# MANAGING YOUNG STANDS IN WESTERN WASHINGTON TO EXPEDITE COMPLEX FOREST STRUCTURE AND BIOTIC DIVERSITY: REVIEW, RATIONALE, AND RECOMMENDATIONS.

by
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## ABSTRACT


Managing young stands in western Washington to expedite complex forest structure and biotic diversity: review, rationale, and recommendations.

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In the Pacific Northwest, second-growth forests are wide spread and this oversimplified forest structure fails to meet the diverse needs for maintaining a wide species composition. Maintaining and replacing older forest habitat to preserve species of concern has become one of the greatest challenges to natural resources management in western Washington. Ecosystem management emphasizing spatial heterogeneity and environmental variability may increase successional development towards older forest characteristics by providing niche differentiation that potentially can help meet the diverse needs for maintaining high biological diversity.

Truffles, the fruiting bodies of mycorrhizal fungi, permit enhance tree nutrient absorption, and serve as the primary food for mycophagous small mammals, and if populations of small mammals are abundant, then there is an adequate prey base for maintaining abundances and diversity of predators. Mycorrhizal fungi are also important in promoting tree productivity and complex soil communities which are at the core of the forest food web. There is an important cyclical relationship between trees, truffles and small mammals which may be indicative of a keystone complex relationship that could be used as an objective in managing second-growth forests to promote biological diversity. By using variable-density thinning, snag creation, and coarse woody debris maintenance along with forest models that can predict future forest succession, this vital keystone complex relationship may be promoted along with increased biological diversity.

The literature reviewed for this analysis points to the possibility that late-seral communities could be restored with minimal intervention with a high probability of success. Yet, while the management of forests to maintain or produce older-forest conditions holds great promise, it remains a grand experiment, the results which may not be clear for many decades.

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## Acknowledgements

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# 1. Introduction

One of the greatest challenges to natural resources management in the Pacific Northwest is maintaining and replacing older forest habitat to preserve species of concern and watershed processes. Logging during the 20th century greatly reduced the area of old-growth forests in the Pacific Northwest, reducing the habitat available for species which depend on their habitat structure. Subsequently, the emergence of plantation forestry simplified forest structure with low species diversity. Public lands have considerable area of these simpler forests without active management, due to lower intensity of management. Second-growth forests are widespread and there is much debate about how to best manage for multiple uses, but in particular for high biological diversity. Large tracks of forests on public lands can remain for decades in the competitive-exclusion stage, which is poorly suited to older forest species, also known as late-seral wildlife. Species recovery plans emphasize that suitable habitat needs to increase if we want to ensure survival and long-term viability of older-forest dependent species (U.S. Fish and Wildlife Service 2011).

**Role of ecosystem management**

It has been suggested that ecosystem management emphasizing spatial heterogeneity and environmental variability can increase successional development towards older forest characteristics (Franklin et al. 2006). This spatial heterogeneity and variability provides niche differentiation that potentially can help meet the diverse needs of old-growth dependent species, and is important for maintaining high biological diversity (Carey and Curtis 1996). Additionally, because the presence of the northern spotted owl (*Strix occidentalis caurina*) and other wide-ranging predator species cannot be reliably used to evaluate stand levels at small scales, achieving prey species abundances of small mammals (particularly mycophagist abundances) similar to those in resilient old-growth forests, could better serve as an indication of forest ecosystem management success in Pacific Northwest forests.

Truffles, the fruiting bodies of mycorrhizal fungi, permit enhance tree nutrient absorption, and serve as the primary food for mycophagous small mammals, which in turn are important prey for the northern spotted owl.  Small mammals enhance truffle abundances, through the dispersal of fungal spores; there is an important cyclical relationship between these species. This relationship not only benefits tree growth, but subsequently benefits a variety of birds and larger mammals which prey on these small mammals.  An example of this is the northern flying squirrel, which eats truffles and is also the main food source of the northern spotted owl.  This interaction between trees, truffles and small mammals as well may be indicative of a keystone complex relationship which could be a vital objective in managing second-growth forests to promote biological diversity and structural heterogeneity characteristic of old-growth forests.

**Understanding the challenges of ecosystem management**

The challenge for forest managers today, is to encourage the development of complex forest structures in support of biological diversity and habitat through new forestry.  It is a huge task because predicting behavior in ecosystems relies on multiple variables and the interactions of those variables, of which causes and effects are difficult to replicate.  One tool being used to help guide forest managers in predicting forest treatment outcomes is through the use of forest models.  Predicting the consequences of management actions is one of the hallmarks of new forestry. Models can help predict forest development and yields and have been instrumental in the maturing of commercial forestry. The adaptability of non-spatially explicate stand models for the highly developed science of plantation management to variable-density thinning used to create habitat is a major challenge. Stand dynamics relay on the simulation of inter-competition. The assumption in all but a few models is that trees are evenly distributed in the stand. New forestry is increasingly dismantling that assumption and the predictions from existing models. Now forest models can summarize current stand conditions and predict future stand conditions under various management alternatives showing how management practices may affect stand structure and composition, important to evaluating whether a stand will be appropriate as wildlife habitat (Dixon 2002).

My research hypothesis is: management or disturbance mimicking old-growth structural complexity can increase second-growth forests habitat functionality by promoting greater vegetation variety, snags, and coarse woody debris. This results in increasing abundances of truffles and small mammals, which are part of a vital keystone complex relationship indicating relative health in forests west of the Cascades. My null hypothesis is: management or disturbance mimicking old-growth structural complexity cannot increase second-growth forests natural succession because complexity is based on synergistic interactions among plant and animal communities which can take centuries to establish. In short structure alone cannot replace the time required to develop decadence and large structure characteristic of old forests.

My research questions are:

- Can late-successional/old-growth structure be accelerated in young stands with new forestry techniques?
- Will this enhanced structural diversity in young stands translate to late-successional functionality; i.e. ecosystem processes?
- Is there evidence that small mammals and truffles are part of a vital keystone complex relationship indicating relative health in Pacific Northwest forests which could be used as an indicator of success in restoring forest complexity?
- Do experts agree that modeling is a useful tool in predicting future forest dynamics?

# 2. Background

## History of forest practices and current forest structure

Early European immigrants to North America viewed the vast forests they encountered as limitless. They saw game, lumber and firewood to be taken and land to be cleared. These forests were viewed as being hostile and in need of being tamed (Worster 1979). Though it took two and a half centuries, from 1600 to 1850, to deforest the first 40 % of the eventual total amount cut, it only took fifty years to deforest 150 million acres, which is far more land than was cut the previous 250 years (Berger 2008). In the beginning, timber was cut for fuel and building materials or cleared for farming. In the Pacific Northwest, early settlers largely avoided the dense forests because of scarce labor for logging operations, difficulty in accessing timber more than two miles from streams or river, and the poor quality soil for agriculture (Goble and Hirt 1999).

At the turn of the century, with the technological advances of the steam donkey and later with railroads, areas of forests which were formerly inaccessible began to open up. Even though it took commercial foresters until the 1920s to reach the Pacific Northwest, by the 1860s, forests were beginning to be cleared at a much faster pace. Then, after WW II when logging roads and logging trucks appeared, the region's economy became tied to lumber production. Limits on cutting began to be put in place when land was set aside into national park and national forest status.

In the Pacific Northwest, in the early to mid-20$^{th}$ century selective logging of the largest and most vigorous tress was the norm in Douglas-fir old-growth stands. By the 1950s through the 1980s, clear-cutting replaced selective logging in most areas. Clear-cut systems dominated by timber production of which gave rise to even aged landscapes.

It left behind interspersed clear-cuts of various sizes, followed by slash burning and planting. Planting and species discriminating thinning encouraged reduced tree species forests. Within less than a century, forest structures resulting from natural disturbances were replaced by forests originating from human activities. Wild-fire, windstorms, and insect outbreaks of varying size, frequency, and intensity have been replaced by short-rotation timber harvest and prescribed burning; both are disturbances that are more frequent and less variable in size and intensity.

On federal lands, management plans have caused rapid declines of old-growth between the 1950s and 1980s, calling for the virtual elimination of all late-successional forests on federal lands outside of parks and wildness areas (Franklin 1997). If the logging rates of the mid to late 1990s were to be sustained, all remaining Pacific Coast old-growth would be gone by 2025 (Berger 2008). Today, since the time of European settlement about 72 percent of the original Pacific Northwest old-growth forest is gone and only approximately 28 percent of it remains today (Strittholt et al. 2005), and to get it back we have to wait a very long time.

**What is biodiversity and why is it important?**

Biodiversity is an extremely broad and complex subject that is usually defined as the diversity of life on earth. Yet included in this definition should also be the interconnections and processes supporting these numerous forms of life. Biodiversity includes genetic, species, and ecosystem diversity (Wilson 1988). It can be seen has having three parts to it; (a) compositional diversity which refers to the number of elements in a system; (b) structural diversity which refers to the physical organization; and (c) functional diversity which refers to the different processes (Zavala and Oria

1995).

The maintenance of the earth's biological diversity is necessary for ecosystem health as well as being aesthetically desirable (Hunter 1999) and there also is evidence that multiple ecosystem services are enhanced by high local and regional diversity (Duffy 2009). The ability to draw from native biological diversity is an importance aspect of adaptation to environmental climate change (Washington State Department of Ecology 2012). In ecosystems such as forests, which provide a range of resources, the theory and practice of maintaining biodiversity are now seen as fundamental to successful management. In the old-growth forests of the Pacific Northwest, the biodiversity attributes include not only the diversity of conifers, mammals, birds, and understory plants but also the myriad of mostly poorly understood fungi, lichens, insects, and soil invertebrates.

**Conventional forestry and its impact on biological diversity**

Forestry during the mid-20$^{th}$ century accelerated disturbance in the forest at a rate which was largely unseen naturally. The disturbance regime imposed by humans in this region is typically based in intensive forest management with relatively short rotations (40-80 years), clear-cut logging and preference for conifers, especially Douglas-fir (Table 1). On federal lands, which occupy about half of the forested area, the rate of cutting has been substantially reduced since the early 1990s (FEMAT 1993). Despite these recent changes, 30-40 percent of public forest landscapes contain a legacy of a patchwork of forest plantations that were established in the 1950s through the 1980s (FEMAT 1993). Relative to natural disturbance regimes, logging disturbances have typically been more frequent, more severe, left fewer biological legacies (i.e., structure and species that survive disturbances) and created more edge and fragmented landscapes (Spies et al. 1994). Clear-cutting, heavy soil disturbances, slash burning, and the removal of snags and dying or diseased trees left a heavy impact on a forest's biological diversity. The resulting structures that remained depleted the forest of features which are essential to many necessary functions in maintaining some types of habitat and wildlife species.

**Table 1. Types of forest disturbance**

| Old forestry/lack of management | New forestry/managing for complexity |
|---|---|
| Clear-cut | Variable-density thinning |
| Single entry | Repeated entries |
| Slash fires | Westside forests evolved w/infrequent fires |
| Removal of snags dying or diseased trees | Maintains snags, dying and diseased trees |

Soil disturbance from ground-based clear-cutting can leave a lasting legacy of compaction and impacts soil hydrology. As soil bulk density increases and soil becomes resistant to penetration, tree roots cannot as easily absorb water and nutrients, leaving behind a less productive site (Curran et al. 2008, Han et al. 2009). Forest soils can also become less productive due to the removal of the trees and vegetation which uptake nutrients, leaving these nutrients to leach out and be lost (Allen 1997). Clear-cutting has been associated with decreased soil stability and therefore increases the occurrence of landslides after the stabilizing effect of tree roots and the ability of the canopy to trap rain is removed (Kimmins 2004). Logging roads also play a significant role in soil instability, increasing slides significantly where the primary soil mantle is less stable (Kimmins 2004, Pgs. 324-325). Soil disturbance may have a direct impact on mycorrhizal fungi or an indirect affect through changes to soil properties. Mycorrhizal fungi can be severely influenced by damage to vegetation and soils resulting from conventional forestry practices such as clear-cutting, intense fires, and exposure of subsurface soil to erosion (Brundrett 1991). Disturbance impacts on fungi may include; (a) a reduction in viable spores, (b) loss of the hyphal network in the soil, and (c) the prevention of hyphal growth from root inoculum to new roots (Brundrett 1991). All of these factors decrease the productivity of a site and the probability of future plant growth.

After live trees are removed in a clear-cut, without host trees, some mycorrhizal fungi including many truffles cannot survive. Many fungi are also susceptible to the low moisture conditions after the coarse woody debris (CWD) are removed during a clear-cut (Amaranthus et al. 1994). The once common practice of slash-burning after a clear-cut ended in western Washington in the mid 1980's. However this once practiced slash-burning also removed nutrient accumulations along with the slash. Slash-burning negatively impacted fungi by removing the thick protective organic layers which they colonize, and this lack of thick organic layer can impede their re-colonization after young-stands have grown back (North and Greenberg 1998); in addition, the fungi in the wet and mild climate of western Washington may not be adapted to frequent fires due to their low historical occurrence (North and Greenberg 1998).

The practice of clear-cutting in forestry removes snags primarily because of the United States Department of Labor Occupational Health and Safety Administration's requirement for worker safety (Carey and Wilson 2001). Snags are a vital feature for many species to forage, den and nest. Primary cavity excavators such as the pileated woodpecker create cavities for many small birds and mammals to den in, which could not otherwise create themselves. Large mammals use hollowed out trees for denning which would otherwise be removed in a clear-cut system (McComb 2003). Lack of snags, defective or dying trees always means lower plant and animal diversity (Ohmann and Waddell 2002).

In clear-cut forestry, there will be a shift in small mammals due to the lack of understory development and CWD. Small mammals will have to travel farther to meet their dietary needs and will not have adequate cover for dispersal and hiding areas. Clear-cuts change the small mammal landscape, relative truffle abundance and loss of legacy structures. When planted trees grow back into dense young stands, there will not be a diversity of understory plants for these small mammals to forage. As a result, unthinned clear-cuts that develop into dense young stands have lower densities of flying squirrels, the primary diet of the endangered northern spotted owl (Carey 1995). In general, the fewer number of small mammals, the less the area will be able to sustain larger predator mammals and avian species which rely on an abundance of small mammals.

Our current decrease in biodiversity is from human conversion of land and subsequent loss of habitat without connectivity (Anderson and Jenkins 2006). Clear-cuts likewise leave behind a highly fragmentation landscape. What late-successional/old-growth forests that remain, are in patches fragmented by dense second-growth that is inhospitable to many late-seral dependent species (Carey et al. 1992). Habitat loss not only negatively affects species richness, population abundance, distribution, and genetic diversity, but also indirectly effects species interactions reducing trophic levels, and the number of large-bodied specialist species, as well as the general success rate in breeding, dispersal, predation, and foraging (Fahrig 2003). Although populations of declining animals still persist in some areas, their long-term viability is questionable as these populations become more isolated from each other. Since the turn of the century, most of Washington's forested areas have been converted to other uses, resulting in the loss of most of the state's old-growth forests and the subsequent decline in biological diversity and habitat for old-growth dependent species (Fisch 2000).

**Changing management on public lands deals with the legacy of clear-cutting**

The management objectives of public lands underwent a rapid evolution with emergence of the concept of ecosystem management. The clear-cutting legacy reflected in the even-aged age class distribution and landscape patterns on a large scale in forests will take a decade's if not a century to reshape. Commercial forestry plantations have impressive homogeneity. Planting of a single species and controlling density and species composition are the principles that make a tree farm productive and economically attractive to investors. These stands, left unthinned, can have a high diameter to height ratio leaving them susceptible to wind throw. Due to lack of management funding after the emergence of ecosystem management, which occurred on much of our public lands, forests can stay in the competitive exclusion stage decades. The competitive exclusion stage does not support high species diversity due to the lack of understory, large trees, and CDW. Commercial forestry removes less valuable trees, favors one tree species, and maintains stocking levels and even spacing, all of which reduce heterogeneity important for abundant wildlife (Carey and Wilson 2001). Though, pre-commercial thinning can delay the onset of the stem-exclusion stage, it can only delay the loss of understory development is understory plants are already well established (Zarborske et al. 2002).

Traditional timber production creates forests that lack spatial heterogeneity found in late-successional/old-growth forests necessary for species diversity (Suzuki and Hayes

2003). Conventional forestry traditionally views understory as competition to crop trees and saw no needed to maintain various trophic levels in a forest and tends to see understory development only as a by-product to timber (Thysell and Carey 2000). Yet, understory is very important to small mammals and birds for forage, hiding and nesting (Carey and Harrington 2001). Because a site has been held in clear-cut mode, favoring a single species of tree, there will often not be a seed bank left of shade tolerant tree species or some understory plants to be able to recolonize (Halpern and Spies 1995). Therefore even if a site is left after a clear-cut and not entered again, it can remain very simplistic in its diversity. Perpetual clear-cutting may also maintain persistent weedy plant species or exotics that have evolved with disturbance and in the less shady conditions clear-cutting offers (Halpern and Spies 1995).

By centuries end, our knowledge about forest ecology has increased as well as a diminishing social acceptance for the continued harvest of old-growth pushing forestry in a new direction. Now, in the 21st century, we are seeing different management objectives and a change of focus, one which not only includes timber production, but also management for biological diversity. Yet, due to loss of the regions old-growth forests, many species that rely on old-growth for at least some part of their life cycle are at risk of extinction.

**New forestry and its influence on biological diversity**

Ecosystem management was a tectonic shift of management objectives away from entirely being about timber production and instead to balancing managing for biological diversity with production. The results from these changes have demonstrated the importance of maintaining the natural structure either currently or formerly present. By maintaining or restoring the complex structure of the forest, it is assumed that the complex ecological functions in the forest, which so many plant and animals rely upon, can be restored.

**Implementing the new forestry paradigm**

The new forestry paradigm is based on the assumptions that: (a) ecosystems and landscapes are dynamic; (b) disturbance is a critical component of systems; (c) ecosystems are controlled by biotic and physical processes that occur at different spatial scales and levels; (d) succession does not necessarily follow the same path and end at the same equilibrium point; (e) spatial pattern is important to biological diversity; (f) pattern-process interactions are organism specific; and (g) human activity of the recent and distant past have had strong influences on many ecosystems that we may perceive as 'natural' today (Pickett and Ostfelt 1995). These new metaphors of ecology may help us to sustain biological diversity but they also make management more complex and difficult.

One of the foundations for conserving biological diversity in forested landscapes is first to understand and then manage by mimicking disturbance regimes of a landscape under past natural or semi-natural conditions (Table 2). The most important way for new forestry to do this is through the practice of variable-density thinning (VDT). This is the primary treatment in forest management which creates canopy variation through irregular thinning, which helps to create a more uneven aged multi-canopy layer seen in older forests.

**Table 2. Resulting structures from forest disturbance**

| Old forestry/lack of management | New forestry/managing for complexity |
| --- | --- |
| Heavy one time soil disturbance | Minimal soil disturbance if certain types of equipment, entry time of year and low impact techniques are used |
| Depleted below ground food webs | Minimal/short-term negative effect on below ground biotic community |
| Lack of CWD | Maintains CWD |
| Homogeneity | Heterogeneity |
| No snags | Snags present |
| Fragmented forest ecosystems | Maintains a matrix of types of suitable forest ecosystems |
| Even-aged single species | Multiple species, uneven age |
| High diameter to height ratio susceptible to wind fall | Promotes larger diameter trees less susceptible to wind fall |

New forestry practices look to maintain connectivity between forests of similar characteristics. In order to benefit species which need larger areas of land or which are reliant on a more heterogenetic canopy, both of which new forestry tries to emulate. Soil disturbance tries to be minimized in new forestry by using less intensive logging techniques. This is important also for the development of CWD, which is vital to ecosystem functioning in the fungal community. New forestry looks to leave skip areas where important decadent features of snags, dying, and diseased trees are located in order to protect them since they are a major wildlife habitat feature. These structural legacies if maintained, which sustain species and processes, can provide managed stands with characteristics of a more successionally advanced forest (Franklin et al. 2002). VDT also promotes development of understory herbs and shrubs by creating areas where more light can penetrate to the forest floor and where there is less competition for water resources.

By increasing understory vegetation and CWD, it also helps to increase habitat for small mammals which are a major prey base for many predator species. These variables in new forestry which help promote biological diversity will be reviewed in detail in the results section of this essay.

**The beginnings: the northern spotted owl and old-growth controversy**

The northern spotted owl remains at the heart of a controversy that still continues today (U.S. Fish and Wildlife Service 2011). The core of the argument lies in the fact that a pair of spotted owls requires very large tracts of old-growth conifer forest, and the timber in these stands is extremely valuable. By the mid-1980s, most old-growth on private lands in the Pacific Northwest had been logged, and pressure shifted to federal lands. Also at this time, public concern about the spotted owl and the old-growth forests it depends upon grew. By the late 1980s, evidence of the dependence of spotted owls on old-growth was mounting, and their numbers and viability were declining (Thomas et al. 1990). Lawsuits began to mount from environmental groups against the United States Department of Agriculture Forest Service and United States Department of the Interior Bureau of Land Management. In 1990, the northern spotted owl, which ranges from Washington to northwestern California, was listed as threatened under the U.S. Endangered Species ACT (ESA), bringing into full force the requirement of the ESA to provide the means to protect the ecosystems of which endangered and threatened species depend upon. With the listing of the northern spotted owl, the question shifted from whether the cost of saving the owls was worth the lost revenue from timber harvest, to how the owl itself was going to be sustained.

In 1993, President Clinton commissioned the Forest Ecosystem Management

Assessment Team (FEMAT) along with other pivotal groups such as the Interagency Scientific Team and the Scientific Analysis Team to create a management plan. This plan came to be known as the Northwest Forest Plan (NWFP) and was heralded by some as ushering in a new era of forest ecosystem management on federal public lands (Aubry et al. 1999). Core elements of the NWFP, which covers a total area of about 9,896,900 ha and 90% of the northern spotted owls range on federal lands, included the establishment of late-successional reserves (LSRs) and adaptive management areas (AMAs) (Marcot 1997). LSRs, which comprised just over 30 % of the planning area, would maintain varying but significant amounts of existing old-growth forests, and were to be used for aggressive management of younger stands to attain old-growth characteristics (Thomas et al. 1993). AMAs were designed in various forest types to allow tests of alternative approaches to maintaining threatened species and comprised just over 6 % of the planning area (Marcot 1997). Additional lands totaling 17 % (designed matrix and managed late successional areas) were to be available for timber harvest if environmental regulations were met (Marcot 1997).

While some might applaud the NWFP as a huge conservation success story, the plan was not followed. Active management within LSRs was not aggressively pursued, and experiments were not conducted within AMAs (Thomas 2003). Only modest amounts of experimentation have occurred on AMAs. Restrictions on AMA management in the NWFP, lack of flexibility or reluctance to approve habitat modifications or departures from the plan, and lack of financial support have been the limiting factors (Thomas 2003). The NWFP has been better at halting actions which would diminish conservation of LSRs than it has been in promoting restoration or AMAs

(Thomas et al. 2005). As a result, the overall strategy became one of essentially static reserve management. To many people, managing old forests may seem straightforward and this may seem like a good idea -you protect as much as feasible, then lock it up. Unfortunately, it is not quite that easy. This is not going to work if we want to increase old-growth characteristics faster than they will be created on their own to provide habitat for various species which require older forest conditions. Furthermore, old-growth forests are dynamic and it will not be possible to provide cathedral groves of ancient forest for future generations simply by preserving existing old-growth stands. Creating reserves as should not be the only form of forest management. Given the large areas required for managing spotted owls and other older forest species, active landscape management is necessary, which requires an understanding of an ecosystem's dynamics.

## 3. Methods

I conducted a systematic literature review of research being done to better understand functional relationships within late seral/old-growth forest ecosystems and research projects underway looking to increase structural complexity in forests. I employed habitat analysis through the review of current literature concerning western Washington and Oregon forest health, analysis of current forest restoration treatments and ecological goals.

I consulted with three experts in the field of forest restoration, forest ecology, and wildlife biology; Todd Wilson from the Pacific Northwest Research Station, Constance Harrington from the Pacific Northwest Research Station, and Joe Buchanan from Washington Department of Fish and Wildlife. Interview questions were: Is creating complexity in forests working to restore biodiversity? What are, if any, indications of success? How useful are models in planning future structural diversity?

# 4. Results

## 4.1 Literature review

### Pacific Northwest old-growth forest biotic diversity

. The old-growth forests of the Pacific Northwest are ecosystems dominated by large conifers at least 250 years old and ranging beyond one thousand years. Twenty-five species of conifer are found in these forests, but Douglas-fir tends to be the dominant tree in Oregon and Washington. These forests historically covered millions of acres of land before wide spread logging took hold (Marcot 1997). Old-growth forests are known to have high biological diversity within plant, vertebrate, invertebrates and aquatic organism communities (Maser et al. 2008). Many of these species are highly specialized to old-growth conditions with some exclusively preferring these types of forests (Franklin and Spies 1991).

One of the most undeniable features of old-growth forests are their structural diversity. This structure is what sets them apart from managed forests and is what many wildlife species seek for their survival. It is believed that at least 118 vertebrate species rely primarily on old-growth for habitat; of these, 41 rely exclusively on old-growth for their nesting, breeding and forage habitat (Norse 1990), and over 1,000 species of plants and animals are suspected to be closely associated with late-successional forest conditions (Thomas et al. 1993). Often this is because they require some feature or features, such as large standing snags or high density of large down timber that only old-growth forests can provide. Most forest-dwelling species are not associated with a particular tree species, but with the structure of those species within the forest. Availability of prey species is also crucial, because most of the vertebrate species found in old-growth are predators.

**Figure 1.** Examples of the structural heterogeneity found in old-growth forests (wilderness.org and bcfederationist.com).

Old-growth forests have many characteristics present at the same time. There will be various large living tree species at differing age-classes giving the forest a multi-layered canopy. The largest trees, two hundred feet tall or more, will have wind-damaged tops with relatively few branches with the exception of a few large epicormic branches, with a thick growth of mosses and lichen harboring many insects, birds and small mammals. Because these forests have been there a very long time, each tree takes on various forms which are important structural features. Some of these features are deep fissures in the bark and very large irregular crowns. Overtime, these trees have outcompeted others so they are spaced well apart from other similar dominate trees. The huge thick trunks of these trees often show evidence of charcoal from a previous fire of several centuries past which they have survived. Gaps form where some trees fell, being replaced by understory vegetation giving a heterogenic patchy appearance (Figure 1). This understory development is most complex in old-growth forests where more plant species diversity is found (Spies 1991).

Large snags are another feature which is characteristic of old-growth forests.

Large standing snags may stay erect for over two hundred years. As their branches slough off, sunlight is able to reach the forest floor, allowing species that require light, such as Douglas-fir, to germinate. Insects and woodpeckers open up the dead wood, providing habitat for many other species. These are of vital importance to many vertebrate den and cavity nesters. In turn, these become food for larger predators such as the northern spotted owl, marten and black bear.

Large down trees and accumulated downed wood in old-growth forests serves multiple purposes and can remain for up to several centuries for some species (McComb 2003). Large logs crisscross the forest floor and as they decay over several hundred years, dozens of species of insects, birds and mammals use them for shelter, as well as for foraging and dispersal habitat. All this activity helps raise the concentration of nutrients in the rooting wood, and the rootlets of nearby live trees tap them for food (Harmon 2009). Like live trees, down logs can hold extraordinary amounts of water. In this way, they also serve as a substrate for microbial and fungal species which are a food source for many small mammals and invertebrates. These fungi, called mycorrhizae, also form a symbiotic relationship with the surrounding conifers and are responsible for adding them in the uptake of nutrients and water from the soil. The downed trees themselves later also become nurse logs for other trees to grow on.

The general structure of an old-growth forest will be varied with gaps and multiple canopy layers, which is precisely what makes them so unique. Any of these features may occasionally occur in younger forests, yet only old-growth has them all.

**Pacific Northwest truffles, trees and animals in symbiosis**

Soil organisms play an essential role in an ecosystems health, with truffles playing a critical role in these dynamics, yet are often overlooked in forest management. Truffles are the below-ground fruiting bodies of mycorrhizal fungi, often called hypogeous fungi. These fungi assist trees and other plants in the uptake of water and nutrients from the soil by forming thread-like hyphae mates which penetrate the root tips (Figure 2). In return, carbohydrates are absorbed back to the fungi from the trees and this carbon then supports a wide range of soil organisms (Carey 2004, Carey 2003).

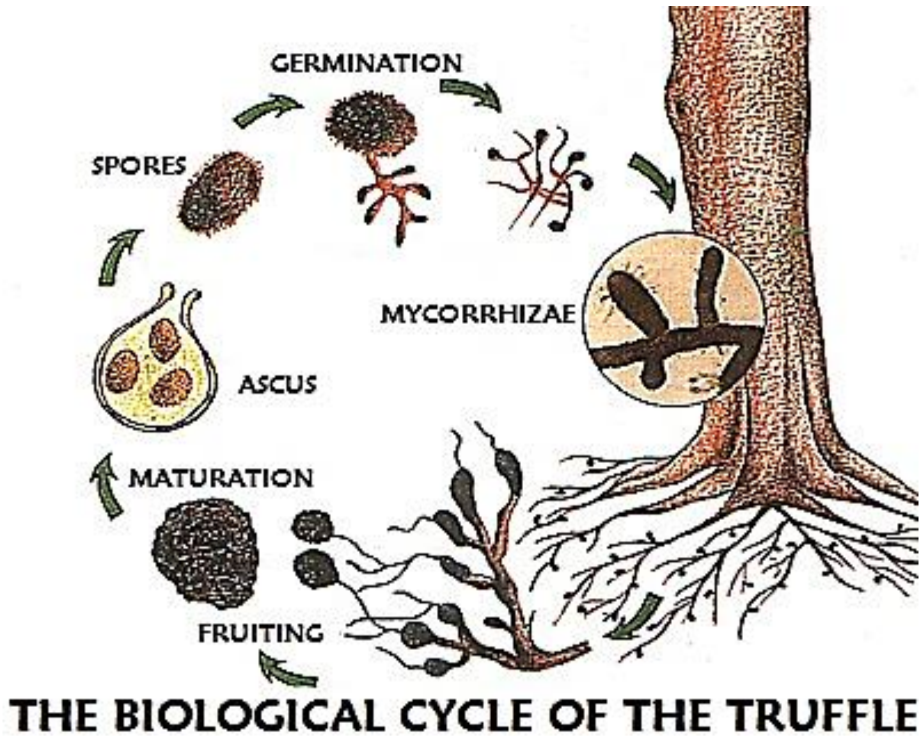


**Figure 2.** The truffle life cycle (tartufiinlanga.it).

Truffles have evolved to depend on being eaten by animals for their spore dispersal. When they reproduce, they emit a very aromatic odor that attracts animals. When the truffles are eaten, the spores, bacteria and yeast pass through the digestive tract unharmed (Carey et al. 2002). The spores of the fungi are then spread throughout the forest in the feces of the animal and can relocate to other trees and plants to begin the cycle again (Figure 3).

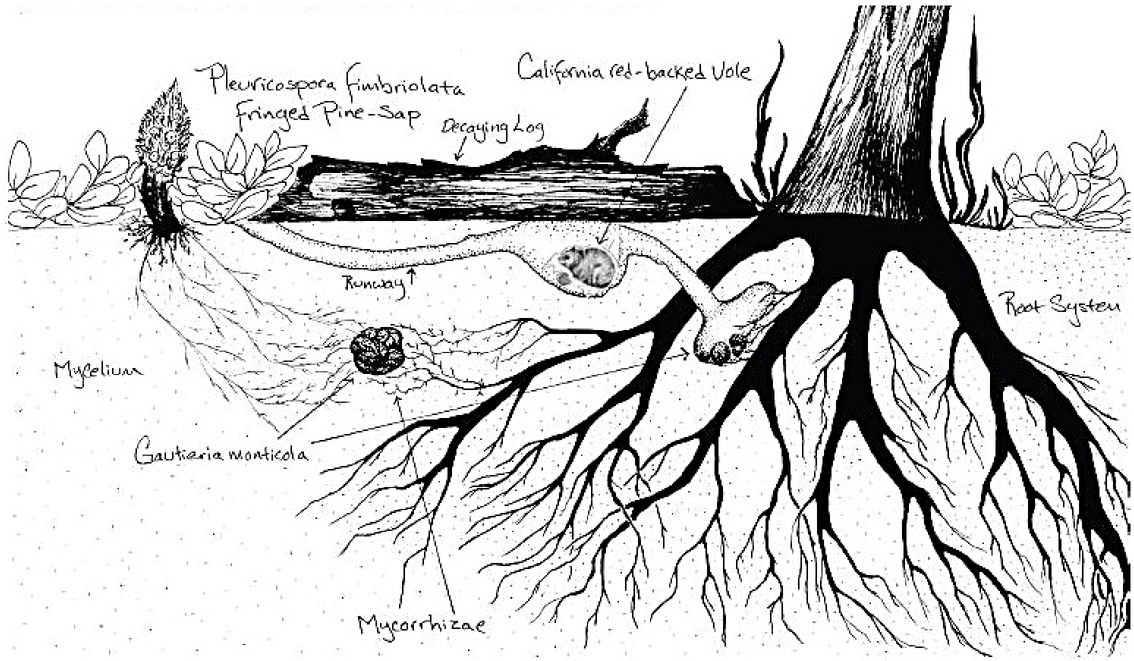


**Figure 3.** The tree, truffle, and small mammal symbiosis (natruffling.org).

Many animals will eat truffles as a food source, but the major mycophagists in the Pacific Northwest are the northern flying squirrel (*Glaucomys sabrinus*), Douglas' squirrel (*Tamiasciurus douglasii*), and Townsend's chipmunk (*Tamias townsendii*) (Carey et al. 2002) (Figure 4). These small mammals then become an important food source for many avian and mammalian predators, like the northern spotted owl. Diversity of truffles is important to maintaining abundant prey bases (Carey 2004). It has been shown that some species of squirrel will decline in body mass corresponding to diminishing availability of fungi (Smith et al. 2003). Fungi are also an excellent source of water for small mammals. When the host plant of the mycorrhizae are removed, such as in clear-cutting, the energy source for the fungi is lost and therefore will not fruit. Without the mycorrhizal fungi and the truffles they produce, multiple plant and animal species are negatively impacted.

**Figure 4.** Northern flying squirrel, Douglas' squirrel, and Townsend's chipmunk: important spore dispersers for truffles (moonshineink.com, nationalgeographic.com, and en.wikipedia.org).

The fungi are important to the growth and health of many Northwest tree species such as Douglas-fir, spruce, and hemlock. It is believed that most plants in the forest have developed mycorrhizal associations, with more than 100 Pacific Northwest plant species having been identified that associate in mycorrhizal symbiosis with truffle fungi (Molina and Smith 2009). In North America as a whole, there are over 2,000 species of ectomycorrhizal fungi that have a symbiotic relationship with trees (Fisher and Binkley 2000).

**Rationale and treatments for increasing forest structural complexity**

One way to conserve biodiversity on managed lands is to create complexity by using silvicultural practices patterned on natural disturbance. In this way, we can mimic some of the physical and biological characteristics typical of an older forest, and therefore influence a young stand onto the path of forest succession faster. In the early 1990s, several private research institutions and public interest groups in Washington and Oregon sought federal funds for research aimed at addressing whether we can increase the extent of forest stands with old-growth characteristics in the hopes of finding new methods for management (Berger 2008). All these large-scale silvicultural experiments (LSSEs), which are scattered throughout Washington and Oregon, use variations of VDT to increase biological diversity in forests by providing spatial heterogeneity in composition and structure that mimics conditions found in old-growth forests. Desired structures include: 1) a multi-layered canopy consisting of a large range of tree species, ages, and sizes; 2) large-diameter standing snags and fallen logs; and 3) a diverse understory of many species and a variety of available habitats (Table 3). LSSEs in young forests are an important part of adaptive management of natural resources on public land.

Two examples of the treatments being applied within LSSEs are the Forest Ecosystem Study (FES) implemented in 1991-1993 located on Fort Lewis Military Base and the Olympic Habitat Development Study (OHDS) with initial installation in 1997-2006 with several locations on the Olympic Peninsula. Both if these studies have response variables looking at over, mid, and understory development, arboreal and small mammals, fungi, woody debris, and snags among others. Both pretreatment sites were dominated by even-aged Douglas-fir between the ages of 35-65 years (Poage and Anderson 2007).

Within the FES, root rot thinning was applied to 15 percent of the stand with low vigor trees removed and healthy ones being retained producing approximately 16 trees per acre (TPA) of > 7.9 diameter at breast height (dbh). A light thinning was applied to 50-60 percent of the stand taking co-dominate trees of >7.9 dbh reducing the densities to about 125 TPA with an average spacing of 19 feet between trees. A heavy thinning was applied to 25 to 30 percent of the stand of trees > 7.9 dbh to create spacing of approximating 24 feet between trees. They also retained any standing dead tree and all deciduous trees. No underplanting was done and no coarse woody debris (CWD) was supplemented. Den augmentation (nest boxes installed and/or cavities created) was done at one control site (Poage and Anderson 2007).

At the OHDS sites they thinned 75 percent of the stands to 75 percent basal area, cut 15 percent of the stand to create small gaps, left 10 percent of the stand as uncut skip area. At the first site they did no underplanting. CWD was clumped and slash dispersed. At the second site they did an identical treatment except that the CWD and slash were both dispersed. The third site was identical except both CWD and slash were clumped; native understory species were planted or seeded in newly created openings. The fourth site treatments were identical except there was no underplanting and the CWD was removed and the slash dispersed (Poage and Anderson 2007).

**Table 3. Response to resulting forest structures from disturbance**

| | **Old forestry/lack of management** | **New forestry/managing for complexity** |
|---|---|---|
| **Soil compaction** | Impacts soil hydrology and productivity. Increases bulk density (BD) and soil resistance to penetration (SRP) i.e. porosity and soil strength. Although disturbs less area for a given amount of timber volume then VDT.<br><br>Curran et al. 2007, Han et al. 2009, Zarborske et al. 2002 | Repeated entries for thinning will have a higher impact on soil than a one-time clear-cut. Can have lower impact though, depending on type of equipment used and time of year for entry. Cut-to-length harvesting uses and leaves slash to decrease soil compaction over whole-tree removal.<br><br>Han et al. 2009, Kimmins 2004, Zarborske et al. 2002 |
| **Downed wood** | Slash and burn debris on site, does not leave behind CWD. | Keeps CWD on the ground, keeping shelter, foraging, and dispersal areas small mammals. CDW creates a moist substrate for many plants and fungi to occupy.<br><br>Bunnell and Houde 2010 |

| | | |
|---|---|---|
| **Snags** | Lack of snags, defective or dying trees means lower plant and animal diversity, OHSA requires most snags to be removed for worker safety.<br><br>Carey and Wilson 2001, Ohmann and Waddell 2002 | Keeps snags intact by arranging skip areas around them with no treatment. Promotes primary cavity excavators (woodpeckers) which create cavities important to some small mammals and birds for den/nest use. The larger, the snag the better (snags or limbs less than 10cm in diameter have little to no value to wildlife).<br><br>Harrington 2009, McComb and Lindenmayer 1999 |
| **Belowground fungi** | Truffles can be completely absent from clear-cut areas. Once trees and CWD are removed, fungi are unable to survive (no trees for mycorrhizae, high heat and low moisture areas). High soil disturbance and slash-burning has negative impact on fungi. Young-stands lack thick organic layer needed for mycorrhizae to live.<br><br>North and Greenberg 1998 | Maintains canopy cover and CWD for mycorrhizae. Some species decrease after thinning, yet some understory plants (i.e. salal) may have a symbiotic mycorrhizae relationship, which can help fungi recover. Thinning seems to change truffle species dominance.<br><br>Luoma et al. 2003 |
| **Small mammals** | Less number of small mammals due to lack of understory development and CWD. Have to travel farther to meet dietary needs. Clear-cuts that develop into dense young stands have lower densities of flying squirrels.<br><br>Carey 1995 | Increases food supply and cover available for small mammals, though depending on spacing between thinning's, can impede travel for flying squirrels. Maintains snags which are very important den sites for flying squirrels that are known to change dens every two weeks. Increase in rodent population also benefits mammalian and avian predators.<br><br>Carey et al.1999, Suzuki and Hayes 2003, Wilson and Carey 1996 |
| **Fragmentation** | Leaves LS/OG in patches fragmented by dense second-growth.<br><br>Carey and Spies 2002 | Helps to improve habitat between residual LS/OG forest fragments. Incorporates the landscape perspective of the matrix into management.<br><br>Franklin 1993 |

| | | |
|---|---|---|
| **Forest canopy** | Leaves crowded, uniform and dense canopies after clear-cutting. High diameter to height ratio. Due to lack of management, stands can stay in competitive exclusion stage for long periods. Conventional thinning removes less valuable trees, favors one tree species, maintains stocking levels and even spacing. Lacks spatial heterogeneity found in LS/OG forests.<br><br>Carey and Wilson 2001, Suzuki and Hayes 2003 | VDT increases individual tree diameter and crown growth by reducing crowding. Creates spatial heterogeneity (vertical and horizontal) similar to older forests. Can eliminate long interval between stem exclusion stage and understory reinitiation. Helps to create niche differentiation by providing a more complex habitat which contains more kinds of microclimates and microhabitats for more species to occupy. Helps to release understory shade-tolerant tree species when present.<br><br>Brokaw and Lent 1999, Carey and Johnson 1995, Carey and Harrington 2001, Thysell and Carey 2000 |
| **Understory** | Gives minimal attention to understory needs in maintaining various trophic levels and looks at understory development only as a by-product to timber. Some plants are capable of recolonizing after clear-cutting & slash burning due to deep tubers, roots or rhizomes. Clear-cutting may maintain persistent weedy plant species or exotics.<br><br>Carey and Harrington 2001, Halpern and Spies 1995, Thysell and Carey 2000 | Promotes development of understory herbs and shrubs by increasing light levels and decreasing water competition, thus contributing to forest vertical structure. Increases plant diversity. Increases habitat complexity and food sources (seeds & berries) to increase faunal biocomplexity, with large shrubs providing cover for small mammals. Some shrubs may decline after thinning depending on pre-treatment conditions, intensity of thinning and amount of ground disturbance, but most commonly increases. Minimizes opportunities for invasion and establishment of exotic plant species, though without residual understory shade tolerant tree conifers and hardwoods, exotics may be able to spread more easily. May not have residual soil seed banks of shade-tolerant tree species or woodland herbs (the later possess limited dispersal capability). Canopy gaps, created with VDT, may promote large shrub growth. VDT increases abundance and probability of flowering/fruiting in some shrub species.<br><br>Halpern et al. 1999, Lezberg et al. 1999, Lindh 2008, Sullivan et al. 2001, Thysell and Carey 2000, Wender et al. 2004, Wilson et al. 2009 |

## How overstory composition affects species diversity

Overstory trees influence the structural and functional characteristics of ecosystems and, consequently, shape the biota of a forest. Overstory trees regulate structure and function by virtue of their physical dominance and in doing so control the distribution and abundance of other taxa in the forest. Specifically, trees affect forest biota through provision of resources, such as nutrients, water, and substrates. Further, they alter light environments and microclimate in the forest understory through their crown characteristics. Trees also affect ecosystem process like nutrient cycling and disturbances, which, in turn, can affect the type, number, and abundances of other species. When thinking about these functional links, it is important to understand that when overstory composition changes, the nature of the links that trees provide to other taxa also changes.

## Variable-density thinning

Variable-density thinning (VDT), used in new forestry, helps to create spatial heterogeneity (vertical & horizontal) similar to older forests, while maintaining canopy cover. Vertical structure is the bottom to top configuration of above-ground vegetation within a forest stand. One can think of vertical structure as vegetation complexity, and horizontal variation among stands as vegetation heterogeneity. In general, the more vertically diverse a forest is the more diverse will be its biota, for two main reasons. First, a more complex habitat contains more kinds of microclimates and microhabitats for more species. Second, it follows that a more complex vertical structure, supporting more kinds of plants and animals, provides more diverse food resources for more diverse consumers (Hunter and Schmiegelow 2011).

Variable-density thinning alters the density of managed stands through the partial removal of trees to enhance the growth of those that remain (Puettmann et al. 2009) (Figure 5). By regulating the stand density through thinning, foresters can accelerate volume and diameter of trees, create trees with deeper crowns, and promote development of understory herbs and shrubs. The variability of the thinning also encourages the growth multiple tree species at uneven ages. It also promotes larger diameter trees and crown growth by reducing crowding with providing space for them to respond to in new growth. Overtime, these trees will be less susceptible to wind fall.

**Figure 5.** A densely stocked un-thinned forest and a variable-density thinned forest (cityofseattle.net and fs.fed.us).

Variable-density thinning can also eliminate the long interval between stem exclusion stage and understory reinitiation (Brokaw and Lent 1999). It helps to create niche differentiation by providing a more complex habitat which contains more kinds of microclimates & microhabitats for more species to occupy (Thysell and Carey 2000). As the overstory layer matures, it becomes more horizontally heterogeneous and vertically complex due to the thinning and to differential height growth and shaping of crowns. This permits more light to penetrate lower levels, and in response an understory layer develops, further complicating vertical structure. It also helps to release understory shade-tolerant tree species when they are present. To avoid negative impacts in multi-cohort management, tree felling should not greatly exceed natural tree fall rates and loggers should practice reduced impact methods of logging and skidding (Brokaw and Lent 1999).

Forest management practices that replace mature, multi-layered coniferous forests with young, structurally homogenous, single-species stands may adversely affect arboreal rodent populations. An important positive outcome of VDT in promoting various tree species at varying ages is in its effect on the habitat requirements of pine squirrels. These squirrels need diverse conifers providing a supply of reliable seed sources, as well, these squirrels need closed-canopy multi-layered forests with large trees that have some interlocking branches to best navigate through, all which VDT can provide (Smith et al. 2003). Older forests between 80-100 years old probably support more Douglas squirrels since cone production increases as a tree ages (Smith et al. 2003). Yet, in old-growth stands greater than 250 years, cone bearing may taper off with age and squirrels may need to look for additional food sources (Smith et al. 2003). Incidentally, a negative outcome of VDT can occur if the spacing is too wide between thinning's, impeding travel for flying squirrels (Carey and Wilson 2001). Most studies report an increase of flying squirrels in older forests or in young forests with old-growth components, than in younger, managed stands. Flying squirrels also consistently chose dens sites with higher amounts of downed logs on the forest floor. Carey (2000) found flying squirrels to be twice as abundant in Douglas-fir forests managed for retention of standing live trees, snags, and fallen trees than in stands intensively managed for timber production.

**Fragmentation and Connectivity**

Fragmentation is the process of creating a scattered network of land patches as a result of disturbances, particularly from human activity (Anderson and Jenkins 2006). Land-use changes fall into three main categories: reduction in total forest acreage; conversion of naturally regenerated forests to even-aged monoculture plantations; and fragmentation of remaining natural forests into progressively smaller patches (Bennett 2003). Fragmentation sets up a process of species loss in response to three types of changes: overall loss of habitat, reduction in size of fragments, and increased isolation of fragments.

Spatial arrangement of habitat becomes critical as availability of habitat declines, and therefore simply managing for total amount of habitat will not necessarily be sufficient for assuring the persistence of species. The reduced ability of animals to move through the landscape has some major consequences; it limits their capacity to supplement declining populations, to re-colonize habitats where extinctions have occurred, or to colonize newly suitable habitats (Anderson and Jenkins 2006). Fragmentation may have more of an impact on species declines and population abundances than from habitat loss alone (Tyler and Peterson 2003).

Connectivity is a measure of the ability of organisms to move among separated patches of suitable habitat and is used to describe the arrangement and quality of elements in the landscape which may affect the movement of organisms among these patches (Hilty et al. 2006). The level of connectivity can be described as the degree at which the landscape facilitates or impedes movements among these habitat patches. Connectivity for dispersal is a problem felt most strongly by late-successional forest species (Noss 1993), which need blocks of habitat which are close together.

New forestry practices look to lesson fragmentation by maintaining connectivity between suitable forest ecosystems by incorporating the matrix into management from a landscape perspective (Franklin 1993). It strives to create improved habitat between residual late-successional/old-growth forest fragments by creating buffers and corridors of other habitat types (Figure 6), in the hope to ultimately help a diverse array of species move more freely between habitats increasing their survival. By creating connectivity between forest habitats, land managers are hoping forest biodiversity will be increased. An example of this concept being implemented to restore spotted owl populations is with the Interagency Scientific Committee (ISC), which in 1990 recognized the importance of lands surrounding reserves and recommended managing for a matrix design between these sites (Marcot and Thomas 1997). By doing so, it would provide for the movement between habitats and for conservation of organisms and processes within the matrix (Thomas et al. 1990).

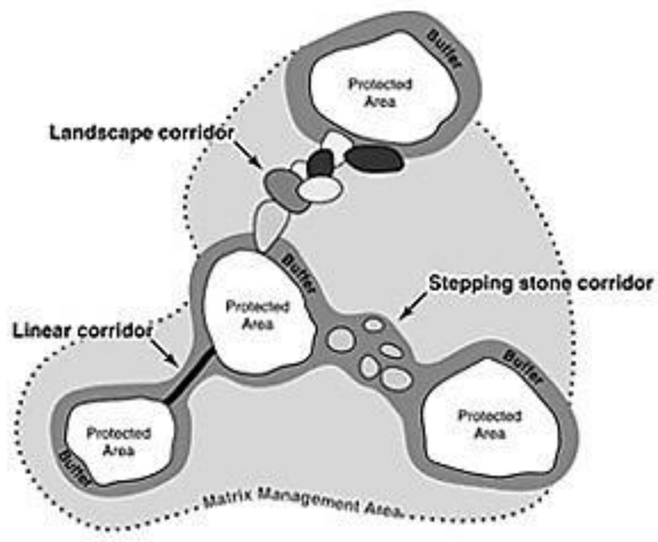


**Figure 6.** Examples of managing connectivity within the landscape matrix. (greateasternranges.org.au).

The ultimate goal in creating a landscape matrix is to maintain habitat at smaller scales, increase the effectiveness of buffers around these habitats, and provide adequate connectivity between habitats (Franklin 1993). This view looks at the interactions among smaller habitats and incorporates them into a greater landscape design, ultimately getting more out of less.

**Forest soil**

Much of the terrestrial biosphere resides in the soil and contains more species diversity than any other terrestrial habitat (Kuyper and Giller 2011), although most of these soil organism have not been identified (Hawksworth 1991). The foundation of a forest ecosystem is in the soil and is dominated by import functions of fungal and bacterial activity (Carey et al. 1995). It is no surprise that an increase in species richness belowground equates to species richness aboveground. Soil organisms are not just inhabitants of the soil; they are part of the soil and are responsible for primary production and decomposition, resources which then move on to sustain aboveground plants and animals (Kuyper and Giller 2011). In particular, mycorrhizal fungi are important assimilators of net primary productivity in Douglas-fir forests and enhance the productivity of Douglas-firs (Carey et al. 1995). These ectomycorrhizal fungi comprise as much as 50-80 percent of the fungal community in forest soils and are fundamental to the many fungal-based trophic pathways (including those which support mycophagous protozoans, arthropods, nematodes, and mammals) found in these forest communities (Allen and Allen 1992). The fungi are also known to form mats which have been found to cover 25-40 percent of some Douglas-fir forest floors (Kluber et al. 2011). Yet, it is estimated that only 5 percent of living fungi have been described (Hawksworth 1991).

Any entry into a forest for cutting or thinning can damage these sensitive soil communities. Even though VDT requires repeated entries, soil disturbance can be minimized if certain types of equipment, entry time of year, and low impact techniques are taken into account and used. Cut-to-length harvesting uses and leaves slash behind to move equipment in order to decrease soil compaction over clear-cutting's whole-tree removal (Han et al. 2009). As well, protecting soils through the use of low-pressure tires, reduced skidding, and less use of scarification will lessen the impact on functioning soil communities (Thompson and Angelstam 1999). Ground disturbance can also be minimized through the use of high-lead cable yarding, which also leaves understory shrubs and tree seedlings intact (Lindh 2008). In these ways, minimal short-term negative effects on the below ground biotic community are seen. One way to measure the impacts of logging on forest soils is by looking at arthropod abundances, due to their fine-scale associations and quick responses to disruption, they are important indicators of soil disturbance (Brokaw and Lent 1999).

**Understory herbs and shrubs**

Variable-density thinning promotes development of understory herbs and shrubs and therefore increases plant diversity by increasing light levels and decreasing water competition, thus contributing to forest vertical structure. In this way, it increases habitat complexity, food sources (seeds and berries), and the canopy gaps created with VDT promote large shrub growth, all increasing faunal biocomplexity (Lindh 2008, Wender et al. 2004). Wender et al. (2004) found that the determining factor for shrubs to flower was their size, and that larger shrubs are also more common in canopy gaps, an important component to VDT. They also saw that shrub flowering production was consistently lower in unthinned stands than in thinned stands. An example of small mammals response to thinning was shown by Hayes et al. (1995), they observed that abundances of Townsend's chipmunks was related to the percentage cover of salal (*Gaultheria* spp.) in the Oregon Coast Range. Also several other small mammals are strongly associated with shrubby habitats such as shrews, voles, and mice (Bunnell et al. 1999). Plant and small mammal diversity will be preserved if understory vegetation and avoidance of the stem-exclusion stage are goals in management (Carey et al. 1995). Carey and Thysell (2000) found that VDT generally increased the diversity of native shrubs and trees and suggested that maintaining some minimally disturbed areas could help to conserve any native species that may be negatively impacted by thinning.

Some shrubs may decline after thinning depending on pre-treatment conditions, intensity of thinning and amount of ground disturbance, but commonly understory cover will increase within 3-5 years (Thysell and Carey 2000). Although a study Oregon found that mechanical damage by thinning may be less disruptive to understory species than the restriction from light resources that the stem-exclusion stage maintains for long periods of time (Bailey 1996). The plants most likely to recover are the ones with deeper regenerative structures like tubers, roots and rhizomes (Halpern and Spies 1995). Salal rhizomes expanded 23.7 percent annually in thinned stands compared to 0 percent in unthinned stands (Bailey 1996).

Variable-density thinning minimizes opportunities for invasion and establishment of exotic plant species by lack of large disturbances, though if residual understory shade tolerant tree conifers and hardwoods are missing, exotics may be able to spread more easily by over-competing with native vegetation (Thysell and Carey 2000). If other habitat elements are also not present like CWD, fungi, and mosses for instance, the potential for VDT to decrease the spread of exotics is even more weak (Thysell and Carey 2000). In stands that have been conventionally thinned vegetation control of exotics may be necessary to restore ecological function.

Lindh (2008) found that five years after low-intensity thinning, old-growth associated herbs and quick release species, both of which have evolved to respond to canopy gaps, showed increase in flowering. The level of thinning was the most important source of variation in flowering responses. Ares et al. (2010) studied three sites in western Oregon eleven years after thinning which showed an increase in diversity of plant species from varying levels of successional stages without decreasing tree regeneration or triggering exotic plant invasion. Lindh and Muir (2004) speculated that thinning probably affected understory composition most by slowing the occurrence of species that would have increased following canopy closure. Because colonizers are often weedy species of plants that do well in open areas, the heavier the thinning the more likely you will have widespread persistent weedy species. Yet, if the thinning's are small scale, extensive or long-term weed colonization does not appear to be a problem (Carey et al. 1995). Because some forests may not have residual soil seed banks of shade-tolerant tree species or woodland herbs, since the later possess limited dispersal capability, planting or seeding may be needed (Halpern et al. 1999, Lezberg et al. 1999). In a study on the Olympic Peninsula, Halpern et al. (1999) found that young, closed canopy forests supported a well-developed and diverse community of buried seeds, although 30 percent of all species were exotics. They also found that the seeds of many conifer species were absent. They concluded that when native vegetation and disturbance regimes have been vastly altered by human activity, native seed banks will be greatly decreased. Underplanting thinned stands with shade-tolerant tree species may be a necessary component to developing an understory cohort (Peterson and Anderson 2009).

**Snags, dying and diseased trees**

New forestry maintains snags, dying and diseased trees because these are all important to wildlife. VDT keeps snags intact by arranging skip areas around them with no treatment (Figure 7). Snags can also be created from live trees using a number of techniques, including topping with a chainsaw, girdling, injection with herbicide, and inoculation with fungus.

**Figure 7.** A snag to be maintained as a wildlife feature after thinning and a snag with prevalent woodpecker cavities (fs.fed.us/pnw/olympia/silv/ohds/virtual-trail/tour2/station3 and en.wikipedia.org).

By maintaining or creating snags, new forestry promotes primary cavity excavators (woodpeckers) which create cavities important for small mammals and birds as den and nest sites (McComb and Lindenmayer 1999) (Figure 8). This is important, because if the habitat requirements are not meet for these primary cavities excavators, secondary bird and mammal cavity nesters will also be eliminated from the site (Bunnell et al. 1999). In this way, some woodpecker species are considered keystone modifiers because they excavate cavities which are essential for other species to successfully produce (Thompson and Angelstam 1999). In most forest types, about 25 to 30 percent of vertebrate species use cavities for either preproduction or roosting (Bunnell et al. 1999).

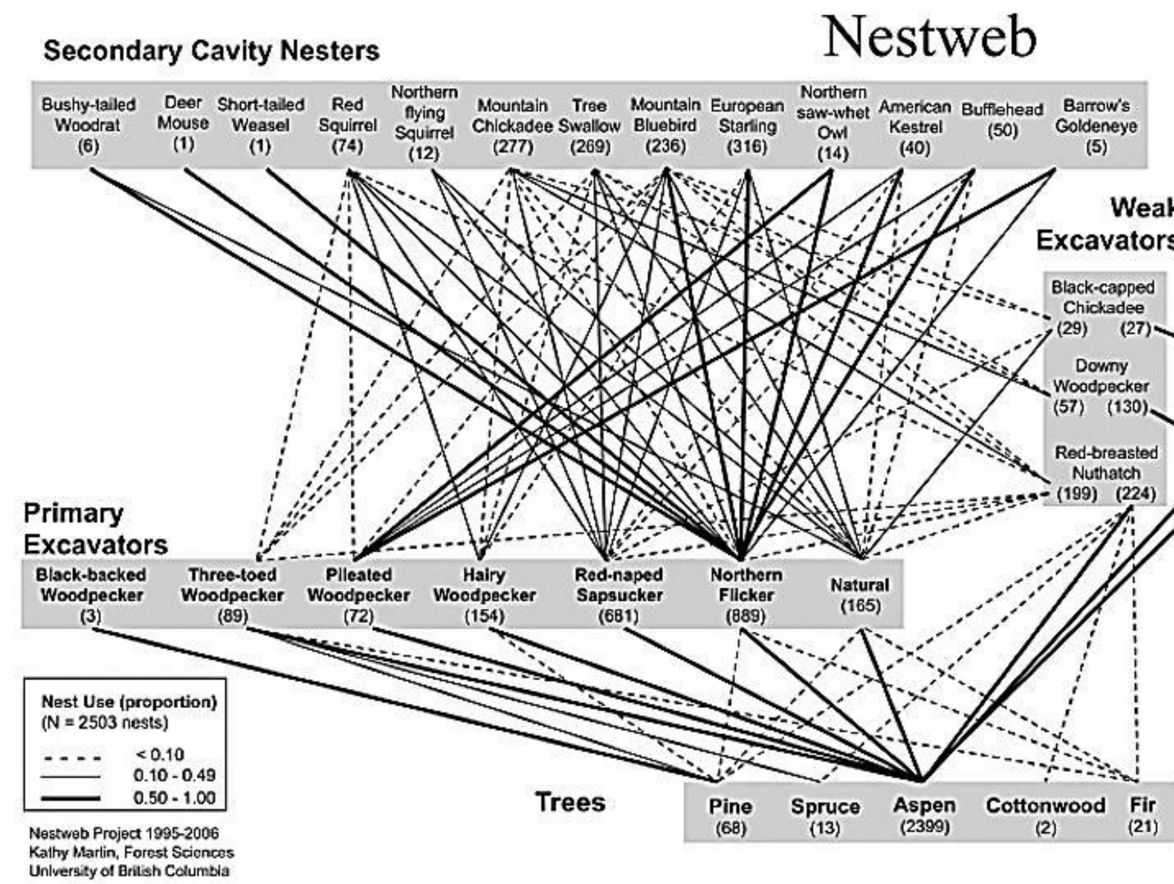


**Figure 8.** A nest-web diagram showing which animals prefer which trees, and the primary and weak excavators responsible for making the cavities (Hunter and Schmiegelow 2011).

While a range of snag sizes is important, lack of larger sizes appears to be the limiting factor or wildlife. The larger, the snag the better, snags or limbs less than 10cm in diameter have little to no value to wildlife (Harrington 2009). In cedar-hemlock forests of British Columbia, only 14 percent of 18-to 32-cm-diameter trees were considered "wildlife trees", compared to 64 percent of trees with diameters greater than 100 cm (Stevenson et al. 2006). The same study also found that "wildlife logs" were much larger than logs that did not have features characteristic of wildlife use. The average difference in size was about 20 cm with wildlife logs consistently greater than 50 cm in diameter. Bats in Douglas-fir forests also selected larger trees for roosting- the odds of a snag being used increased by about 20 percent for every 10 cm increase in diameter (Arnett and Hayes 2009). The main reason for this may be that larger trees provide a more stable thermal environment due to the thicker insulation of the wood and bark.

Diameter is probably the main consideration, but height is important too. Some animals will use a cavity that is practically on the ground, but most prefer to be fairly high, probably because they are more secure from ground predators. Taller trees may also provide better access for species that forage some distance from where they nest or roost; for example, raptors and bats. Carey et al. (1995) found higher abundances of flying squirrels in areas where there were higher potential dens sites of large trees and snags. Virtually all studies agree that large snags and cavity trees and larger logs are more important to keep than small ones. Not only can a greater variety of wildlife use a tall, girthy snag or a big, long log, but larger snags and logs are likely to last longer than smaller ones.

Woodpeckers are known for their chisel-like bill, thick skull, and tough neck, but not all primary excavators are as well equipped to excavate a cavity in a hard snag, and even many woodpeckers prefer to nest in a well-rotted tree (Bunnell et al. 1999). Consequently, it is important to have both soft and hard snags. It is known that up to 40 percent of birds in North America are cavity nesters (McComb and Lindenmayer 1999). In southwest Oregon, an abundance of snags was the primary determinant of a diverse bird community (Carey et al. 1999).

Having snags in various stages of decay, as well as living trees that can be recruited into the dead wood pool, is necessary to ensure a continuous supply of snags over time (Figure 9). Although most forest models estimate that when a tree dies it will remain as a snag, it has actually been found that half of all trees that die will fall within the first ten years (McComb and Lindenmayer 1999). The most important features that will determine when and how large a tree will be when it falls are the site productivity and stocking levels. High quality sites with low stocking levels will produce larger trees which will remain as snags for longer periods (McComb and Lindenmayer 1999).

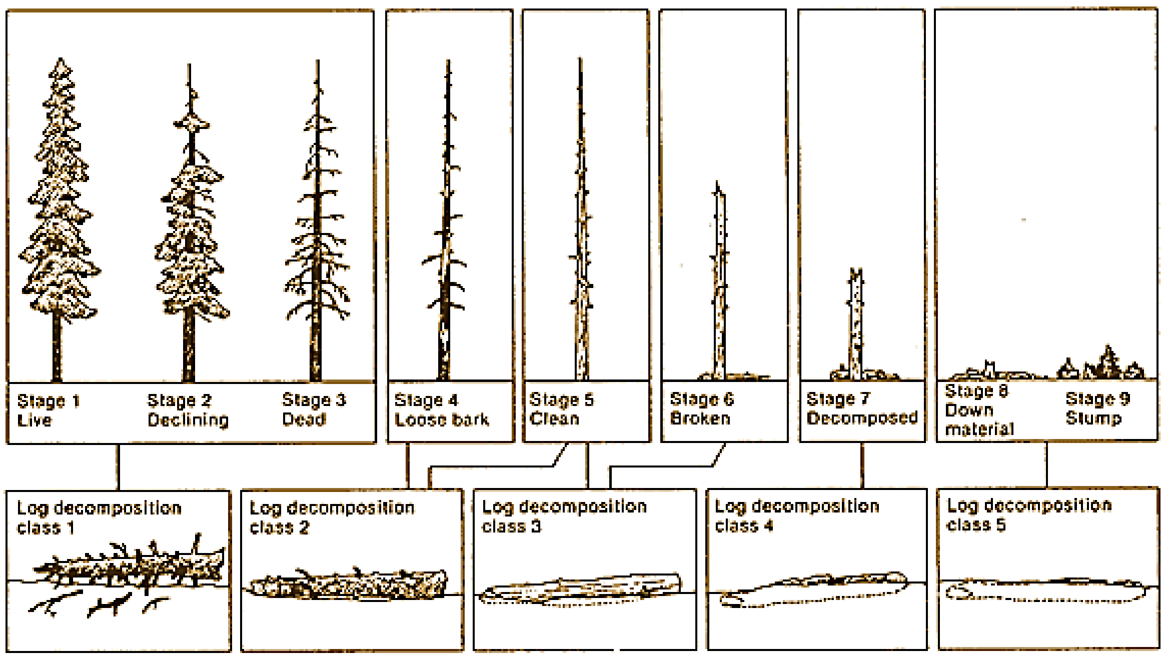


**Figure 9.** Decay stages of snags and logs in the Pacific Northwest (Maser et al. 1979).

### Coarse woody debris

The accumulation of dead wood and its subsequent decomposition are essential forest ecosystem processes. Dead wood is an important element of productive and diverse forests and provides a mechanism for energy flow into detrital-based ecosystems (Harmon et al. 1986). Dead wood is also an important structural feature that has many ecological functions, including habitat for organisms, energy flow and nutrient cycling.

The density of a stand plays a major influence on coarse woody debris (CWD) input to a site and therefore the availability of the site as wildlife habitat. High-density stands produce many small dead stems early on in stand development, but they are of small size and are not useful to wildlife promoting a much less array of biotic diversity (McComb 2003). And because these stands can remain in this stage for decades, it can take a very long time to become available has habitat. The longer a forest in on the successional pathway the greater in size the snags it will produce, which will be beneficial as wildlife habitat.

Clear-cutting and the reduction in downed wood are thought to be the cause of local reductions in seven salamander species in the Pacific Northwest (Bunnell and Houde 2010). Birds will be more abundant and have a greater variety of species with higher amounts of downed wood, presumably due to better foraging and nesting sites (Bunnell and Houde 2010).

In this regard, new forestry strives to either maintain or promote CWD on the ground (Figure 10). This is done by either leaving slash or logs after harvest, or by retaining trees which will fall to the ground and become downed wood. These structures are vital to the biotic community as hiding shelter, food sources, and dispersal pathways. CWD also creates a moist substrate for many plants and fungi to occupy (Bunnell and Houde 2010). It is important to retain all levels of decay classes of downed wood if we are to sustain a wide range of biodiversity.

**Figure 10.** Examples of coarse woody debris on the forest floor (tru.ca and gov.ns.ca).

In many forests logs are a major site for tree regeneration, and a line of small trees growing on a well-rotted log called a “nurse log”, is common (Harmon and Franklin 1989). One of the reasons seeds find logs a favorable place to germinate is because these are good sites for forming a symbiotic relationship with mycorrhizae fungi.
This could be particularly important to forest regeneration on a cleared site. For example, Townsend’s chipmunks regularly venture into forest openings from the surrounding cover and undoubtedly leave behind sport-bearing feces from which new mycorrhizal partnerships can develop.

**Small mammal abundances**

VDT increases food supply buy increasing understory fruiting and cover available for small mammals and therefore increases rodent populations. It is assumed that the increase in pray base also benefits a wide range of mammalian and avian predators. Suzuki and Hayes (2003) reported that thinning appears to increase the abundances of small mammals in both the short-term and long-term. It is claimed that squirrels are good indicators of ecological productivity in the Pacific Northwest because they specialize in eating the fruiting bodies of plants and fungi and that their numbers correlate to the carrying capacity of their predators, primarily raptor, owls, and mustelids (Carey et al. 1999). Wilson and Carey (1996) captured more short-tailed weasels in thinned areas than unthinned areas of the Olympic Peninsula. This was hypothesized to be because their primary small mammal prey was more abundant in thinned areas with high understory development. Subsequently, they found that long-tailed weasels preferred more closed-canopy sites with little understory and greater amounts of CWD which would be have a greater abundance of northern flying squirrels.

Although timber harvest profoundly influences the composition of small mammal communities, it has been shown that once the forest develops certain structural features adequate for certain species to survive, any additional age does not significantly improve habitat conditions (Hallett et al. 2003). Carey (1995) reported that a prevalence of certain flowering plants was highly correlated to northern flying squirrels and Townsend's chipmunks on the Olympic Peninsula. These plants most likely have a high value as food, both in fruits and in mycorrhizal linkages promoting truffle production, and as protection from predators. An earlier study in the southern coast ranges of Washington found that densities were greater, diets more diverse and movements less for northern flying squirrels in older forests than in young forests (Carey 1995), all of these being important factors to their survival.

Leaving slash-piles can also be beneficial to small mammals, where an increase was seen of small mammals around slash piles compared to open clear-cuts (Bunnell and Houde 2010). In southwest Oregon, northern flying squirrels were highly correlated with CWD and this abundance may be due to the increase in truffles from the retention of the CWD (Carey et al. 2002). Yet, in the Olympic Peninsula, flying squirrels were more highly correlated with understory development (Carey 1995). Snags are also a very important habitat feature for flying squirrels as den sites, since they are know the change dens every two weeks, with about 25 percent changing nests any given week (Carey et al. 1995). Even though, Carey et al. (1999) found that of all the habitat elements, CWD proved to be the best indicator for the carrying capacity of northern flying squirrels and Townsend's chipmunk. They also found that canopy stratification was the single best descriptor of chipmunk habitat. To solidify this finding, Carey and Harrington (2001) found local extirpations of northern flying squirrels and Townsend's chipmunk in young-managed stands, which may result in small mammal communities being non-supportive of predator populations.

Recent studies have shown a reduction in northern flying squirrel abundances following thinning and hypothesized that this may be driven by increased susceptibility to predation created by removal of critical mid-story cover. One study confirmed that abundances are lower in second-growth or partially harvested stands and revealed that there may be a snag density threshold below which managed forest are unable to sustain these squirrels' populations (Holloway and Smith 2011). Because northern flying squirrels are an important prey for the northern spotted owl, maintaining their abundance levels is a high priority. It is important then to vary the levels of thinning and create areas of skips to ensure that north flying squirrels have adequate hiding refuge. The long-term benefits of some thinning treatments may be positive for northern flying squirrels, but may not be realized for several decades or more.

**Belowground fungi**

Because of the important role mycorrhizal fungi play in belowground food webs and in the productivity of a forest, any alteration of the fungal community can negatively impact the succession of the forest (Figure 11). Therefore, it is wise to manage by looking at the needs of this community first.

**Figure 11.** Truffles, the friuting bodies of belowground fungi imporant to tree productivity and the diets of some small mammals (source unknown and chrismaser.com).

Since the Pacific Northwest is believed to have one of the largest assemblages of mycorrhizal host tree species in the world (Trappe et al. 2009), and mycorrhizal fungi need the energy from their tree host to survive, using new forestry techniques of VDT, and which also retains CWD, allows this relationship to continue and therefore truffles to be produced. Luoma et al. (2004) found that while all harvested treatments in their study showed some reduction initially in sporocarp production compared to the control, the 75 and 40 percent basal area retention generally maintain higher levels of ectomycorrhizal sporocarp biomass over the 15 percent basal area retention plot. They inferred that an important factor in maintaining mycorrhizal fungi is in retaining a certain level of trees while thinning enough to increase moisture to the forest floor. They found that certain fungi species respond to disturbance at varying levels, reinforcing the benefit VDT can have on diversity of belowground fungi.

There is a thread commonly see in multiple studies showing that truffles increase with the increase in downed wood and also increase in natural-mature and old-growth stands compared to young-managed stands. Maintaining mycorrhizal development through CWD is vital because it is an important food source for 45 identified animals (Molina and Smith 2009). One study found that 60 percent of the truffle biomass was consumed by mycophagous small mammals (Colgan et al. 1999). Cazares et al. (1999) observed that truffle sporocarps were significantly more abundant in the diets of the northern flying squirrel, Douglas' squirrel, and Townsend's chipmunk over mushroom sporocarps which were equality readily available. They made the suggestion that truffles are the preferred food for these three small mammals in Douglas-fir forests. Jacobs and Luoma (2008) observed high diversity in fungal genera in the diets of five small mammals they studied, indicating the importance of mycophagy as a dispersal agent for truffle fungi. Additionally, North and Greenberg (1998) saw that truffles made up 60 percent of the dietary needs of voles, pocket gophers, chipmunks and squirrels in their study. Yet, because truffles are relatively low in nutrients, it is therefore important for mammalian mycophagists to have a diet of multiple truffle species (Carey et al. 1999, Carey et al. 2002).

If we are to restore diversity to forests, thinning is a priority. Unfortunately, as a result from thinning, below ground fungal abundances may temporarily decline due to soil microbial community alterations. Even though, if there are understory plants (i.e. salal) present which have a symbiotic relationship with mycorrhizae, it is believed that they can help fungi recover (Carey et al. 1995, Carey et al. 1999). Carey et al. (2002) found that if some legacies from the previous stand (i.e. snags, logs, or soil communities particularly from a previous old-growth stand) are retained after thinning, management may actually increase truffle species diversity. Maintaining belowground fungal communities could be a key component of an ecosystem's resilience by being important pathways for seedlings and other plants in the uptake of nutrients vital to their growth (Luoma et al. 2006).

Thinning seems to initially change truffle species dominance, since different species have adapted to different microclimate (Luoma et al. 2003). Yet, Colgan et al. (1999) found that fungal diversity seemed to increase in areas of forest which had been lightly thinned. Gomez et al. (2005) concluded that the density of belowground fungi was positively associated with the proximity to large trees, whose growth is encouraged through thinning. Belowground fungi also benefit from new forestry, by not having the common conventional forestry practice of slash-burning being applied. These fires not only remove the necessary organic layer on the forest floor for fungi to thrive, but the high heat conditions harm the fungi which are not adapted to frequent fires in the wet climate west of the Cascades (North and Greenberg 1998).

### 4.2 Interview responses

I consulted with three professionals in the field of forest restoration, forest ecology, and wildlife biology and asked them each the same questions: 1) Is creating complexity in forests working to restore biodiversity? 2) What are, if any, indications of success? 3) How useful are models in planning future structural diversity?

In response to whether creating complexity in forests is working to restore biodiversity and are there indications of success, Todd Wilson, from the Pacific Northwest Research Station in Olympia Washington, answered that for the most part at least all of the biotic measures that they have studied, including plants, small mammals, birds, and amphibians have increased after complexity was increased. The exception is arboreal rodents, including flying squirrels and red tree voles, which are primary prey for northern spotted owls, which decline after thinning. He thinks that eventually, conditions will likely favor arboreal rodents, but it could take several decades or more. Increases in species richness and/or abundance (or neutral response) in the first decade or so after thinning by mice, voles, shrews, terrestrial salamanders, understory plants, and resident and neotropical songbirds is seen and a development of the start of a shade-tolerant mid-story tree layer on some sites is seen.

Constance Harrington, also from the Pacific Northwest Research Station, responded to whether creating complexity in forests is working to restore biodiversity and are there indications of success by saying that she believes adding complexity to young stands with simple stand structures will help accelerate the development of stand structures and plant and animal communities associated with late-successional forests. She thinks using the term "restore" can be tricky as it implies restoring something to a previous condition when we don't necessarily know what conditions (species assemblages and stand structures) were previously present. For example, much of the Puget Sound lowlands were in prairies and oak savannas when the European settlers arrived. Are we interested in restoring those conditions? For her, biodiversity in the simplest sense means the number of species present. But more species isn't necessarily good if the species are not the ones you are interested in. Most projects designed to add complexity are fairly recent in scope so it is premature to judge them.

Joe Buchanan, from the Washington Department of Fish and Wildlife in Olympia, when asked whether creating complexity in forests is working to restore biodiversity and are there indications of success answered that with the exception of sedentary species, most forest wildlife respond to successional changes, and most species are more abundant in one forest age class than in others. This is an indication that many species recognize differences in forest structure. It is logical that various species would then respond to forests recruited, modified or restored by humans. Joe explained to me that the Washington Department of Natural Resources began a snag creation program about 10-12 years ago on one of their state forests and they invited him to participate in a field trip to some of their study sites 4-5 years ago. These snags were created by a variety of methods applied to living trees (topping, girdling, etc.), and this work occurred in managed forest patches that otherwise lacked snags. The response by pileated woodpeckers to these created snags was remarkable. He also said that A.J. Kroll (Weyerhaeuser) has been working on a project where bird response to created snags in clear-cuts was monitored. In addition, he has seen several examples where northern spotted owls have subsequently occupied and nested in forests “sloppily” harvested in the 1930s (retaining legacy trees and large logs in the harvest unit because it was inconvenient to remove back then) in western Washington. Responses likely differ from one species to the next and also as a function of subtle differences in site conditions. Indications of success might include measures such as increases in abundance, nest success, survival rates, etc. Changes in abundance can sometimes be misleading, especially if the individuals involved are not breeding. Increases in species richness might be an appropriate indicator, but that depends on the composition of change in richness (e.g. an increase in generalist or exotic species might not be a very meaningful indicator); an increase in the richness of the cavity-user guild in a conifer forest might be an excellent early indicator of a successful snag creation project. The best measures of success will be those that involve estimates of productivity or survival, because this information would indicate that not only are the species present, but they are also breeding (and measures of this will range from low to high reproductive output) or experiencing increased survival rates.

When asked how useful are models in planning future structural diversity, Todd Wilson responded that in theory, they could be very useful, but much of what went into any such model would probably still rely heavily on expert opinion rather than data. It would be critical to include any site-specific conditions that could affect development of structural diversity (e.g., presence of an aggressive understory like salal that could impede tree regeneration, slope and aspect, presence of a shade-tolerant seed source for regeneration, type and pattern of thinning, etc.), saying that it gets complex pretty fast. Also, natural stochastic events at a variety of spatial and temporal scales could greatly alter stand trajectories and structural complexity (everything from a localized pocket of disease to a catastrophic, stand-replacing windstorm) making long-term predictability difficult.

Connie stated when ask about the usefulness of forest models in predicting structural diversity that models predicting tree growth and mortality have traditionally done fairly well in stands with simple structure and not so well in more complex stands. She has found that the models generally under-predict growth and over-predicts survival of trees in the understory. She says that several people are working to improve the models. For example, in her office they have been working this year on better predicting growth of small trees (regenerations) in the USDA Forest Service Forest Vegetation Simulator (FVS) so the models better reflect what they see in their field plots in terms of growth and mortality. Lastly, she mentioned that models predicting aspects of stand structure such as branch diameter and crown length probably also need revision for use in complex stand conditions.

Joe thinks that models are very important tools that can help guide planning for future forest complexity and diversity. Though he feels that some models are better than others; the complexity of the community or ecosystem and the level of uncertainty associated with species habitat associations or vegetation growth have the potential to influence the model. However, he said that even those limitations can be addressed in modeling efforts if there is a desire to understand the potential effects of various information gaps or hypothesized interactions. He also feels that modeling sophistication is increasing and thinks models are becoming increasingly important in wildlife work.

# 5. Discussion

## Themes in literature

One of the themes that emerges from the literature is that old-growth likely develops from a variety of initial conditions along a variety of pathways toward a variety of old-growth endpoints. It is also clear that today's dense young plantations exhibit unprecedented uniformity of initial conditions, which could end up limiting both the diversity of pathways and endpoints. While recognizing that disturbances will continue to play a role in diversifying and resetting stands, there seems to be a consensus emerging that some form of variable-density thinning can help diversify some young forests in order to reintroduce more diversity. Another important area of agreement seems to be that we do not fully understand how to create old-growth, nor is there one right way to achieve restoration in dense young plantations. There are a variety of tools that should be applied in a variety of ways at a variety of scales, and possibly, some areas, even dense young plantations, should be left unthinned and undisturbed.

The available information indicates that thinning causes positive, negative, neutral, and unknown consequences. It will be important to consider the costs of both action and inaction (i.e., thinning and not thinning). Active management will realize some ecological benefits while causing some unavoidable short-term adverse consequences. Passive management will certainly avoid some negative consequences that may be caused by thinning, but it will also cause some of its own negative consequences (e.g., extended periods of competitive exclusion, unstable height/diameter ratios) and forgo other benefits.

There is a growing body of evidence that using VDT in young plantations can enhance development of many features associated with late-successional forests such as large trees, well developed tree crowns and canopies, patchy mosaics of a variety of habitat types, tree size diversity, tree species diversity, understory vegetation development, wildlife habitat development, and large woody debris. There are also numerous potential adverse impacts associated with thinning young forests on the Westside of the Cascades, including adverse effects on soil, water quality, aesthetics, invasive species, some wildlife species, and an increase in the risk of damage from wind. Yet, the adverse consequences of thinning will be less intense than the effects of traditional clear-cutting and the effects will usually be short-lived.

**Management considerations for snags and coarse woody debris**

Obviously with species using dead, dying or diseases trees representing a range of organism sizes from microbes, mites, salamanders, fishers, and bears, managing the spatial distribution of logs must consider a wide range of home range sizes. Ideally, the habitat requirements of each species must be considered when deciding where logs should be retained and what log characteristics are sufficient to meet their needs. If this is not possible, than the desired size class distribution for the suite of species being managed in the stand or landscape should be determined by the species requiring the largest piece size. Alternately, a manager can assess functional relationships between animals and CWD and manage for these conditions as part of a desired future condition (McComb and Lindenmayer 1999). Natural and created snags are continually being lost and degraded through disturbance and decay. Therefore, snag recruitment is an on-going process requiring forethought and planning for the retention of green trees for future snags.

**Factors to consider when applying variable-density management**

Most variable treatments are inherently more expensive to apply than uniform ones, primarily because they require covering more ground to get the same amount of work done.  Therefore when starting a new type of treatment, managers with a limited information base to work with may be tempted to use the same approach and treatment each time, yet prescriptions will be most successful if they are varied.  Additionally, although many of the same general types of variables are sampled at multiple LSSEs, very few specific values are sampled identically at multiple sites.  This may hinder the extraction of general patterns, making results difficult to compare or separate from treatments applied at each site, therefore giving inconsistent results.  This could be improved if all studies were done with more uniformity between variables measured. Also another reoccurring problem is in the time scale of these experiments; we have to wait a long time to see results and maintaining their relevance could be a challenge with changing societal values.

Variable-density thinning will be an important tool for forest manager charged with promoting or creating old-growth structure within all or part of a landscape.  But like any tool, VDT will not be appropriate for all stands at all times.  Dense stands of young trees are a natural part of the landscape and should be maintained at appropriate levels for those plants and animal species dependent of that type of habitat.  Stands with open canopies and existing vigorous shrub growth may not respond to thinning in terms of confer regeneration without additional management (e.g. vegetation control or planting).

Overstory trees with high height to diameter ratios may be susceptible to extensive windthrow shortly after treatment with thinning and increasing gaps in forest stands. Top breakage may also be greater in widely-spaced trees. By not thinning near roads or on ridges where trees may be more susceptible to high winds, wind throw can be minimized. In addition, creating too large of gaps may encourage colonization, growth, or retention of exotic plants. These sized gaps or overly thinned forests also may negatively impact the belowground fungi and northern flying squirrels relationships causing populations declines in the short-term. It is important to maintain truffles and flying squirrels in the landscape for the necessity of mycorrhizal fungi for tree growth and northern flying squirrel as prey for the northern spotted owl, an endangered species. It is unknown whether northern flying squirrel populations decline in thinned stands due to their greater predation or if they are negatively influenced by the initial decrease in truffles. However, by varying the intensity and arrangement of thinning's, and how they are interspersed with other treatments, for instance, northern flying squirrel and truffle abundances may be less impacted. A forest may need a re-thinning treatment if the original thinning was minimal due to concerns to belowground fungi and flying squirrel populations, as a way to decrease these negative impacts. A single thinning may also not be enough for a very young stand to achieve old-growth characteristics, here again a re-thinning may be advisable (Tappeiner 2009).

An existing landscape can be manipulated at the stand-level to provide more old-growth-type habitat over time and across a landscape. This type of active management is a preferred alternative to strict preservation given: 1) reduced time to create old-growth-type structures in young forested landscapes lacking such habitat; 2) an ability to emphasize the creation of specific features lacking in a landscape (e.g. large snags); and 3) a lack of evidence showing negative long-term impacts on plant and animal species composition and productivity following thinning.

**Limitations of forestry models**

Most growth and yield models were based on uniform stands with one or a few species and a limited number and range of treatments. Most of these models assume the treatments are applied uniformly and are not spatially explicit. Thus, existing models may only provide general trends for spatially complex treatments like VDT. Existing models may not reflect the wide range of growing conditions in a more complex stand by under-predicting the potential growth influence resulting from internal edge effects (Roberts and Harrington 2008). Gould and Harrington (2011) found that some models under-predict growth and over-predict survival of understory trees. In response, they are working toward making models better reflect growth rates they are seeing in their own research plots in the hope that models will show greater variability than seen in previous models. Forest models have been very good at predicting growth of uniform stands, but with new forestry's goal of complex un-even aged stands, this will be more challenging to model.

# 6. Conclusion

Given that millions of acres of our federal forest lands are covered with uniform dense plantations with relatively low habitat value, the challenge we face is how to prioritize restoration actions and continue to learn so that we can (a) increase the benefits of biodiversity from thinning, (b) find ways to avoid, minimize, and mitigate the adverse impacts of thinning, and (c) acknowledge and manage the risks and inherent uncertainty involved in the choices about how to manage young stands.

Maintaining truffle productivity and diversity is critical to the maintenance of small mammal populations because many small mammals use truffles as a food source, with some using them as a major food source.  If populations of small mammals are abundant, then there is an adequate prey base for maintaining abundances and diversity of predators.  This is particularly important in maintaining the northern flying squirrel and northern spotted owl species relationship.  Mycorrhizal fungi are also important in promoting tree productivity and complex soil communities which are at the core of the forest food web.  By using the techniques of VDT while retaining CWD, we can promote this vital keystone complex relationship, which is at the center for maintaining biological diversity in forested ecosystems.

The literature reviewed for this analysis points to the possibility that late-seral communities could be restored with minimal intervention with a high probability of success.  One potential factor that stands out for success is the high degree of resiliency in soil food webs, fungi, and vascular plant diversity in forest ecosystems.  This resiliency in the forest community may be due to the functional connections and pathways among plant, microbial, and small mammals communities which we are only beginning to shed a light on. By providing an adequate prey base for predators and creating a complex forest structure we can go a long way in improving habitat for multiple species. Continued research is needed to better understand how these interactions are taking place and the role that other species relationships may be playing in the ecosystem which we may have overlooked. More research is also needed to improve our understanding of the functional relationships of soil biota, which is at the core of ecosystem health, in order to better address forestry impacts on soil biodiversity. In the meantime, forest managers should make the least possible entrances into a forest to minimize soil disturbance.

Models are limited in how they can help plan for future complex forest structure and should not be relied upon exclusively since they do not predict complex forest structure on a landscape scale. More time for a forest to develop that has had VDT treatments applied and the subsequent research from them should be our guide. In time, models will become more accurate indicators of forest successional changes and forest managers will more easily be able to meet a wide range of objectives through the design and implementation of increased biological diversity on public lands.

Managing forests as dynamic ecosystems and landscapes will help meet the multiple goals currently desired such as; reserves for biological diversity, connectivity on a landscape scale for wildlife, human needs for wood products, a clean environment, and recreational experiences in nature. Creating complex structure and composition leads to complexity in forest function that translates to a high carrying capacity for diverse animals, high productivity for plants, effective regulation of nutrients and water cycling, and healthy, resilient forests.

While the management of forests to maintain or produce older-forest conditions holds great promise, it remains a grand experiment, or more accurately, a series of grand experiments, the result which will not be clear for many decades or, in some cases centuries. Yet, it is my hope that as we move forward in forest management we use the functions, relationships and linkages within a forest as our guides in maintaining and restoring forest ecosystem health.

**Recommendations for future forest management**

1) Retain diversity of trees sizes starting with the largest trees, and then implementing some smaller trees in all age-size classes.
2) Reduce tree densities to increase rates of diameter growth to produce large-diameter trees and encourage development of large and deep crowns. Such trees are more resistant to windthrow and remain standing longer after they are dead, providing habitat to snag-associated species.
3) Retain and protect under-represented conifer and non-conifer trees and shrubs that would have been eliminated under intensive Douglas-fir timber production. Plant shade-tolerant tree species when seed sources of desired species are lacking.
4) Vary densities and frequency of entries by planning a variety of approaches within a given area so that treatments will mimic natural disturbances seen in forests and better meet the needs of wildlife.
5) Be creative in the use of moderate sized skips and small gaps to establish diversity and complexity both within and between stands.

6) Retain or create abundant snags and course woody debris both distributed and in clumps so that thinning mimics natural disturbance.  Retain important features of wildlife trees such as hollows, forked tops, broken tops, leaning trees, etc.

7) Thin heavy enough to stimulate development and diversity of understory vegetation, but don't thin too heavy, which may deplete belowground fungi and northern flying squirrel populations.

8) Leave some cut trees and a portion of the tops in the forest to retain nutrients on site.

9) Avoid the damaging effects of soil compaction by making the least possible entries into a stand and by using less intensity timber harvest practices.

10) Take proactive steps to avoid the spread of weeds.  Wash weed seeds off of equipment before it enters the forest.

11) Avoid road construction.  Where road building is necessary, ensure that restoration benefits far outweigh the adverse impacts of the road.

12) Management should ultimately focus on the ecological processes that lead to the development of beneficial forest structures, rather than solely on the structures themselves.

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# Appendices

## Appendix A.

**<u>Glossary of terms</u>**

**Adaptive management**: A formal process for a) evaluating the current resource status, b) evaluating the effectiveness of rules and guidance necessary to meet the goals and objectives for the protection, maintenance, and enhancement of resources, c) making any necessary adjustments to management practices, and d) requiring mitigation, where necessary to achieve resource objectives.

**Basal area (BA)**: The area of a cross-section of a tree, including bark, at breast height. Basal area of a forest stand is the sum of the basal areas of all individual trees in the stand, usually reported as square feet per acre.

**Biodiversity**: The variety, distribution and abundance of living organisms in an ecosystem. Maintaining biodiversity is believed to promote stability, sustainability and resilience of ecosystems.

**Canopy**: The continuous cover of branches and foliage formed collectively by the crowns of adjacent trees and other woody growth.

**Clear-cut**: A harvest method in which all or almost all of the trees are removed in one cutting.

**Coarse woody debris**: Large pieces of wood on the ground include logs, pieces of logs, and large chunks of wood; provides habitat complexity.

**Competitive exclusion stage**: Also called stem exclusion stage. This predominantly developmental stage lacks the very large trees and multiple canopy layers found in the later stages of stand development, and are usually deficient of large snags and significant amounts of down wood. Within competitive exclusion developmental stages, understory vegetation is generally severely depressed.

**Crown ratio or live-crown ratio**: The length of a tree's crown divided by the total height of the tree.

**Diameter and breast height (dbh)**: The diameter of a tree measured 4.5 feet above the ground on the uphill side of the tree.

**Ecosystem**: An ecosystem is a biological system consisting of all the living organisms or biotic components in a particular area and the nonliving or abiotic components with which the organisms interact, such as air, mineral soil, water, and sunlight.

**Ecosystem function**: Ecosystem functions are a subset of ecological processes and ecosystem structures. Each function is the result of the natural processes of the total ecological sub-system of which it is a part. Natural processes, in turn, are the result of complex interactions between biotic (living organisms) and abiotic (chemical and physical) components of ecosystems through the universal driving forces of matter and energy.

**Endangered species**: A formal classification by federal and/or state agencies defining a population of organisms which is at risk of becoming extinct because it is either few in numbers, or threatened by changing environmental or predation parameters.

**Endangered Species Act (ESA)**: The federal Endangered Species Act of 1973 sets up processes by which plant and animal species can be designated as threatened or endangered. Once species are listed the act provides for the development of recovery plans for these species, including conserving the ecosystems on which listed species depend.

**Even-aged**: A system of forest management in which stands are produced or maintained with relatively minor differences in age.

**Forest**: A biological community of plants and animals that is dominated by trees and other woody plants.

**Forest fragmentation**: The splitting of forestlands into smaller, detached areas as a result of road building, farming, suburban development, and other activities. This can isolate wildlife populations, and may result in forested areas too small to meet the habitat requirements of some species. Wildlife corridors help remedy this problem.

**Forest Vegetation Simulator (FVS)**: Is an individual-tree, distance-independent, growth and yield model which has been calibrated for specific geographic areas of the United States. FVS can simulate a wide range of silvicultural treatments for most major forest tree species, forest types, and stand conditions.

**Forestry**: The science of establishing, cultivating, and managing forests and their attendant resources.

**Habitat diversity**: The variety of wildlife habitat features and types in a specific area. Habitat diversity takes many forms: the variety of plants and animals on a site; structural diversity or the vertical arrangement of vegetation from canopy to forest floor; horizontal diversity or the distribution of habitat types across the landscape; and temporal diversity or habitat changes over time. Generally, areas with substantial habitat diversity will support more wildlife species than areas with less habitat diversity.

**Hypha (plural hyphae)**: Any of the threadlike filaments forming the mycelium of a fungus.

**Indicator species**: An organism that occurs only in areas with specific environmental conditions. Because of their narrow ecological tolerance, the presence or absence of these species on a site is a good indicator of environmental conditions. Foresters often use the distribution of indicator understory plants to get a quick estimate of site conditions, for example, drainage and fertility. Biologists may use indicator species to evaluate the health of an ecosystem.

**Keystone species**: An organism that has a greater role in maintaining ecosystem function than would be predicted based on its abundance. Concept named after the wedge-shaped keystone that holds together the parts of an arch. If the keystone is removed, the arch collapses.

**Keystone complex**: A more complicated idea that recognizes a number of components that are building blocks of an ecosystem and supporters of it processes.

**Large-scale silviculture experiments**: Silviculture experiments conducted at operational scales.

**Late-successional forest**: A mature and or old-growth forest stand, also called late seral-stage forest. Typical characteristics are moderate to high canopy closure, a multi-layer, multi-species canopy dominated by large overstory trees, many large snags, and abundant large woody debris (such as fallen trees) on the ground. Typically, stands 80-120 years old are entering this stage.

**Late-successional reserve (LSR)**: An area of forest where the management objective is to protect and enhance conditions of late successional and old-growth forest ecosystems.

**Mycelium (plural mycelia)**: The vegetative part of a fungus, consisting of a mass of branching, thread-like hyphae.

**Mycorrhizae**: The symbiotic association of beneficial fungi with the small roots of some plants, including pines. Mycorrhizae may improve the water and nutrient uptake of trees.

**Niche**: The unique environment or set of ecological conditions in which a specific plant or animal species occurs, and the function the organism serves within that ecosystem.

**Niche differentiation**: Refers to the process by which natural selection drives competing species into different patterns of resource use or different niches. This process allows two species to partition certain resources so that one species does not out-compete the other; thus, coexistence is obtained through the differentiation of their realized ecological niches.

**Old-growth forest**: A forest that is the successional stage after maturity, which may or may not include climax old-growth species; the final seral stage. Typically, it contains trees older than 200 years. Stands containing Douglas-fir older than 160 years which are past full maturity and starting to deteriorate may be classified as old-growth.

**Overstory**: The trees that form the upper canopy layer in a forest that has more than one story.

**Pre-commercial thinning**: Cutting trees from a young stand so that the remaining trees will have more room to grow to marketable size. Trees cut in a pre-commercial thinning have no commercial value and normally none of the felled trees are removed for utilization. The primary intent is to improve growth potential for the trees left after thinning.

**Sensitive species**: A state designation. A state sensitive species are species native to Washington that are vulnerable of declining, and are likely to become endangered or threatened in a significant portion of their ranges within the state without cooperative management or the removal of threats.

**Seral stage**: One of the developmental stage that succeed each other as an ecosystem changes over time; specifically the stage of ecological succession as a forest develops.

**Shade tolerance**: The ability of a tree species to survive in relatively low light conditions.

**Silviculture**: The theory and practice of controlling the establishment, composition, growth, and quality of forest stands in order to achieve management objectives.

**Site Density Index (SDI)**: A measure of the stocking of a stand of trees based on the number of trees per unit area and diameter at breast height of the tree of average basal area. It may also be defined as the degree of crowding within stocked areas, using various growing space ratios based on crown length or diameter, tree height or diameter, and spacing. A SDI of 600 is the stand density limit. This is equal to a basal area factor (BAF) of 400 or a relative density (RD) of 100.

**Soil compaction**: Compression of the soil resulting in: reduced soil pore space (the spaces between soil particles); decreased movement of water and air into and within the soil; decreased soil water storage; and increased surface runoff and erosion. The use of heavy machinery during forest operations contributes to soil compaction.

**Stand**: A group of trees that possess sufficient uniformity in composition, structure, age, spatial arrangement, or condition to distinguish them from adjacent groups.

**Structure**: The presence, size, and physical arrangement of vegetation in a stand. Vertical structure refers to the variety of plant heights, from the canopy to the forest floor. Horizontal structure refers to the types, sizes, and distribution of trees and other plants across the land surface. Forestlands with substantial structural diversity provide a variety of niches for different wildlife species.

**Symbiosis**: The intimate association of two kinds of organisms.

**Threatened species**: A formal classification by federal and/or state agencies defining any species (including animals, plants, fungi, etc.) which are vulnerable to endangerment in the near future.

**Understory:** Forest undergrowth; the lowest canopy layer of trees and woody species.

**Uneven-aged**: Forests composed of trees that differ markedly in age; may be a result of partial cutting practices or natural disturbance.

**Wildlife habitat**: The arrangement of food, water, cover, and space required to meet the biological needs of an animal. Different wildlife species have different requirements, and these requirements vary over the course of a year. Also, different plants provide fruit and food in different seasons. Maintaining a variety of habitats generally benefits wildlife.

**Wildlife tree**: Includes large live trees, snags, cavities, and downed logs that provide forest-habitat structures for wildlife.

**Windthrow**: A tree pushed over by wind. Most common among shallow-rooted species on sites with shallow soils, and in areas where cutting has reduced the density of a stand, exposing residual trees to the wind and depriving them of the accustomed support of neighboring trees.

## Appendix B.

**Forest Vegetation Simulator model results**

I analyzed two simulations from the USDA Forest Service Forest Vegetation Simulator. One was an unmanaged stand and one a managed stand. Each had 300 TPA planted on bare ground in 2010 with the model extending 180 years out. The thinning's were determined when the RD approached 40 to 60. The managed site was thinned once in 2060 to 217 TPA, then again in 2130 to 58 TPA. At the end of the 180 year period, the managed site had 43 TPA, a BA of 282, and a SDI of 316. The unmanaged stand with no treatments after 180 years had 72 TPA, 349 BA, and SDI of 415.

The managed stand had fewer trees per acre, but the trees were overall larger in diameter and had greater crowns. These trees, which grew larger, later provided larger snags and downed wood than the unmanaged stand, although the managed stand was still limited in the size of the downed wood. Snags were also larger overall in the managed stand compared to the unmanaged stand. The unmanaged stand had a significantly higher number of small snags in the >= 0-12" category then the managed stand.

The merchantable board feet generated from the managed stand with the first thinning was $7800 per acre and $12,000 per acre in the second thinning. Not only is there an economic benefit to thinning, but an ecological one, as some trees could be left on site as downed wood. In addition, the income generated from the timber thinning could also go towards other habitat enhancements or species presence monitoring.

Models are helpful, but are designed to grow trees, not habitat. The benefit to managed stands seen in the models is that we can purposefully create snags by having the flexibility to decide which trees would best serve as snags to enhance wildlife habitat, and get to them early.

By using the Forest Vegetation Simulator, we can see that active management has a role to play in shaping forests. Thinning allows us to create habitat as we go. Forest models can give us an insight into what the possible outcomes may be in a forest when it is managed or unmanaged, therefore making better management decision beforehand.

Summary statistics for managed stand

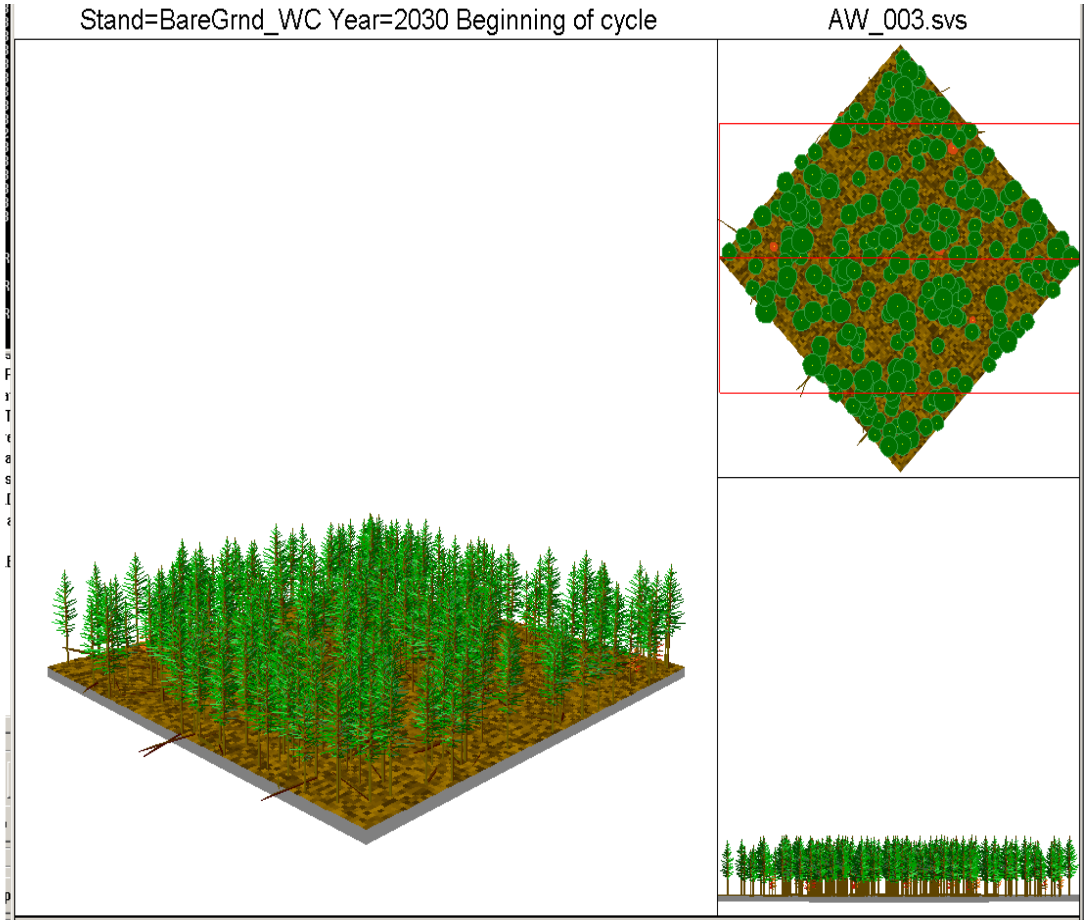
SUMMARY STATISTICS (PER ACRE OR STAND BASED ON TOTAL STAND AREA)

| | | START OF SIMULATION PERIOD | | | | | | | | | REMOVALS | | | | AFTER TREATMENT | | | | | GROWTH THIS PERIOD | | | MAI | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| YEAR | AGE | NO OF TREES | BA | SDI | CCF | TOP HT | QMD | TOTAL CU FT | MERCH CU FT | MERCH BD FT | NO OF TREES | TOTAL CU FT | MERCH CU FT | MERCH BD FT | BA | SDI | CCF | TOP HT | RES QMD | PERIOD YEARS | ACCRE PER | MORT YEAR | MERCH CU FT | FOR TYP | SS ZT |
| 2010 | 0 | 0 | 0 | 0 | 0 | 0 | 0.0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.0 | 10 | 0 | 0 | 0.0 | 999 | 55 |
| 2020 | 10 | 300 | 13 | 39 | 45 | 20 | 2.8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 13 | 39 | 45 | 20 | 2.8 | 10 | 126 | 0 | 0.0 | 201 | 34 |
| 2030 | 20 | 284 | 61 | 134 | 109 | 41 | 6.3 | 1256 | 507 | 2772 | 0 | 0 | 0 | 0 | 61 | 134 | 109 | 41 | 6.3 | 10 | 286 | 8 | 25.4 | 201 | 23 |
| 2040 | 30 | 266 | 145 | 266 | 204 | 63 | 10.0 | 4037 | 3655 | 19506 | 0 | 0 | 0 | 0 | 145 | 266 | 204 | 63 | 10.0 | 10 | 367 | 36 | 121.8 | 201 | 12 |
| 2050 | 40 | 242 | 212 | 354 | 271 | 85 | 12.7 | 7350 | 6967 | 34216 | 0 | 0 | 0 | 0 | 212 | 354 | 271 | 85 | 12.7 | 10 | 360 | 76 | 174.2 | 201 | 12 |
| 2060 | 50 | 217 | 253 | 399 | 308 | 104 | 14.6 | 10187 | 9739 | 49227 | 92 | 2663 | 2487 | 12999 | 182 | 275 | 214 | 104 | 16.3 | 10 | 258 | 54 | 194.8 | 201 | 11 |
| 2070 | 60 | 116 | 209 | 302 | 239 | 121 | 18.2 | 9565 | 9138 | 47330 | 0 | 0 | 0 | 0 | 209 | 302 | 239 | 121 | 18.2 | 10 | 238 | 69 | 193.8 | 201 | 12 |
| 2080 | 70 | 107 | 231 | 322 | 258 | 137 | 19.8 | 11255 | 10786 | 57847 | 0 | 0 | 0 | 0 | 231 | 322 | 258 | 137 | 19.8 | 10 | 233 | 78 | 189.6 | 201 | 12 |
| 2090 | 80 | 100 | 248 | 337 | 272 | 151 | 21.3 | 12802 | 12230 | 67793 | 0 | 0 | 0 | 0 | 248 | 337 | 272 | 151 | 21.3 | 10 | 222 | 87 | 184.0 | 201 | 12 |
| 2100 | 90 | 93 | 262 | 348 | 284 | 163 | 22.8 | 14153 | 13412 | 76215 | 0 | 0 | 0 | 0 | 262 | 348 | 284 | 163 | 22.8 | 10 | 215 | 91 | 176.7 | 201 | 12 |
| 2110 | 100 | 87 | 274 | 355 | 293 | 174 | 24.0 | 15391 | 14633 | 84916 | 0 | 0 | 0 | 0 | 274 | 355 | 293 | 174 | 24.0 | 10 | 201 | 93 | 171.2 | 201 | 12 |
| 2120 | 110 | 81 | 283 | 360 | 299 | 183 | 25.2 | 16465 | 15667 | 93332 | 0 | 0 | 0 | 0 | 283 | 360 | 299 | 183 | 25.2 | 10 | 198 | 99 | 165.0 | 201 | 12 |
| 2130 | 120 | 76 | 291 | 364 | 305 | 190 | 26.4 | 17460 | 16688 | 101247 | 16 | 3583 | 3425 | 20780 | 231 | 289 | 243 | 186 | 26.4 | 10 | 168 | 69 | 159.8 | 201 | 12 |
| 2140 | 130 | 58 | 241 | 295 | 250 | 192 | 27.7 | 14867 | 14156 | 87844 | 0 | 0 | 0 | 0 | 241 | 295 | 250 | 192 | 27.7 | 10 | 166 | 71 | 154.4 | 201 | 12 |
| 2150 | 140 | 55 | 249 | 300 | 257 | 198 | 28.9 | 15815 | 15127 | 94939 | 0 | 0 | 0 | 0 | 249 | 300 | 257 | 198 | 28.9 | 10 | 165 | 74 | 150.3 | 201 | 12 |
| 2160 | 150 | 52 | 257 | 305 | 263 | 203 | 30.1 | 16728 | 15979 | 102020 | 0 | 0 | 0 | 0 | 257 | 305 | 263 | 203 | 30.1 | 10 | 164 | 77 | 145.9 | 201 | 12 |
| 2170 | 160 | 49 | 265 | 309 | 269 | 208 | 31.3 | 17601 | 16851 | 109150 | 0 | 0 | 0 | 0 | 265 | 309 | 269 | 208 | 31.3 | 10 | 150 | 75 | 142.3 | 201 | 12 |
| 2180 | 170 | 47 | 271 | 312 | 274 | 211 | 32.4 | 18357 | 17555 | 115022 | 0 | 0 | 0 | 0 | 271 | 312 | 274 | 211 | 32.4 | 10 | 150 | 77 | 138.0 | 201 | 12 |
| 2190 | 180 | 45 | 276 | 314 | 278 | 215 | 33.5 | 19086 | 18241 | 121290 | 0 | 0 | 0 | 0 | 276 | 314 | 278 | 215 | 33.5 | 10 | 147 | 79 | 134.2 | 201 | 12 |
| 2200 | 190 | 43 | 282 | 316 | 282 | 218 | 34.6 | 19773 | 18907 | 126819 | 0 | 0 | 0 | 0 | 282 | 316 | 282 | 218 | 34.6 | 0 | 0 | 0 | 130.6 | 201 | 12 |

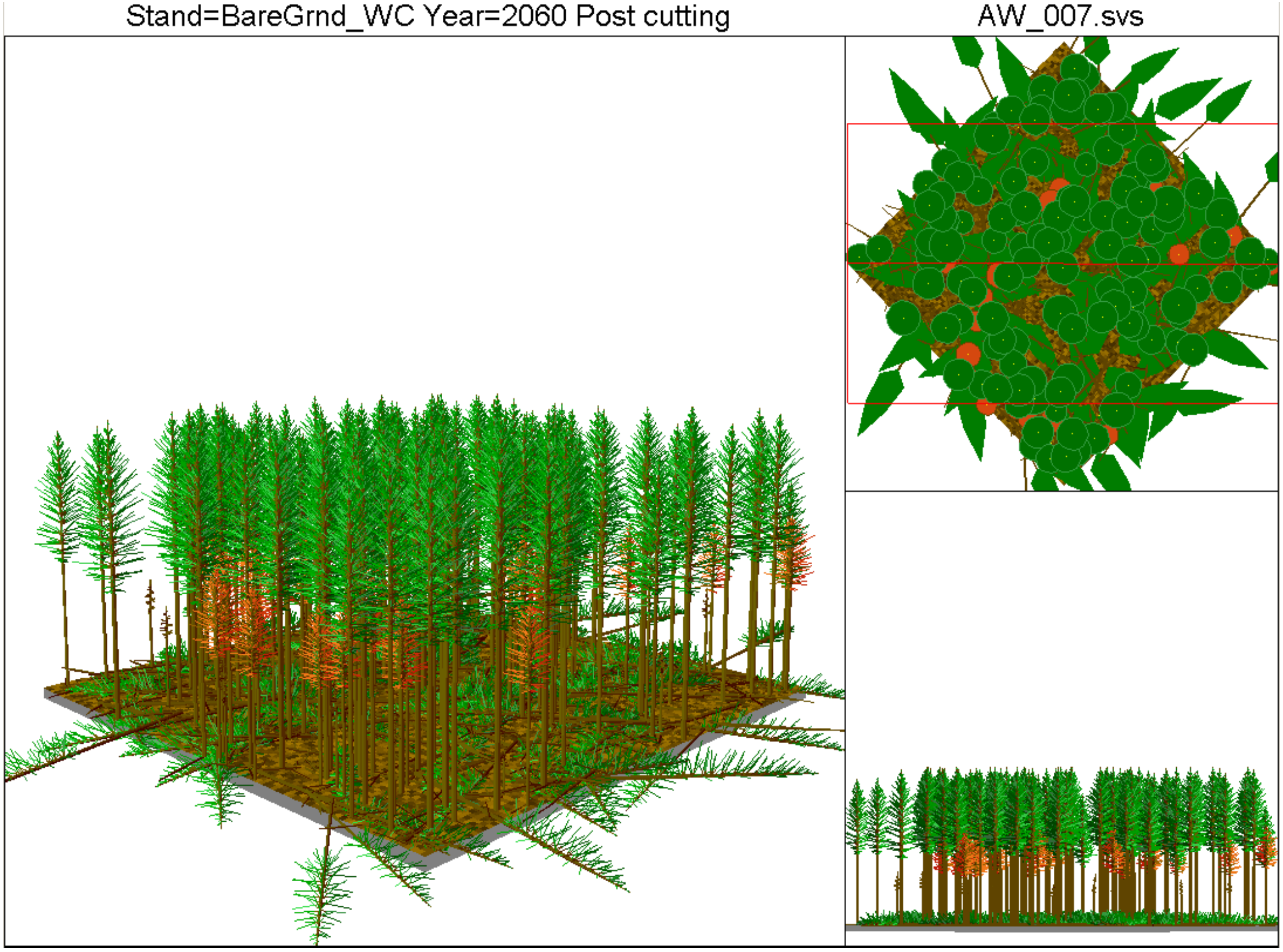
Summary statistics for unmanaged stand

SUMMARY STATISTICS (PER ACRE OR STAND BASED ON TOTAL STAND AREA)

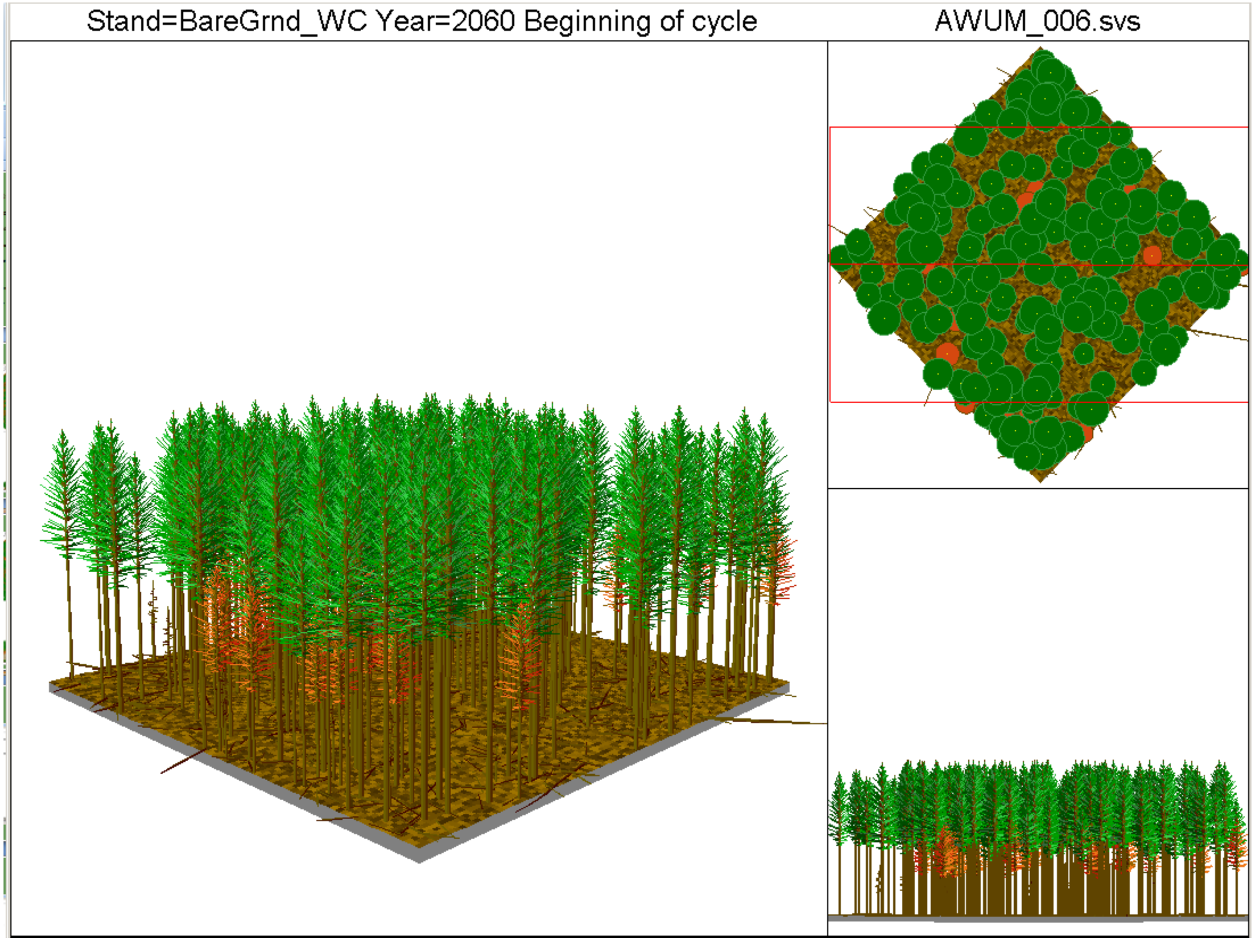
| | | START OF SIMULATION PERIOD | | | | | | | | | REMOVALS | | | | AFTER TREATMENT | | | | | GROWTH THIS PERIOD | | | MAI | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| YEAR | AGE | NO OF TREES | BA | SDI | CCF | TOP HT | QMD | TOTAL CU FT | MERCH CU FT | MERCH BD FT | NO OF TREES | TOTAL CU FT | MERCH CU FT | MERCH BD FT | BA | SDI | CCF | TOP HT | RES QMD | PERIOD YEARS | ACCRE PER | MORT YEAR | MERCH CU FT | FOR TYP | SS ZT |
| 2010 | 0 | 0 | 0 | 0 | 0 | 0 | 0.0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.0 | 10 | 0 | 0 | 0.0 | 999 | 55 |
| 2020 | 10 | 300 | 13 | 39 | 45 | 20 | 2.8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 13 | 39 | 45 | 20 | 2.8 | 10 | 126 | 0 | 0.0 | 201 | 34 |
| 2030 | 20 | 284 | 61 | 134 | 109 | 41 | 6.3 | 1256 | 507 | 2772 | 0 | 0 | 0 | 0 | 61 | 134 | 109 | 41 | 6.3 | 10 | 286 | 8 | 25.4 | 201 | 23 |
| 2040 | 30 | 266 | 145 | 266 | 204 | 63 | 10.0 | 4037 | 3655 | 19506 | 0 | 0 | 0 | 0 | 145 | 266 | 204 | 63 | 10.0 | 10 | 367 | 36 | 121.8 | 201 | 12 |
| 2050 | 40 | 242 | 212 | 354 | 271 | 85 | 12.7 | 7350 | 6967 | 34216 | 0 | 0 | 0 | 0 | 212 | 354 | 271 | 85 | 12.7 | 10 | 360 | 76 | 174.2 | 201 | 12 |
| 2060 | 50 | 217 | 253 | 399 | 308 | 104 | 14.6 | 10187 | 9739 | 49227 | 92 | 2663 | 2487 | 12999 | 182 | 275 | 214 | 104 | 16.3 | 10 | 258 | 54 | 194.8 | 201 | 11 |
| 2070 | 60 | 116 | 209 | 302 | 239 | 121 | 18.2 | 9565 | 9138 | 47330 | 0 | 0 | 0 | 0 | 209 | 302 | 239 | 121 | 18.2 | 10 | 238 | 69 | 193.8 | 201 | 12 |
| 2080 | 70 | 107 | 231 | 322 | 258 | 137 | 19.8 | 11255 | 10786 | 57847 | 0 | 0 | 0 | 0 | 231 | 322 | 258 | 137 | 19.8 | 10 | 233 | 78 | 189.6 | 201 | 12 |
| 2090 | 80 | 100 | 248 | 337 | 272 | 151 | 21.3 | 12802 | 12230 | 67793 | 0 | 0 | 0 | 0 | 248 | 337 | 272 | 151 | 21.3 | 10 | 222 | 87 | 184.0 | 201 | 12 |
| 2100 | 90 | 93 | 262 | 348 | 284 | 163 | 22.8 | 14153 | 13412 | 76215 | 0 | 0 | 0 | 0 | 262 | 348 | 284 | 163 | 22.8 | 10 | 215 | 91 | 176.7 | 201 | 12 |
| 2110 | 100 | 87 | 274 | 355 | 293 | 174 | 24.0 | 15391 | 14633 | 84916 | 0 | 0 | 0 | 0 | 274 | 355 | 293 | 174 | 24.0 | 10 | 201 | 93 | 171.2 | 201 | 12 |
| 2120 | 110 | 81 | 283 | 360 | 299 | 183 | 25.2 | 16465 | 15667 | 93332 | 0 | 0 | 0 | 0 | 283 | 360 | 299 | 183 | 25.2 | 10 | 198 | 99 | 165.0 | 201 | 12 |
| 2130 | 120 | 76 | 291 | 364 | 305 | 190 | 26.4 | 17460 | 16688 | 101247 | 16 | 3583 | 3425 | 20780 | 231 | 289 | 243 | 186 | 26.4 | 10 | 168 | 69 | 159.8 | 201 | 12 |
| 2140 | 130 | 58 | 241 | 295 | 250 | 192 | 27.7 | 14867 | 14156 | 87844 | 0 | 0 | 0 | 0 | 241 | 295 | 250 | 192 | 27.7 | 10 | 166 | 71 | 154.4 | 201 | 12 |
| 2150 | 140 | 55 | 249 | 300 | 257 | 198 | 28.9 | 15815 | 15127 | 94939 | 0 | 0 | 0 | 0 | 249 | 300 | 257 | 198 | 28.9 | 10 | 165 | 74 | 150.3 | 201 | 12 |
| 2160 | 150 | 52 | 257 | 305 | 263 | 203 | 30.1 | 16728 | 15979 | 102020 | 0 | 0 | 0 | 0 | 257 | 305 | 263 | 203 | 30.1 | 10 | 164 | 77 | 145.9 | 201 | 12 |
| 2170 | 160 | 49 | 265 | 309 | 269 | 208 | 31.3 | 17601 | 16851 | 109150 | 0 | 0 | 0 | 0 | 265 | 309 | 269 | 208 | 31.3 | 10 | 150 | 75 | 142.3 | 201 | 12 |
| 2180 | 170 | 47 | 271 | 312 | 274 | 211 | 32.4 | 18357 | 17555 | 115022 | 0 | 0 | 0 | 0 | 271 | 312 | 274 | 211 | 32.4 | 10 | 150 | 77 | 138.0 | 201 | 12 |
| 2190 | 180 | 45 | 276 | 314 | 278 | 215 | 33.5 | 19086 | 18241 | 121290 | 0 | 0 | 0 | 0 | 276 | 314 | 278 | 215 | 33.5 | 10 | 147 | 79 | 134.2 | 201 | 12 |
| 2200 | 190 | 43 | 282 | 316 | 282 | 218 | 34.6 | 19773 | 18907 | 126819 | 0 | 0 | 0 | 0 | 282 | 316 | 282 | 218 | 34.6 | 0 | 0 | 0 | 130.6 | 201 | 12 |



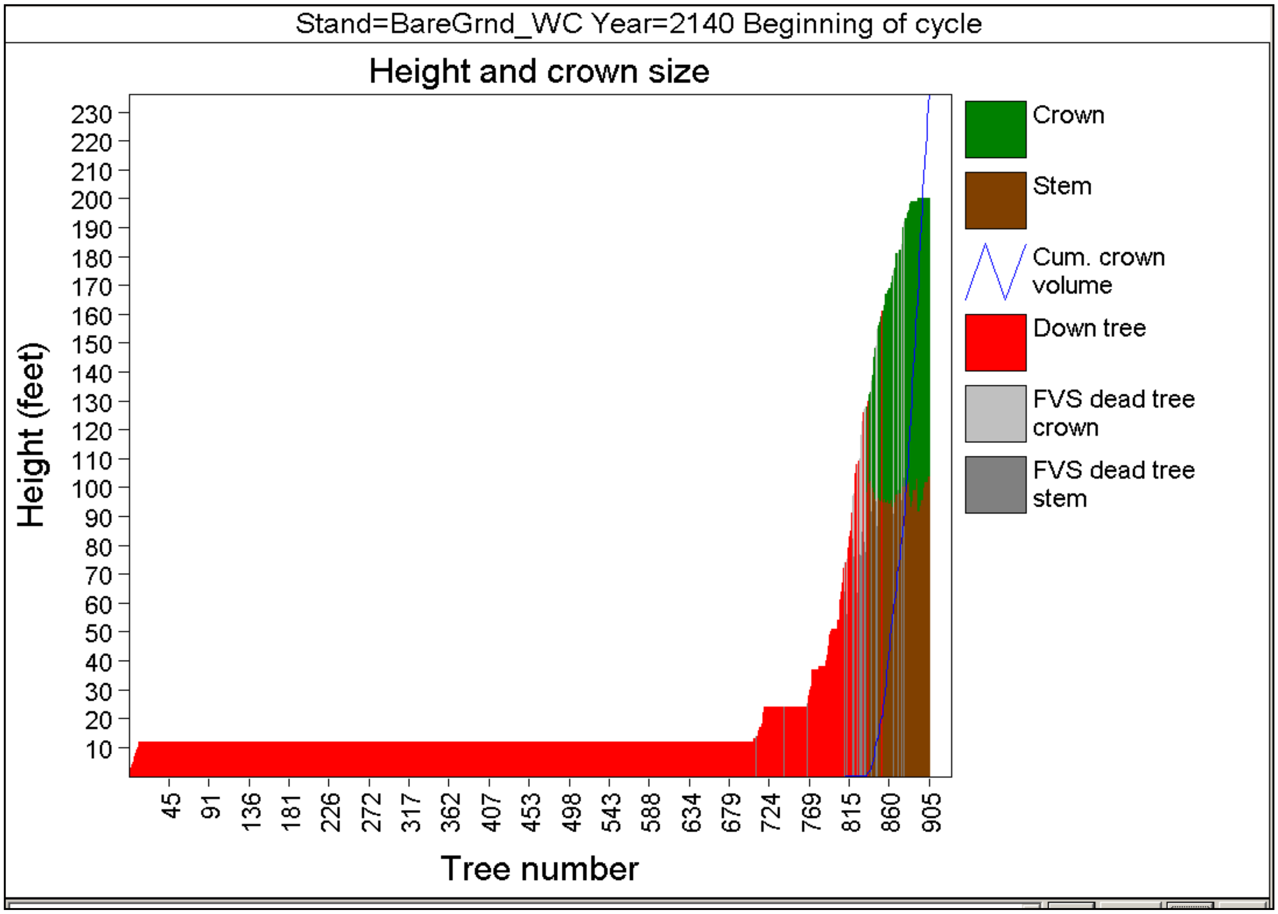

Beginning of cyle.  Forest after 20 years of growth from bare ground planting.



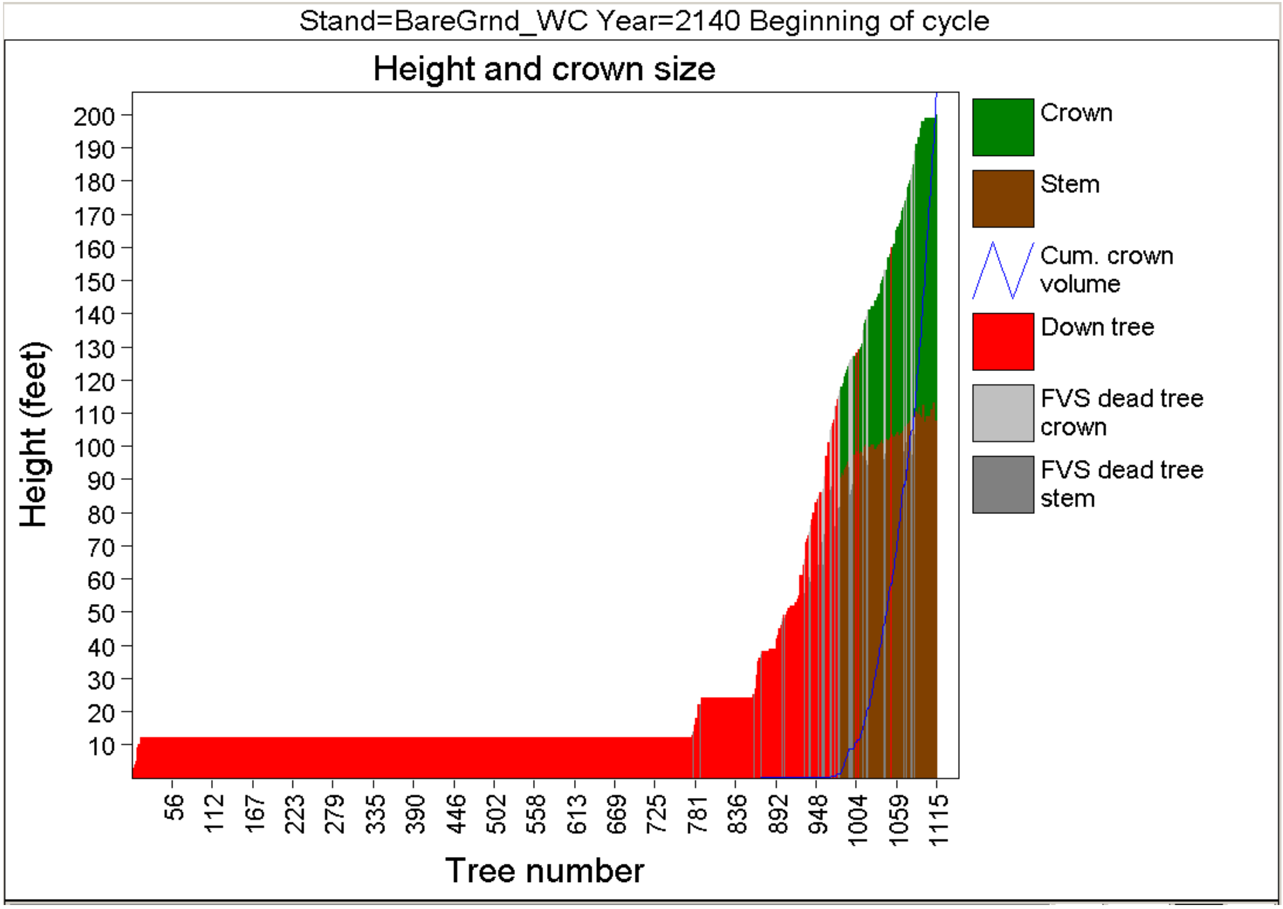

Forest after first thinning, 50 years after planting on bare ground. 92 trees were removed. BA started at 253, was redued to 182. TPA went from 217 to 116. SDI went from 399 to 275.



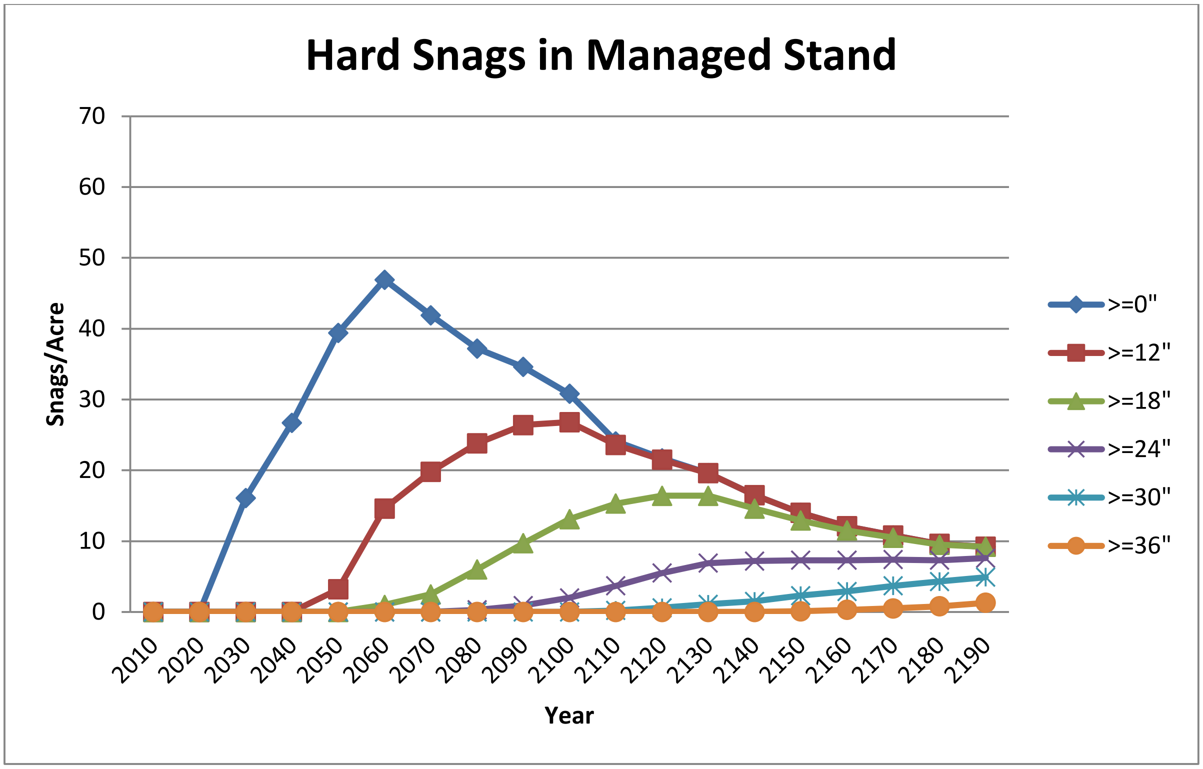

Forest without management after 50 years since planting on bareground. 217 TPA, BA of 253, and a SDI of 399.



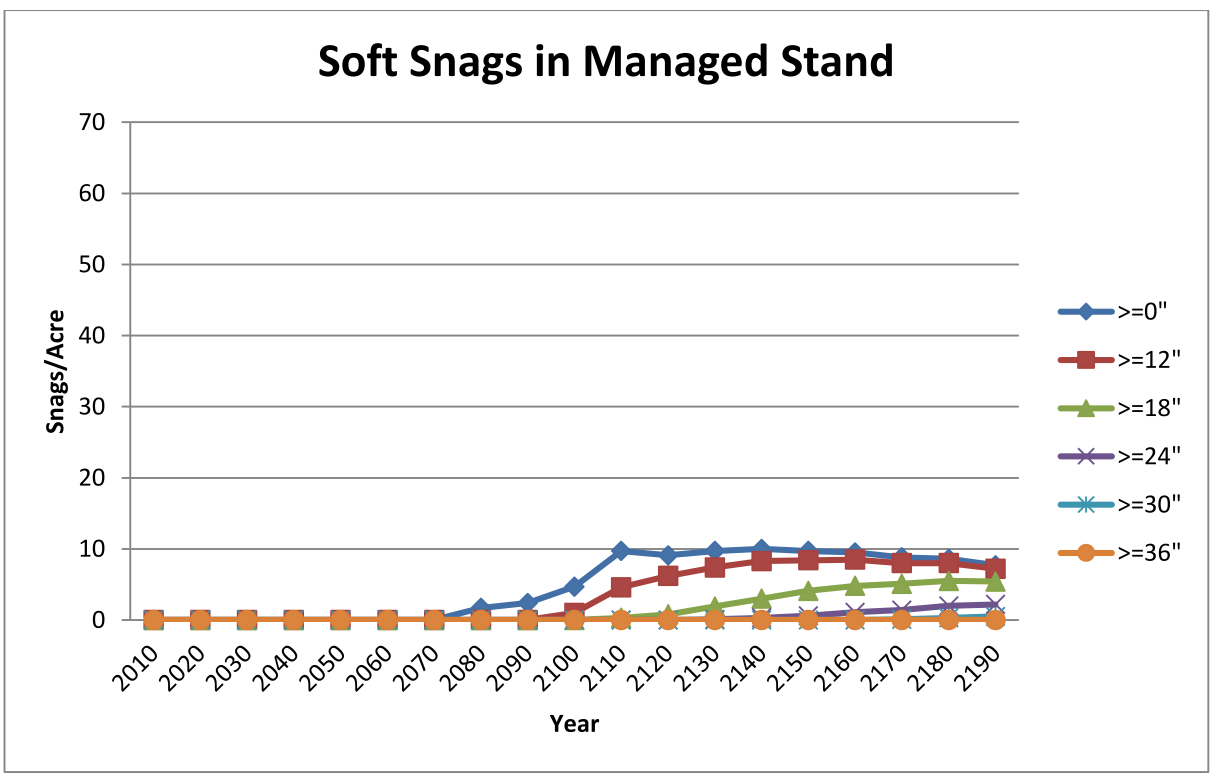

Height to crown ratio in managed stand 140 years after bare ground planting and two thinning's. This diagram demonstrates a low height to crown ratio, which tells us that the trees have adequate space and light resources to grow, increasing their crowns and diameters.



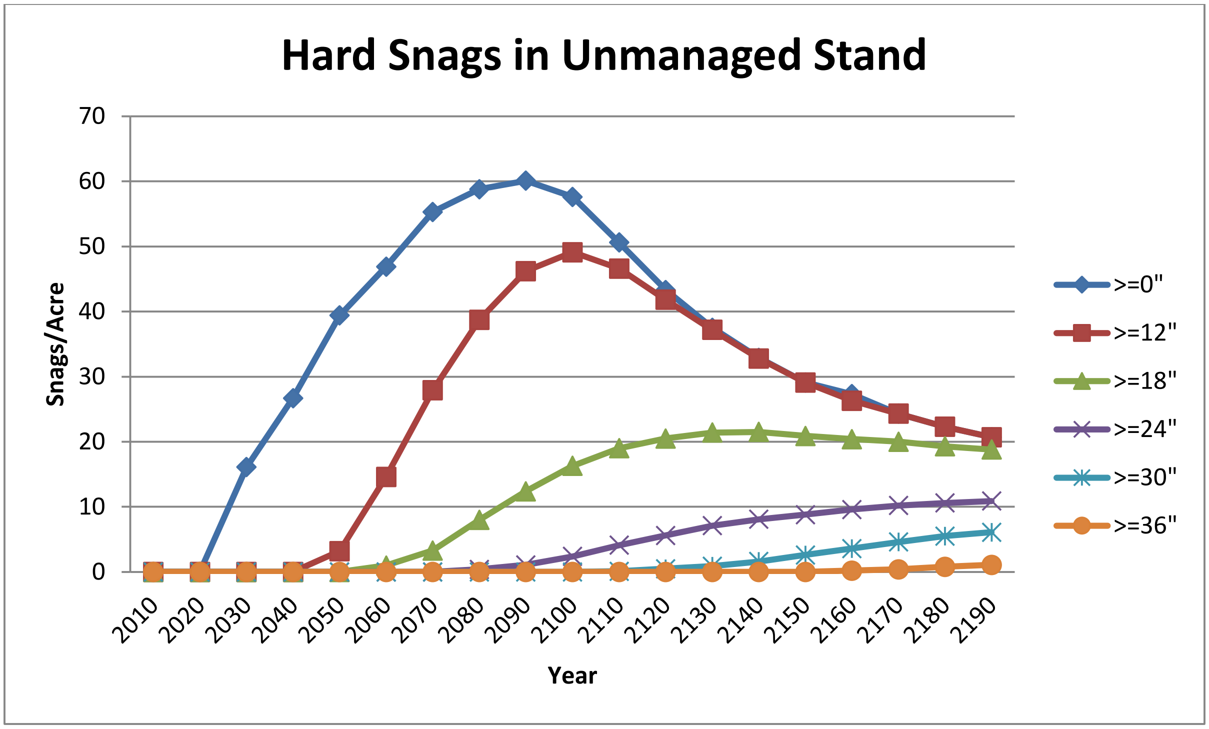

Height to crown ratio in unmanaged stand 130 years after planting on bare ground. This graph demontrates a high height to crown ratio, which is reflected in the small crown volume compared to the height of the trees. This tells us that the trees are overcrowded and competing for light resources.



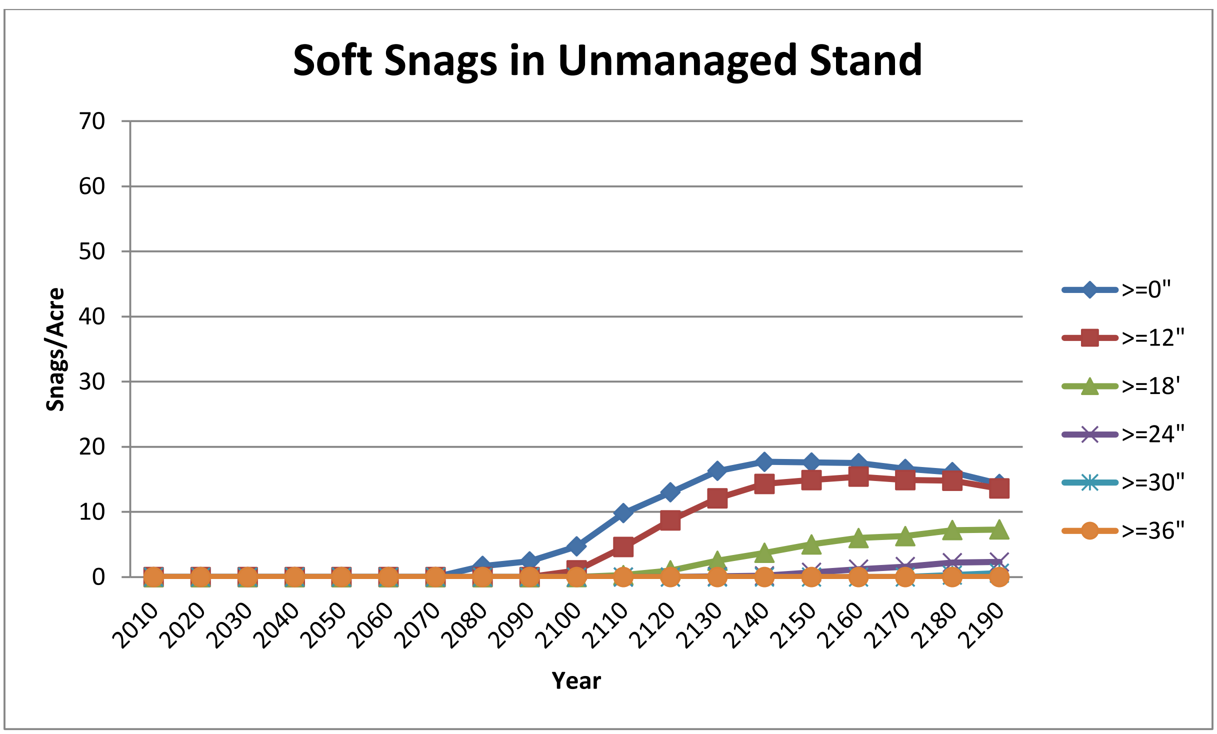

Total number and size of hard snags in managed stand after 180 years.



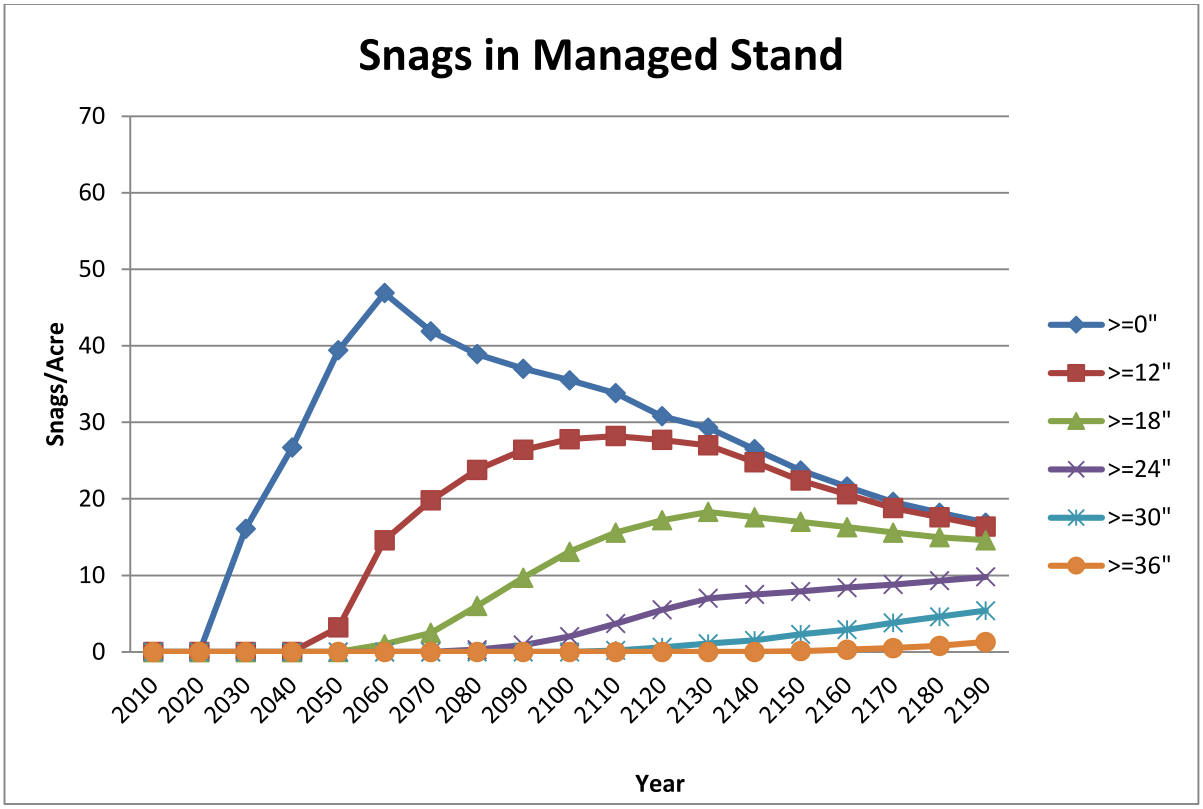

Total number and size of soft snags in managed stand after 180 years.



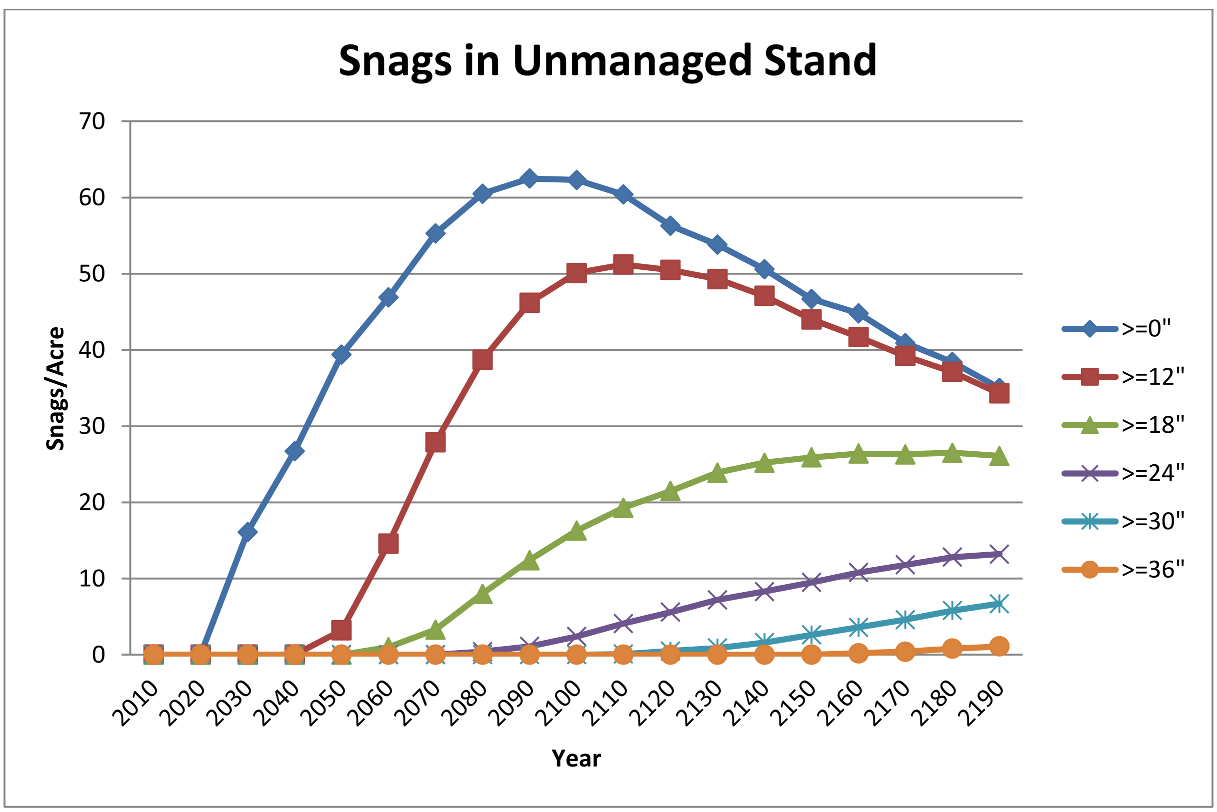
Total number and size of hard snags in unmanaged stand after 180 years.



Total number and size of soft snags in unmanaged stand after 180 years.




Total number and size of all snags in managed stand after 180 years.




Total number and size of all snags in unmanaged stand after 180 years.