. Snail species richness and abundances were significantly linked to these patterns of chemical parameters.

Nekola, J.C. 2002. Effects of fire management on the richness and abundance of central North American grassland land snail faunas. Animal Biodiversity and Conservation 25: 53-66. RS, PR.

- This study examined the land snail faunas from 72 upland and lowland grassland sites in the Midwest United States, including sixteen sites which had been exposed to fire management within the last 15 years. A total of 91,074 individuals in 72 different species were observed.
- In all analyses, a highly significant reduction in richness and abundance was found on fire managed sites. Species richness was reduced by approximately 30% on burned sites, while abundance was reduced by 50–90%. Forty-four percent of 72 snail species experienced a significant reduction in abundance on fire managed sites, while only six species positively responded to fire. The effects of fire differed among snail species, depending on their ecological preferences; most turf–specialists were negatively impacted by fire, while duff–specialists tended to exhibit no significant response.
- It is concluded that frequent use of fire management represents a significant threat to the health and diversity of North American grassland land snail communities. Protecting this fauna requires the preservation of organic litter layers, via an increase of fire return intervals to 15+ years in conjunction with the use of more diversified methods to remove woody and invasive plants.

Niemelä, J., Haila, Y., and P. Punttila. 1996. The importance of small-scale heterogeneity in boreal forests: variation in diversity in forest-floor invertebrates across the succession gradient. Ecography 19: 352-368. RS, PR.

- Heterogeneity in species assemblages of forest-floor arthropods (carabid beetles, ants and spiders) within and between different forest age classes was studied in southern Finland. Land snail assemblages were not examined.
- A number of general and taxon-specific results suggest that regional abundance variation is a primary factor influencing the composition of local assemblages, implying that maintenance of habitat heterogeneity on a small scale (10-15 m) is needed to preserve invertebrate biodiversity in managed forests.

Niemelä, J., 1997. Invertebrates and boreal forest management. Conservation Biology 11: 601–610. S. RP, PR.

- This study reviews the ecological effects of logging on boreal invertebrates.
- Logging effects are strongest for species associated with micro-habitats of natural old-growth forest, such as coarse woody debris, large deciduous trees, and patches of wet swamp-forest.
- Old-growth specialists tend to disappear from clear-cuts, while forest generalists may persist and numerous open-habitat species may appear, resulting in the potential for local invertebrate species richness (a-diversity) to increase, at least for taxa that are not directly associated with micro-habitats characteristic of old growth forests.
- At the landscape scale, intensive logging tends to homogenize forest habitats and lead to declines of sensitive species. Based on these findings three complementary approaches are recommended for the maintenance of boreal biodiversity while harvesting timber. (1) Set aside undisturbed old-growth forests to sustain specialist species and to serve as sources for recolonization. (2) Develop ecologically sound silvicultural practices using natural disturbance regimes as guidelines. (3) Restore disturbed habitats to promote the recovery of associated species assemblages.
- Land snails are mentioned specifically only in terms of the habitat preference of many species for aspen trees.

Nyffeler, M. & W.O.P. Symondson. 2001. Spiders and harvestmen as gastropod predators. Ecological Entomology 26: 617-628.

- This review paper addresses the importance of gastropods as prey of harvestmen and spiders.

Ovaska, K. and L. Sopuck. 2000. Evaluation of the potential of terrestrial gastropods (slugs and snails) for monitoring ecological effects of logging practices on forest-floor conditions on Vancouver Island, British Columbia. A pilot study, October-November 1999. Report prepared by Biolinx Environmental Research Ltd. for Weyerhaeuser Company Ltd., Nanaimo, BC. NS (not available from Ovaska). RS.

- This report presents the results of one gastropod monitoring pilot study (1999). See final report (Ovaska & Sopuck 2010) for summarized results on the impacts of variable-retention logging on gastropods.

Ovaska, K. and L. Sopuck. 2003. Terrestrial gastropods as indicators for monitoring ecological effects of variable-retention logging practices. Report prepared by Biolinx Environmental Research Ltd. for Weyerhaeuser Company Ltd., Nanaimo, BC. RS.

- This report presents the results of one field season (2002) of gastropod monitoring work. See final report (Ovaska & Sopuck 2010) for summarized results on the impacts of variable-retention logging on gastropods.

Ovaska, K. and L. Sopuck. 2007. Terrestrial gastropods as focal species for monitoring ecological effects of variable-retention logging practices, 2006 field season. Report prepared by Biolinx Environmental Research Ltd. for Western Forest Products, Campbell River, BC. RS.

- This report presents the results of one field season (2006) of gastropod monitoring work. See final report (Ovaska & Sopuck 2010) for summarized results on the impacts of variable-retention logging on gastropods.

Ovaska, K. and L. Sopuck. 2008. Land snails and slugs as ecological indicators of logging practices: Recommendations for adaptive management. Report prepared by Biolinx Environmental Research Ltd. for Weyerhaeuser Company Ltd., Nanaimo, BC. RS.

- This report presents the results of one field season (2006) of gastropod monitoring work. See final report (Ovaska & Sopuck 2010) for summarized results on the impacts of variable-retention logging on gastropods.

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. Report prepared by Biolinx Environmental Research Ltd., Sidney, BC. RS.

- The effects of VR-treatments and clearcutting on terrestrial gastropod abundances in coastal forests of British Columbia were examined at six experimental sites, immediately before and 2 – 4 years after logging. In the VR-treatments in this study, trees were retained either in groups (5 sites) or were dispersed within the logged area (1 site).
- A unique sampling method was employed to survey for gastropods: artificial cover-objects constructed of corrugated cardboard were laid flush with the ground on the forest floor and allowed to weather and accumulate moisture for at least 2 weeks, before being inspected for snails on or under the surface. Advantages of this method include ease of sampling, minimal observer bias, and little disturbance to the surrounding habitat, allowing repeated surveys of the same locations. 12 species (2 slugs, 2 large snails, and 8 small snails) were collected in sufficient abundance to permit analyses.
- In this study, some VR-practices were found to better maintain gastropod abundance and diversity than even-aged forests regenerated from clearcutting. However, none of the VR-treatments were equivalent to the control (un-cut) forests in maintaining the

abundance of sensitive species. VR-treatments with large (0.8 – 1.2 ha) groups of trees were more effective at promoting gastropod abundance than small (0.2 – 0.5 ha) groups and clearcuts, and were equivalent to the un-cut control in terms of the number of species. Large VR-groups (0.8 to 1.2 ha) supported a greater abundance of *Pristiloma* species, *Striatura pugetensis*, and small snails as a group than did the clearcut and small VR-groups (0.2 – 0.5 ha), but were not equivalent to the control in species abundance values. In small VR-groups, gastropod abundance and richness was similar to clearcuts (depressed values) regardless of the overall retention level (10%, 20%, or 30%) in the cutblock. At the VR-dispersed experimental site, treatment with 30% retention was more effective than treatments with 5% and 10% retention.

- The relative abundances of two slug species examined were either not affected by any of the treatments or were enhanced in VR-groups, depending on the site. Groups of trees in VR-treatments may have provided shaded micro-sites on the forest floor from which slugs could take advantage of the abundant forage of herbaceous vegetation in the surrounding harvested areas. Logging treatments generated negative short-term effects on the abundances of six species of small snails, one large snail, all small snails combined, and the number of species. Consistent adverse effects were found for *Pristiloma* species and small snails as a group, and for species richness.
- VR-group treatments with overall retention levels of 10%, 20%, and 30% showed no benefits over 20 ha-clearcuts in maintaining sensitive gastropods, possibly due to the fact that although the forest floor in the VR-groups remained physically undisturbed during logging, changes in microhabitat conditions (e.g., edge effects, exposure to wind, elevated temperatures, drying) may have decreased the habitat quality for gastropods.
- With regard to dispersed retention, the relative abundance of six species of small snails, small snails as a group, and *H. vancouverense*, as well as the number of species, were all depressed in all logged treatments relative to the control. Of the logged treatments, the VR-30% dispersed treatment supported the highest abundance of *H. vancouverense* and *V. columbianus*, a species with a positive response to logging, and the highest number of species. Large VR-groups (0.8 to 1.2 ha) supported a greater abundance of *Pristiloma* species, *Striatura pugetensis*, and small snails as a group than did the clearcut and small VR-groups (0.2 – 0.5 ha), but were not equivalent to the control.
- Overall, results of this study indicate that larger groups of trees (0.8 – 1.2 ha) and high levels of dispersed retention (30%) facilitate maintaining pre-disturbance gastropod abundance patterns.

Page, H., Rupp, L., Wiebner, S. and J.G. Goldammer. 2000. Feuerokologie und feuer-management auf augsgewahlten rebboschungen in Kaiserstuhl, Abschulussbericht zur vorlage an das Ministerium Landlicher Raum Baden-Wurttemberg. [Fire ecology and fire management at selected vineyard slopes in the Kaiserstuhl, Final Report to the Baden Wurttemberg Ministry of Agriculture]. University of Freiburg, Germany. RS.

- This study investigates fire ecology and management in an agricultural (grape-growing) area of Germany.

- Findings are reported in German. According to Anderson (2004), this study found that the number of live snails was reduced by more than 50 percent after controlled winter burning, and that small snails have difficulty recolonizing burned areas. Additionally, several recommendations are provided for prescribed burns: (1) Burns should be planned for the time of year that all snails will be hibernating, which the authors consider to be at temperatures ≤ -10°C (14°F), (2) The use of fast fires should be used to minimize the effects on snails, (3) A minimum burn interval of three years is recommended, although small snails may require even more time to recolonize areas.

Page, H. and J.G. Goldammer. 2004. Prescribed Burning in Landscape Management and Nature Conservation: The First Long-Term Pilot Project in Germany in the Kaiserstuhl Viticulture Area, Baden-Württemberg, Germany. International Forest Fire News (IFFN) 30: 49-58. RS.

- The objectives of this study were to determine whether prescribed burning of small plots in late winter could be used to maintain and promote the traditional open vegetation structure and the habitats and occurrences of typical and characteristic animal and plant species on vineyard slopes.
- The direct and indirect effects of fires on gastropods were examined. Results indicate that while snail abundances were significantly reduced on the burned plots, no shift was found in species composition of snails on burned and unburned plots. Earlier investigations conducted in this area indicated that invertebrates hibernating in the grass-layer are killed by prescribed fire conducted in wintertime, while individuals which hibernate in the soil usually survive. The burned plots in this habitat are relatively small (not more than a 50m wide portion of the slope) and surrounded by unburned plots, and the immigration rate after fire is very high and takes place very rapidly, thus concern about the loss of individuals affected by fire is of minor concern. Fire appears to cause a temporary shift of populations with no sustainable change in the species composition observed so far.
- This study reports the average migration rate for big snail species to be 5 to 10 m per year, with the maximum distance covered about 30m per year.

Pfenninger, M., Bahl, A., and B. Streit. 1996. Isolation by distance in a population of a small land snail *Trochoidea geyeri*: evidence from direct and indirect methods. Proceedings: Biological Sciences 263(1374): 1211-1217. RS, PR.

- Population structure was estimated in a continuous population of a small land snail (*Trochoidea geyeri*) using mark-recapture experiments and randomly amplified polymorphic DNA analyses.
- Estimates of density and dispersal suggest a neighbourhood size of 70-208 individuals on an area of 13-21 m^2. DNA analysis revealed clinal variation of genetic composition across the population, as predicted by the neighbourhood concept.
- Genetic distances, expressed as euclidean distances among individuals, was strongly positively correlated with the geographic distance between sampling sites.
- These patterns shed light on the principal processes generating and maintaining genetic diversity within populations of small land gastropods.

Prezio, J.R., Lankester, M.W., Lautenschlager, R.A., 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. RS, PR.

- This study examined changes in terrestrial gastropod density and species composition in regenerating spruce plantations during the second and third years after the application of four conifer release treatments: two herbicides (Vision® and Release®); motor-manual clearing (brushsaw); and mechanical clearing (Silvana Selective or Ford Versatile), in addition to an untreated control on each of the four replicate blocks. Over 15,000 gastropods of 21 species were collected over the two years.
- Gastropod densities in untreated control areas were significantly greater (50–60%) than those in treated areas, both 2 and 3 years post-treatment. (Note that these effects were undetectable in the first summer following treatment (see Hawkins et al. 1997)). Observed declines may be attributable to decreased litter deposition and changes to the near-ground microclimate on the treated sites.
- A separation among individual conifer release treatments became apparent 3 years post-treatment. Densities in untreated control areas were significantly greater than in Vision® ($p = 0.03$) and Release® treated areas ($p = 0.008$) but did not differ from motor-manual and mechanical cutting treatments. Gastropod densities in nonchemical, cutting treatments started to recover more quickly than those in herbicide-treated sites.

Reinink, K. 1979. Observations on the distribution of land snails in the woods of the Ilsselmeer polders. Basteria 43: 33-45. RS, PR.

- Among other findings, this study reports a strong correlation between gastropod species richness and forest plantation age in the Netherlands.

Regan, T.J., Regan, H.M., Bonham, K., Taylor, R.J., and M.A. Burgman. 2001. Modeling the impact of timber harvesting on a rare carnivorous land snail (*Tasmaphena lamproides*) in northwest Tasmania, Australia. Ecological Modeling 139:253-264. MS, PR.

- A stochastic metapopulation model was developed for a rare carnivorous snail, *Tasmaphena lamproides*, occurring in production forest in northwest Tasmania, Australia, in an effort to investigate the impact of a range of plantation options and harvesting strategies on the average population sizes and risk of decline of this species.
- Results indicate that snail populations will remain viable longer in areas where clearcutting occurs if contiguous, unfragmented native forest areas are maintained to allow for dispersal. The timing of harvest activities and the management of dispersal barriers are also important elements of a successful management strategy for this snail.

Richter, K.O. 1979. Aspects of nutrient cycling by *Ariolimax columbianus* (Mollusca: Arionidae) in Pacific Northwest coniferous forests. Pedobiologia 19: 60–74. RS, PR.

- This research examined the feeding ecology and ecosystem function of *Ariolimax columbianus* in Pacific Northwest forests.
- The impact of this species within coniferous forest plant communities is a complex function of its diet, biomass, consumption, assimilation efficiencies, behavioral

constraints, and the distribution and abundance of host and nonhost plants. Seasonal diets, feeding rates, feeding preferences, and other factors are reported. Overall, this species speeds up nutrient cycling by consuming large amounts of fresh and senescing (rather than dead) plants, and by subsequent excretion of partially digested plant tissue.

Rosenvald, R. and A. Lõhmus. 2007. For what, when, and where is green-tree retention better than clear-cutting? A review of the biodiversity aspects. Forest Ecology and Management 255: 1-15. RP, PR.

- This paper reviewed 214 North American and European studies to answer whether green-tree retention cutting (GTR) (a modification of traditional clear-cutting) meets its objective of better conserving biodiversity.
- GTR can improve biodiversity by (1) 'lifeboating' species over the regeneration phase, (2) providing microhabitats for old-forest species in re-established forest stands and for disturbance-phase species on the recent cuts, and (3) enhancing species' dispersal by increasing landscape connectivity.
- Compared with clear-cutting, GTR lowered the harvest related loss of populations or individuals in 72% of studies, and nearly always improved the habitat for disturbance-phase insects and birds in the cut habitat, and for forest species in the regenerated stand. Terrestrial mollusks were not included in this analysis.
- Retention tree species was the most important contribution to the success of GTR, followed by tree density (65% of cases) and the spatial arrangement of the trees (50%).

Roth, B. and P.H. Pressley. 1986. Observations on the range and natural history of *Monadenia setosa* (Gastropoda: Pulmonata) in the Klamath Mountains, California, and the taxonomy of some related species. Veliger 29: 169–182. RS, PR.

- This study monitored a population of a single land snail species, *Monadenia setosa,* over a one year period.
- Findings include the occurrence of reproductive maturity at different seasons of the year; rapid growth of individuals slowing as maturity is approached; and feeding behavior on the ground and on the trunks of trees with smooth bark.

Rykken, J.J., Moldenke, A.R., and D.H. Olson. 2007. Headwater riparian forest-floor invertebrate communities associated with alternative forest management practice. Ecological Applications 17(4): 1168-1183. RS, PR.

- This research examined how alternative forestry management strategies may impact invertebrate communities of headwater stream riparian zones in the Pacific Northwest. Comparisons were made between community composition of forest-floor invertebrates at increasing distances along trans-riparian (stream edge to upslope) transects in mature forests, clearcuts, and riparian buffers of ~30-m width with upslope clearcuts. Invertebrate taxa included 32 families of ground-dwelling beetles, spiders, millipedes, and gastropods, representing a broad range of functional groups and dispersal capabilities.

- Community analyses revealed that invertebrate community composition in buffer treatments was far more similar to that of mature forests than to clearcuts. Since this pattern was mirrored by microclimate variables, it is asserted that forest-floor invertebrate distributions are strongly associated with microclimate and that riparian buffers of ~30-m width do provide habitat for many riparian and forest species.
- Since riparian reserves may serve as effective forest refugia and/or dispersal corridors for invertebrates and other taxa, their incorporation into watershed management plans likely will contribute to meeting biodiversity objectives.

Sarma, K., Tandon R., Shivanna K.R., and H.Y. Mohan Ram. 2007. Snail-pollination in *Volvulopsis nummularium*. Current Science. 93: 826-831. RS, PR.

- Pollination by snails (malacophily) is a rare and obscure phenomenon.
- This study clearly demonstrates the significant role of a snail (*Lamellaxis gracile*) in the pollination of a flowering plant (Convolvulaceae: *Volvulopsis nummularium*).
- This plant is also pollinated by *Apis* bees. However, snail pollination in this plant is especially important on rainy days when the activity of bees is completely lacking.

Shaffer, M.L. 1981. Minimum population sizes for species conservation. BioScience 31(2): 131-134. RP, PR.

- This paper addresses the impacts of habitat fragmentation on species survival. Small and fragmented populations are generally at greater risk of extinction from normal population fluctuations due to predation, disease, and changing food supply, as well as from natural disasters such as floods or droughts. Small populations are also threatened with extinction from a loss of genetic variability and reduced fitness due to the unavoidable inbreeding that occurs in such small populations.

Secrest, M.F., Willig, M.R., and L.L. Peppers. 1996. The legacy of disturbance on habitat associations of terrestrial snails in the Luquillo Experimental Forest, Puerto Rico. Biotropica 28: 502–514. RS, PR.

- This research examined the abundance, distribution, and habitat associations of four species of land snail at two forest sites which were differentially damaged by large scale hurricane disturbance.
- Five years after the impact of the hurricane, significant differences between sites in snail density persisted for all species except one, indicating that terrestrial gastropods respond to disturbance in a species-specific manner. Significant differences in habitat characteristics were also found between the two sites. The factors that affected microspatial differences in snail density within sites also accounted for differences in density between sites.

South, A., 1980. A technique for the assessment of predation by birds and mammals on the slug *Deroceras reticulatum* (Muller) (Pulmonata: Limacidae). Journal of Conchology 30: 229–234. RS, PR.

- The jaws of slugs and snails resist digestion in the gut of bird and mammal predators. In this study, jaw width and body weight show a significant correlation for each of three slugs examined, suggesting that the size of slugs eaten may be estimated from jaws recovered from the gut of a predator, using a regression line. Since slugs are agricultural pests, the technique may be useful for assessing the effect of vertebrate predation on slug populations.

Stiven, A.E. 1989. Population biology of two land snails (*Mesomphix* spp.): variation among six southern Appalachian sites with differing disturbance histories. Oecologia 79(3): 372-382. RS, PR.

- Ecological and genetic properties of two North American terrestrial gastropods (*Mesomphix* spp.) were characterized in paired control and previously logged water-sheds in two North Carolina forests.
- Shell growth was greater in the control sites, but density and mortality were largely independent of prior logging history. Both species exhibited their highest levels of genetic diversity in the forest which had the most extensive and variable history of logging disturbance. It is possible that while over the short term disturbed populations may show classical declines in heterozygosity and fitness resulting from founder effects, drift, and inbreeding, over the long term increased genetic variability may be expected in small disturbed populations occurring in both temporally and spatially patchy environments.

Strayer, D., Pletscher, D.H., Hamburg, S.P., 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. RS, PR.

- This research examined the effects of three types of forest disturbance (agricultural cropping, burning, and clearcutting) on terrestrial gastropods in 16 forested sites in New England.
- Contrary to previous studies reporting strong correlations between stand age and gastropod community structure, no clear relationship was found between gastropod density, species richness, or community composition and time elapsed since disturbance. Species richness and density declined following disturbance, even to the point of causing the local extinction of some species, but declines seemed short-lived; sites disturbed five years earlier had already returned to pre-disturbance levels.
- With regard to fire: Fire-disturbed sites had been burned at least three years previously; no significant evidence was found that fires permanently affected the snail community in the forest. According to Anderson (2004), "several factors make it difficult to apply these results directly to western forests. First of all, the burned sites were small (Strayer et al. considered them to be small, but did not give actual sizes) and within a landscape of forest from which they could be recolonized. Secondly, the deciduous component of the Maine forest is greater than the deciduous component of most western forests. In general, eastern forests are moister than western forests. Finally, it is not clear how

intense the fires were in this study. Small, cool, low intensity fires may have quite different effects than the severe wildfires in the western forests."

- With regard to clear-cutting, cut areas were mostly less than 10 ha; no clear relationship was found between gastropod community structure and time elapsed since logging disturbance (2 to >60 years).
- The quick recovery of gastropod communities following forest disturbance in this study was attributed to the rapid recovery of the vegetation, and to the small size of disturbed areas, facilitating recolonization from surrounding, undisturbed areas.
- Another explanation posed by later researchers (e.g., Hawkins et al. 1997b) is that a large reservoir of gastropods in the soil was the source of colonizers. Vertical movement of these organisms can quickly restore the detectable community on the surface, provided that suitable microclimate is re-established for all of the original species.

Ström, L. 2004. Long-term effects of riparian clear-cutting – richer land snail communities in regenerating forests. M.S. Thesis. Umeå, Sweden: Umeå University. 23 pp. RS.

- This study examined the long-term effects of riparian clear-cutting on litter dwelling land snails in Swedish boreal forests. This research was motivated in part by findings in Hylander et al. (2004) regarding the short-term (2.5 years) negative effects of riparian clear-cutting.
- At ten localities in northern Sweden, snails were sampled from an old small stream forest of at least 150 years and a matched regenerating forest 40 – 60 years after clear-cutting. Nearly 2,000 snails belonging to 16 snail species were found.
- Both abundance and species richness were significantly higher in regenerating forests. An average of 134 individuals and 9.6 species were found in the regenerating plots, compared with 55.6 individuals and 6.4 species in the old forests. Abundance and species richness correlated very well with cover of moist ground and litter pH, the latter of which was significantly higher in regenerating forests.
- While Hylander et al. (2004) found that most snail species were negatively affected by clear-cutting over the short term, this study found that when clear-cut areas were in later successional stages, only two of sixteen species were more abundant in the old forest plots, and the rest were more abundant in the regenerating forest.

Ström, L., K. Hylander, and D. Mats. 2009. Different long-term and short-term responses of land snails to clear-cutting of boreal stream-side forests. Biological Conservation 142(8): 1580-1587. RS, PR.

- This study is the published (and somewhat expanded) version of Ström 2004, above.
- The long-term effects of clear-cutting on litter dwelling land snail abundance, species density, and species composition was studied in a pair wise design of 13 old seminatural stream-side stands and 13 matched young stands developed 40–60 years after clear-cutting.
- From the young regenerating stands a mean of 135 shells and 9.5 species was found, which was significantly higher than the 58.1 shells and 6.9 species found in old forests.

Only two of the 16 species encountered showed a stronger preference for old than young forests.
- In other, short-term studies of boreal stream-side forests land snail abundance has been found to be reduced by clear-cutting. This study indicates that this decline may be transient for most species, and within a few decades may be replaced by an increase. It is suggested that surviving land snails may benefit from the higher pH and more abundant non-conifer litter in young than in old boreal forests.

Swengel, A.B. 2001. A literature review of insect responses to fire, compared to other conservation managements of open habitat. Biodiversity and Conservation 10:1141–1169. RP, PR.
- This review addresses insect responses to fire, relative to other feasible and appropriate conservation managements of open habitats.
- Although the impacts of fire management on invertebrate communities are often highly variable, many insect groups decline markedly immediately after fire. The degree of fire-related impact and the potential for animals to rebound post-impact are related to a number of factors, including the degree of exposure to lethal temperature, the stress experienced in the post-fire environment, the suitability of post-treatment vegetation as habitat, and the ability to rebuild numbers in the site (from survivors and/or colonizers)
- In general, less decline has been recorded for species below ground, within or beneath unburned wood, or above flames in treetops, and greater decline for species in the herb (fuel) layer or near the soil surface, particularly for individuals with low mobility.

Underhill, J.E. and P.G. Angold. 2000. Effects of roads on wildlife in an intensively modified landscape. Environmental Reviews 8: 21–39. RP, PR.
- This paper reviews the ecological impacts of road networks and roadside habitat on biological communities in a highly modified landscape.
- Many studies show that loss, fragmentation, and degradation of habitat by roads can interrupt and modify natural processes, resulting in altered community structures and population dynamics in a diversity of organisms. Although less studied, there is potential for roadside habitat to act as biological corridors in an otherwise fragmented landscape, thus off-setting some of the adverse impacts of road networks.
- In order to restore habitat connectivity and prevent further fragmentation, it is recommended that efforts be made to enhance the habitat adjacent to existing roads, and, when possible, to constrain further development of the existing road network.

Wäreborn, I. 1979. Reproductive success of two species of land snails in relation to calcium salts in forest litter. Malacologia 18, 177–180. RS, PR.
- This study experimentally examined reproductive success of *Cochlicopa lubrica* and *Discus rotundatus* in response to additions of calcium salts in the substrate. Animals were cultured in plexiglass boxes in outdoor conditions using a calcium-deficient leaf litter.

- Both calcium citrate and calcium oxalate additions increased reproductive success (number of offspring), although calcium citrate generated significantly higher number of offspring than calcium oxalate.
- These differences may be related to habitat preferences of mollusks between different types of deciduous woods, since oak and beech leaves are rich in oxalate-bound calcium, while leaves of ash, lime, maple, and elm are dominated by calcium citrate and other more soluable calcium.

Wessell, S.J. 2005. Biodiversity in Managed Forests of Western Oregon: Species Assemblages in Leave Islands, Thinned, and Unthinned Forests. M.S. Thesis. Corvallis, OR: Oregon State University. 74 pp. RS, PR.

- This study examined differences in the abundance and diversity of mollusks and other biota with respect to thinning and leave island size in four western Oregon managed forests (regenerated stands of 50 to 70 years). Five forest types were studied: unthinned (600 trees/ha), thinned (200 trees/ha), and thinned with three sizes of leave islands (0.1, 0.2, and 0.4 ha) embedded in the thinned forest matrix. Mollusk sampling was conducted two to five years post-thinning, on two nonadjacent 5 x 20 m belt transects in each sampling area. Within the transects, garden claws were used to search substrate (to a depth of 3-5 cm) and other material for mollusks.
- Thinning effects were more pronounced for vascular plant species than for arthropods, mollusks, and amphibians. Thinned and unthinned forests differed in microclimate and vascular plant species composition, while plant composition within leave islands approximated that of an unthinned forest. Exotic and early successional species had higher proportions in thinned forest than unthinned forest, and in small leave islands than larger leave islands.
- Treatment effects of thinning on mollusk density were mixed. Of the 5 species examined, *Haplotrema vancouverense* was the only one with a significant negative response to decreasing leave island size. Leave islands of increasing size generated positive effects on mollusks, resulting in increased overall mollusk density, snail density, and density within three mollusk species groups.
- Results suggest that a silvicultural approach of aggregated green tree retention (leave islands) provides refugia for mollusks and other low-mobility, ecologically sensitive species in managed forests of the Pacific Northwest.

Werner, S.M. and K.F. Raffa. 2000. Effects of forest management practices on the diversity of ground-occurring beetles in mixed northern hardwood forests of the Great Lakes Region. Forest Ecology and Management 139: 135-155. RS, PR.

- This research examined ground beetle communities in even-aged, uneven-aged, and old growth forests in the Great Lakes Region.
- No differences in overall species richness or abundance were observed among forest management regimes or habitat types, but there were substantial differences in species composition.

- The importance of microsite features for high beetle diversity was reflected in the high variability observed among sites and among traps within sites. Results indicate that conservation of a range of forest types and habitats is required in order to maintain the diversity of ground-occurring beetles on a regional scale.
- Although snails were not included in this study, these groups exhibit similar habitat needs and have similar dispersal limitations, thus results regarding microsite importance may be relevant.

Wirth, T., Oggier, P., and B. Baur. 1999. Effect of road width on dispersal and population genetic structure in the land snail *Helicella itala*. Journal of Nature Conservation 8: 23-29. RS, PR.

- This paper tests the effect of road width on dispersal and genetic differentiation in the land snail *Helicella itala*.
- A brief review of road impacts on animals reports traffic as a major source of mortality, particularly for animals that cross roads to move between habitats. In addition to causing direct mortality, roads can negatively impact adjacent habitat, i.e., by introducing noise, air turbulence, and exhaust fumes from traffic as well as increased run-off of water, debris, deicing salt, and other roadway contaminants.
- Additionally, roads can act as barriers to animal movement, changing the direction and intensity of gene flow across the landscapes and fragmenting/isolating populations to varying extents. Small, fragmented populations are at greater risk of local extinction due to demographic and stochastic effects.
- In this study, the following road types were examined: a 6- and a 9-m wide high traffic paved road, a 3-m wide low traffic paved road, a 3-m wide unpaved track, and a 0.3-m wide overgrown path.
- Movements of marked snails were largely confined to roadside verges, with several snails covering large distances (e.g., 17.45 m) over the one-month monitoring period.
- None of the 560 marked snails crossed the 6- and 9-m wide roads with heavy traffic, suggesting that snail dispersal is inhibited by wide roads with high traffic density. Only one individual crossed the 3-m wide unpaved track, and 2 individuals crossed the 3-m wide low traffic road. In contrast, snail movement was not restricted by a 0.3-m wide overgrown path. Molecular data, however, indicate a moderate amount of gene flow between populations on opposite sides of even wide roads, possibly a result of passive dispersal by wind on leaf litter or mown vegetation (a common phenomenon in snails). The extent of genetic differentiation between subpopulations on opposite sides of the road might also be affected by the age of the road (i.e., duration of isolation), although the variety of repeated road-building activities and disturbances in this study did not allow for such analysis.