forests

Review

Forest Restoration Using Variable Density Thinning: Lessons from Douglas-Fir Stands in Western Oregon

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Abstract: A large research effort was initiated in the 1990s in western United States and Canada to investigate how the development of old-growth structures can be accelerated in young even-aged stands that regenerated following clearcut harvests, while also providing income and ecosystem services. Large-scale experiments were established to compare effects of thinning arrangements (e.g., spatial variability) and residual densities (including leave islands and gaps of various sizes). Treatment effects were context dependent, varying with initial conditions and spatial and temporal scales of measurement. The general trends were highly predictable, but most responses were spatially variable. Thus, accounting for initial conditions at neighborhood scales appears to be critical for efficient restoration. Different components of stand structure and composition responded uniquely to restoration thinnings. Achieving a wide range of structures and composition therefore requires the full suite of silvicultural treatments, from leave islands to variable density thinnings and creation of large gaps. Trade-offs among ecosystem services occurred as result of these contrasting responses, suggesting that foresters set priorities where and when different vegetation structures are most desirable within a stand or landscape. Finally, the results suggested that foresters should develop restoration approaches that include multiple treatments.

Keywords: Douglas-fir; variable density thinning; late successional stand structure; understory vegetation

1. Introduction

At the time of European settlement, vast areas in the western portion of the Pacific Northwest in the United States were covered with old-growth conifer forests, primarily dominated bylong-lived Douglas-fir (*Pseudotsuga menziesii* (Mirb.)) and western hemlock (*Tsuga heterophylla* (Raf.)) capable of attaining massive sizes [1]. Native Americans living in the region used wood for various purposes, such as building harpoons, mats, and baskets, but did not harvest and manufacture products from trees on a large scale. Nevertheless, they managed forests by setting fires, e.g., to encourage food crops such as huckleberry or camas, or to improve traveling and hunting opportunities [2]. Euro-American settlers viewed the vast stands of trees as a hindrance for gardening and farming opportunities, but soon recognized the economic opportunities that these massive trees provided. Starting in the 1820s, encouraged by the large demand during the 1848 gold rush, a lumber industry developed aimed at profiting from an "inexhaustible" amount of timber. Over time, tree harvesting became more efficient and large areas of the landscape were impacted. Douglas-fir and western hemlock often naturally regenerated after early harvests, as planting and seeding was uncommon. Starting in the 1930s, reforestation practices shifted more and more towards re-planting with Douglas-fir in monocultures. Improved planting material (e.g., genetic selection, better seedling stock) and increased use and efficiency of vegetation control practices starting in the 1960s, resulted in the current landscape with millions of hectares in dense, homogenous Douglas-fir plantations. These plantations are typically on relatively easily accessible, high-quality sites, while the scarce remaining old-growth stands are concentrated on public lands, at higher elevations, or areas with limited access [3,4].

Starting in the 1970s, scientists and the general public became concerned about the environmental implications of this large-scale shift in forest conditions (e.g., [5]). These concerns culminated with the listing of the northern spotted owl (*Strix occidentalis caurina* (Merriam)) in 1990, an old-growth obligate species, as threatened under the Endangered Species Act. Concurrently, the focus of federal management agencies began shifting from a dominant emphasis ontimber production towards a broader ecosystem management paradigm that emphasized a balance between economic and ecological goals. The Northwest Forest Plan (NFP), in particular, aimed to resolve conflicts over federal forest management by integrating social, economic, and ecological concerns into a long-term management plan for federal lands [6].

One specific goal of the NFP was reversing the trend of a loss of old-growth habitat. Thus, it included guidance to manage existing Douglas-fir plantations in a way that accelerated the development of old-growth characteristics while also providing income. These characteristics included a range of tree sizes and ages, large snags and downed wood, the development of multiple canopy layers from emergent super-canopy trees with large crowns and thick, furrowed bark to dense regeneration layers, diverse understory plant communities of early- as well as late-seral species, and associated wildlife species. With very limited information on how to do this, researchers set up a number of large-scale management studies; sensu [7] (Figure 1; [8]). After more than 20 years, these studies provided new information that is now starting to be applied on many forest ownerships, especially on public lands (for a more comprehensive listing, see e.g., [9]).

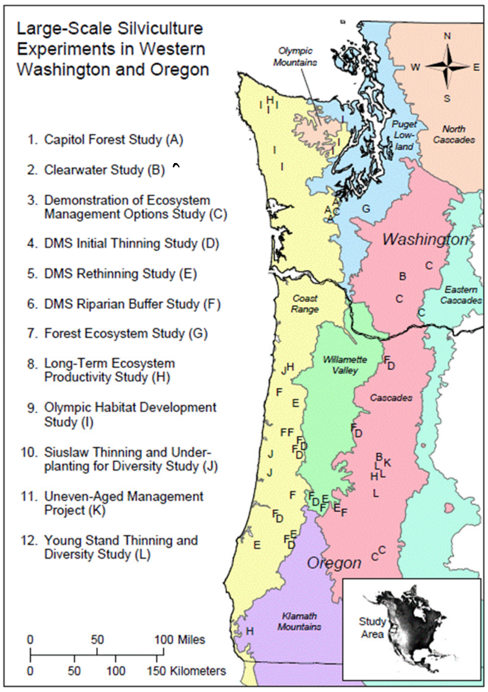

Figure 1. Distribution of locations in large-scale silviculture experiments (LSSEs) in western Oregon and Washington. Copies of a letter indicate multiple installations of a study. Note that each LSSE location shown may include multiple blocks, treatments, and replicates. The LSSE locations are superimposed on Omernik's [10] level III ecoregions. For more details and more information about the studies, see [8] (Figure 1 is from [8]).

Herein, we provide first an overview of two experiments. Then, we discuss what we learned in terms of challenges associated with forest restoration and large-scale silvicultural experiments, including operational issues, issues of scale and treatment choice and implementation. Finally, we provide a general summary of findings and associated management implications. To stay within the scope of a journal article, we focused our discussion on results from the Young Stand Thinning and Diversity Study (YSTDS; [11]) and the Density Management Study (DMS; [12]). We supplement our discussion with information from similar experiments, as necessary. In doing so, we emphasize the lessons when integrating the various results. More in-depth discussions of specific results in a larger scientific and management context, as well as details about specific measurements, results, and assumptions, can be found in the cited articles.

2. Materials and Methods

The YSTDS was installed in four 40- to 60-year-old stands, located on two Ranger Districts of the Willamette National Forest in the western Cascade Range (Figure 2). In contrast, the DMS sites reflected the wider variety of conditions found on Bureau of Land Management lands. Study sites spread across a broad area including the Cascade and Coast Range mountains. Each of the four (YSTDS) and seven (DMS) study sites contained a single replication of the treatment.

Selected stands had been successfully regenerated (either naturally or planted) to Douglas-fir with minor components of other conifers or hardwoods. Some had been precommerically thinned, but none had undergone commercial thinnings, i.e., all stands were in the stem exclusion stage (sensu [13]) at the time of study initiation. The large size of treatment areas (up to 300 ha) allowed operational layout and restoration treatments. The restoration treatments included an untreated control and thinning to operational density levels (e.g., 300 tpha) or lower density levels (e.g., 100 or 200 tpha). Thinnings were from below with added stipulation to maintain minority species (e.g., hardwoods, western redcedar (*Thuja plicata* Donn ex D. Don)). Selected treatments also included interspersed gaps (both studies) and leave islands (DMS only), with the DMS having gaps and leave islands of three different sizes (Figure 3). Treatments were applied in the mid to late 1990s, over a two- to three-year period necessary to accommodate the large scale of the study operations.

The vegetation response of both studies has been measured repeatedly following treatment implementation in subplots that were either randomly (DMS) or regularly spaced (YSTDS). All DMS sites received a second thinning entry twelve years after the initial treatment. Because of the size and anticipated long study period, very detailed information about the study conditions and setup of the YSTDS and the DMS are documented in [11,12], respectively.

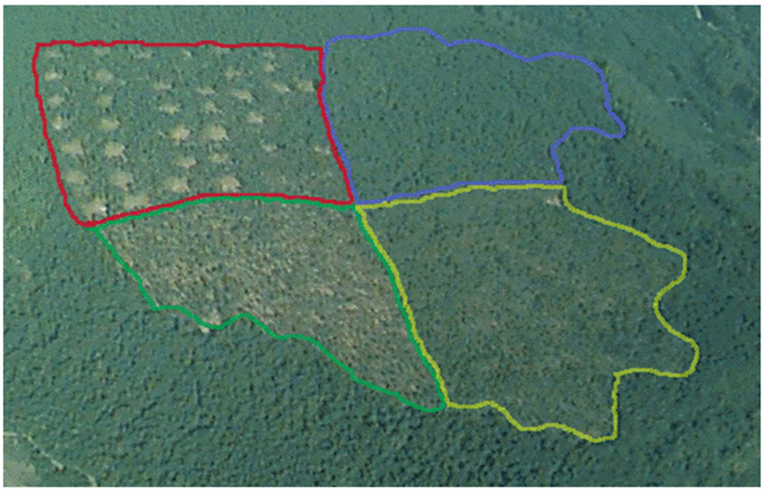
(**a**)

Figure 2. *Cont.*

(**b**)

Figure 2. (**a**) Overview of one replication (Christi Flats) of the Young Stand Thinning and Diversity Study right after study installation. The control (upper right), light thin (lower right), light thin with gaps (upper left), and heavy thin (lower left) are surrounded by a blue, red, light green, and dark green line, respectively. Photocredit United States Department of Agriculture Forest Service; (**b**) Pictures highlighting treatments in the Young Stand Thinning and Diversity Study right after installation. Picture locations match 2a, i.e., the control is depicted in the upper right photo, light thin in the lower right, light thin with gaps in the upper left, and heavy thin in the lower left. Photo credit: United States Department of Agriculture Forest Service.

Figure 3. Overview of one replication of the Density Management Study right after installation. Note the range of densities, various gap and leave island sizes, and range of riparian buffer widths. Photo credit: Bureau of Land Management.

3. Results and Discussion

3.1. Lessons Learned about Restoration Treatments and Large-Scale Experiments

3.1.1. Financial and Operational Feasibility

Overall, our studies showed that restoration treatments in mature, even-aged monoculture stands are technically feasible, i.e., both agencies were able to efficiently design, layout, and apply the treatments with available staffing and technology. Moreover, initial concerns about financial burdens of restoration treatments were unwarranted as the restoration treatments were profitable, including the second entry at all study sites (despite lower prices in 2008 and 2009). Of course, the profitability was a function of the amount, size, and quality of trees harvested. Minimum merchantable diameters on the study sites ranged from 22 to 28 cm. However, the more intensive thinning treatments and gap creation were of specific interest in this context, as both these treatment aspects lead to harvesting of larger, high quality trees [14]. Thus, compared to standard thinning operations, such restoration treatments may be profitable in younger stands and could possible replace precommerical thinning operations. In addition, all study sites had been harvested before and were accessible through an established road system. Thus, only minimal investments in road infrastructure were needed. Finally, slash treatments were only necessary on some sites, this included slash piling followed by burning during the rainy season.

3.1.2. Variability and Multiple Scales

Large-scale, long-term studies provide a unique challenge in terms of variability within and among treatments, leading to special challenges regarding how to analyze ecosystem responses at proper scales. Most of these studies [8] were established to compare the effects of a limited set of treatments, i.e., replicated treatments designed to be compared with an analysis of variance. However, the high variability inherent in large treatment units (e.g., [15]) limits the statistical power of traditional comparisons with ANOVA. Even during setup, the assumption that differences in initial conditions are not sufficiently large to influence vegetation responses is harder to justify when treatments are applied to larger areas, e.g., 40 hectares where inherent variability in e.g., topography and associated factors, cannot be avoided. Furthermore, the larger treatment areas are harder to implement and costly to install, which often results in a limited (minimum) number of replications. Even with the use of co-variates or before-after control-impact approaches to deal with pre-treatment variation, statistical tests used to compare treatment means are not very strong (high Type II error) due to the limited number of replications. Often, such statistical comparisons are accompanied by statements about the high variability within treatments (e.g., [16]). Instead, we found that newer statistical procedures, such as mixed effects, hierarchical models and multi-step modeling processes, allowed us to accommodate and take advantage of more information in the nested data structure, e.g., trees nested in plots, treatments and sites. Being able to utilize all spatial scales in a nested sampling design allowed us to overcome some of the statistical challenges inherent in the study setup (e.g., [17]) and better understand the scale-dependency of treatment responses (e.g., [18]). Finally, accounting for spatial autocorrelation can be helpful in addressing high within-treatment variability (e.g., [19]).

The large spatial scale of the treatments allowed insights into the variability itself, for example as influenced by initial conditions [15]. Harvesting operations can be responsible for high variability in residual stand density or structure. For example, skid trails or logging corridors resulted in stand densities (at small-scale neighborhood conditions) that were well below the prescribed targets (e.g., see [17]). Geospatial referencing of sample plots in large treatment areas provided opportunities to quantify the influence of potential radiation or heat loads, as influenced by slope and aspect on vegetation responses [18,19]. Moreover, large treatment areas allowed investigations of phenomena that act at broader spatial scales [20]. For example, treatment areas that cover multiple home ranges of songbirds enable investigations about the impacts of restoration treatments on songbird populations directly [21] and which habitat components influence such responses [22]. Having repeated measurements permitted analysis of consistency of songbird responses over time (compared to vegetation responses). Results suggested high temporal variability, which requires multiple sampling years to fully understand treatment effects [22]. Finally, the setup with a single replication on a study site and study sites across a large climate gradient (e.g., DMS) allowed quantification of the influence of climate conditions on treatment responses (e.g., [19,23]).

At the same time, many of the processes that are manipulated with restoration treatments act at small spatial scales. These are not represented in assessments of treatment means, but a fine-grained nested sampling design allowed investigation of some of these aspects as well, e.g., germination and plant neighborhood interactions [18,19]. These last two papers provide examples of how data from such studies can be used to investigate the influence of factors acting at a variety of spatial scales.

3.1.3. Treatment Choices and Definitions

A major issue in any experiment is the choice of treatments. While the first entry into homogenous stands is typically fairly straightforward, the decision if and when to assign follow-up (second or third) treatments highlights the special challenges of long-term experiments. Given that the first treatments are designed to lead to varying or even contrasting responses, the treatment areas likely will not be in sync in regards to timing and intensity of follow-up treatments. However, applying follow-up treatments at different times leads to further complications when statistically evaluating ecosystem responses. For example, "unacceptable" seedling survival [24] has led researchers to implement a second entry for a subset, but not all treatments (pers. observation). We found it more useful when we described treatments as a specific management or restoration strategy, which is reflected in a set of activities. For the DMS and YSTDS, this meant viewing the studies as comparing aggressive versus conservative restoration strategies. Examples of aggressive restoration strategies could be a single thinning treatment sufficiently intense to achieve the final desired residual density, e.g., 100 tpha. In contrast, a conservative restoration strategy would be composed of two or three treatments that reduce overstory densities gradually over time, the first of which is thinning to 300 tpha. Alternatively, assessments of aggressive versus conservative restoration strategies could include quantifying responses to a strategy that includes aggressive weed control via herbicides and planting versus relying solely on manual vegetation control and natural regeneration. Other examples of comparison of restoration strategies include evaluating the impact of spatial variability by comparing treatments that apply clumped versus regular spaced residual trees. Focusing on comprehensive strategies rather than individual treatments allows for the timing and intensity of any treatment to be optimized for the specific set of conditions in each treatment area, and results may ultimately be more relevant to larger audiences. As a tradeoff, such a research approach will provide less information about direct comparisons among specific treatments.

3.1.4. Treatment Implementation

The study setup and design was developed in consultation with forest managers to ensure feasibility and efficiency in implementation. Thus, treatments were designed to fit within the layout and marking procedures of the agencies, with obvious deviations. For example, to efficiently implement and document spatially variable treatments, marking Global Positioning System locations became very important e.g., to mark gaps and leave islands. Additionally, restoration efforts are more cost efficient if harvesting operations can be accommodated in the treatments [25]; e.g., on several DMS sites the gap locations were selected to allow for efficient cable logging. Even though, implementation quality, e.g., as quantified by damage to residual trees, varied by site and operator, with higher damage on slopes that required cable logging operations. Other contract specifications helped reduce logging damage, e.g., restricting the maximum log length for skidding.

Especially challenging was the implementation of non-traditional management practices, such as accelerating the provision of downed wood. To maintain operational efficiency when marking other treatment aspects, such as trees to be felled for downed wood, we calculated the productivity of the tree markers (hectares per hour). Rather than having tree markers consider these aspects throughout the day, we encouraged markers to select the downed wood trees every few hours and mark more trees around the spot where they were currently working. For example, with goals to provide 10 trees per hectare as downed wood and markers covering 0.5 hectare per hour, markers were instructed to select 20 trees twice on a typical 8-hour work day, once in the morning and once in the afternoon. This approach had the additional advantage that it did not result in an even distribution of downed wood at very low densities. Instead, this procedure resulted in a more natural heterogeneous spatial pattern [26], including patches with higher concentrations and areas with no added downed wood.

3.2. *Vegetation Responses*

Figure 4 presents a simplified, visual summary of the vegetation responses that are discussed in more detail below. We cannot statistically compare these trends, because they come from different study setups and without information about values in old-growth stands, we cannot use a common scale on the y-axis. Thus, the figure can only be viewed as a conceptual summary or working hypothesis that was derived from our results. It suggests the direction and relative speed in terms of development of various vegetation components after restoration thinnings.

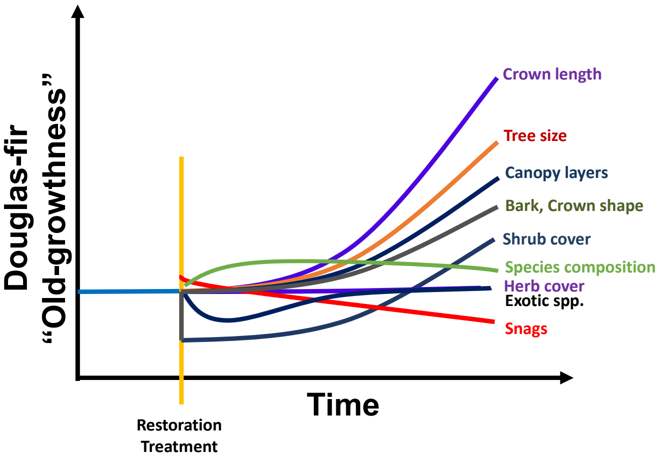

Figure 4. Schematic simplified hypothesis based on results about how different stand structural components responded to restoration treatments. Trends are in relative terms to allow an integrative overview. Douglas-fir "old-growthness" is a reflection of how closely conditions are to old-growth stands. Axis is scaled approximately in perspective to pre-treatment and typical old-growth conditions.

3.2.1. Tree and Stand Growth Responses

Restoration treatments that reduce tree densities increase available resources for residual trees [27,28]. As expected, the lower post-treatment densities resulted in increased average tree diameter growth [15,29]. Closer inspection showed that the smaller trees had the highest diameter growth increase. In contrast, diameter growth of larger trees was still higher than those of smaller trees, but increased less or not at all after thinning, unless densities surrounding the trees were very open [15,29]. The spatial variability created, e.g., by including gaps, was also reflected in diameter growth responses, with trees adjacent to gaps showing higher increases in growth [15,30]. Thus, our results suggest that typical thinning treatments are not efficient at achieving tree sizes typically found in old-growth stands (e.g., [31]). Instead, variable thinning treatments that include extremely low density areas and gaps will lead to a higher diversity of tree sizes in the future and specifically encourages rapid development of large trees.

Restoration thinnings reduced the growing stock, which in the short term may result in a loss of growth potential. This may not be much of a concern for coastal Douglas-fir, as it has fairly constant stand growth rates across a wide range of stand densities, i.e., growth–growing stock relationship [32]. The initial thinning treatments resulted in non-significant losses in terms of stand growth [14,15], e.g., two treatments in the YSTDS had 86% to 88% of basal area growth of the control stands). However, these trends may not apply to studies with a wider range of treatments (e.g., [33]) or other tree species with different growth–growing stock relationships. Such low reductions were partially due to the low thinning, primarily removing smaller, slower growing trees [15]. Obviously, density reductions to extremely low values (e.g., <100 tpha) and gaps will lead to lower stand level growth rates of the overstory trees, even for Douglas-fir. However, comprehensively comparing stand level growth rates in such settings also requires accounting for benefits of seedling establishment in areas with open overstory conditions and for the growth of advanced or newly established regeneration [34].

Trends in carbon storage and sequestration reflected the patterns and processes described for stand growth. Obviously, carbon storage in the forest was lower in treatments with lower residual tree densities. However, carbon sequestration did not differ significantly among treatments with high versus low residual densities, suggesting that increased growth rates of residual trees in low density stands compensated for reductions in growing stock [35]. Effects of restoration treatments on carbon storage appear to be initially related to effects on stores in the live overstory, and over time deficits in detrital C will become more important as legacy wood decays in the absence of augmentation through natural mortality (see below; [35]).

3.2.2. Tree Mortality

Snags and downed wood are important wildlife habitat components and are considered to be lacking in many managed stands. Natural mortality in untreated dense stands was dominated by density dependent mortality and mostly less vigorous, i.e., smaller trees died. Small snags (e.g., <20 cm diameter at 1.37 m height) have limited value for wildlife species. They are too small for many cavity nesters, tend to fall over quickly, and do not create large pieces of downed wood. In contrast, mortality of large trees is typically more stochastic, occurring at irregular intervals and spacings [26]. As expected, restoration treatments that removed most smaller trees led to a reduction of density dependent mortality [15]. Thus, after variable density thinning, snag and downed wood recruitment is reduced, at least in the short term. At the same time, the lower density of residual trees implies that the potential for future snag and downed wood recruitment is also lower. This could be especially problematic in regions that are already considered deficient in these structural components, such as those found in the study region. This problem can be overcome or mediated by designating untreated leave islands or skips in treatments. However, as indicated above, these areas left at higher densities and associated high competition levels exhibited mostly competition related mortality of the smaller trees, i.e., most new snags were from the smaller end of the diameter distributions [15,29]. As an alternative, we modified our restoration treatments to accelerate snag provision and downed wood by intentionally creating snags [36] and downed wood. For example, the DMS study plan suggests creating snags if natural snag recruitment is not considered satisfactory (12 snags/ha) within a decade after the second set of restoration treatments. Similarly, as part of the restoration treatments, we prescribed cutting a few of the larger trees and left them as downed wood.

3.2.3. Canopy and Crown Size and Structure

Overstory canopy cover is an important component of wildlife habitat and it influences tree and stand growth, as well as microclimate and resources conditions in understories [37]. Restoration goals in such settings often include opening canopies sufficiently to provide a niche for regenerating tree seedlings and to maintain the full suite of early and late-seral plant species and associated habitats [38]. Although restoration treatments applied in the YSTDS and DMS resulted in large reduction e.g., from around 80% in controls down to 40% canopy cover [29,39,40], the response was transient and the remaining trees responded to increased space and resources with crown expansion. The associated recovery rate of approximately 1.5% to 2% per year indicated that the canopy closes fairly quickly and benefits of canopy openings will not last. Consequently, our results suggest that for dynamic species, such as Douglas-fir, heavy thinnings to extremely low densities or repeated entries are necessary to maintain open canopy conditions over time [14].

Old-growth trees with large branches and crowns provide nesting habitat for spotted owls and marbled murrelets. At the time of restoration treatments, the tree and crown shapes had been determined by decades of growth in high density conditions. As suggested by Wilson and Oliver [41], these trends are not quickly reversed. However, the variable density thinning does suspend the process of crown lift and lead to the retention of lower crowns and live crown ratios [29,42]. The impact of additional growing space on increasing branch sizes has been well documented [43]. Other changes in crown morphology are slower to develop and/or harder to detect. Yet, after about two decades, compared to trees in which restoration treatments led to regular spacing, trees growing adjacent to gaps showed an asymmetric crown development in the lower crowns [44]. The larger crowns on the side facing the gaps raise concern about future wood quality, especially when younger stands are treated, where the crown lift was not sufficient to provide clear logs at the time of restoration treatments.

3.2.4. Bark Characteristics

The bark of Douglas-fir provides important habitat for a variety of insects, spiders, and bats [45]. Several songbird species have specialized to forage on the bark of Douglas-fir and other species. Large fissures typically found in old-growth trees are especially important microhabitat characteristics lacking in stands solely made up of smaller trees. Our results show that thinning does not directly accelerate the development of bark with deep fissures per se. Instead, these characteristics are strongly related to trunk size [46,47]. Thus, restoration treatments that accelerate tree diameter growth will likely hasten the development of large trees with "older" bark characteristics.

3.2.5. Tree Regeneration (Natural)

Old-growth forests in the region are typically spatially variable [48] and include areas with smaller trees, including seedlings and saplings [49]. By encouraging natural tree regeneration of a variety of species, variable density thinning can encourage the development of multiple canopy layers, a typical characteristic of old-growth forests [16,50]. The variability in stand conditions prior to restoration treatments was reflected in a high variability in the spatial distribution of advanced regeneration. The species composition and densities of the cohorts that initiated after the restoration treatments were highly variable at small spatial scales [51]. However, the densities of tree regeneration did not differ sufficiently to result in statistically significant differences between treatment averages. Instead, densities in all thinning treatments differed from the controls [16,18], suggesting that the disturbance associated with any thinning was sufficient to encourage seedling establishment. In contrast, where advanced regeneration was released by restoration treatments, the thinning intensity mattered, i.e., more saplings were present in thinned areas with more open conditions than in thinned areas with denser canopy cover [18]. Thus, even though any canopy opening appeared to benefit advanced regeneration, heavier thinnings may be required for recruitment into taller sapling and overstory classes. While overstory harvesting damages advanced regeneration [52], these negative effects were more than offset by the benefit of higher resource levels in more open areas, at least as quantified by sapling densities [18]. These results may be driven by better growth of seedlings and saplings at lower overstory densities, especially of shade intolerant species [53]. Thus, initial conditions, especially the presence of advanced regeneration, the residual densities, and the timing and intensity of future entries are essential components for planning restoration treatments that allow both establishment and continued growth of tree regeneration. These findings highlight that restoration efforts will be more efficient if managers can take advantage of the variability in initial conditions, e.g., by harvesting layouts and designing treatments that protect and release advanced regeneration, respectively. However, such opportunities are limited to forest types and tree species where wood quality concerns are not considered sufficient to require removal of all advanced regeneration when opening up the canopy.

3.2.6. Understory Vegetation

Although forest management practices typically focus more on overstory trees and tree regeneration, the majority of plant species are found in understories. Understory layers are a prominent feature in spatially variable old growth forests and provide wildlife habitat, contribute to nutrient cycling and control forest regeneration processes (e.g., [18]). More recent studies have highlighted the role of early seral stages in these forests, including for community composition [38] and for ecosystem dynamics [54]. In contrast, in stands with homogenous, dense overstories (in the stem exclusion phase (sensu [13]) there was a limited amount of early or late seral understory vegetation present before the restoration treatments. This is likely due to combination of weed control practices during stand establishment and limited resources as the overstory closes in [55]. Overall, restoration treatments led to increases in understory vegetation diversity, mostly through establishment of early seral species [56], particularly in larger gaps [57]. The small-scale vegetation patterns found in the gaps on the study sites differed from patterns found in natural gaps in other forest types. Fahey and Puettmann [58] suggested that this was due to a combination of the damage to the understory vegetation and exposure of mineral soil associated with the harvesting procedures and the increased resource level available for the understory layer. The former likely facilitated germination and early establishment, while the latter allowed growth and survival of early seral species. After restoration treatments, the cover of the early successional species first stabilized and then showed a decline within a decade [56,59]. Clearly, the time window for these species is short and additional disturbances and/or treatments are required to maintain these species over longer time periods in a stand. In contrast, late successional species seem to be less influenced by the restoration treatments, with notable exceptions of a few saprophytic species that declined with thinning [60].

Introduced (non-native) species followed a similar trend as described for early seral species. Cover was very low pre-treatment, likely due to the same factors that limited understory vegetation in general. It increased initially, but stayed at very low levels; typically less than 2 percent [59,60]. A notable exception was one site with an adjacent high density population of exotic scotch broom (*Cytisus scoparius* (L.) Link). In this treatment, cover of exotic species increased to 5%. However, even on this site, exotic species cover declined within a decade. Thus, restoration treatments appear not to initiate a major problem with exotic species invasions, especially with proper hygiene, such as cleaning of transportation and logging equipment.

Shrubs are an important structural component for soil stability and nutrient cycling after disturbances. They are crucial habitat elements as a food source for many vertebrate species [17] and as a food and structural element for invertebrate species' (e.g., spiders, insects) habitat that form the base of a food web that supports songbird species [22] and flying squirrels [61]. A meta-analysis of three large-scale studies (including the DMS and YSTDS) showed that initial conditions of the shrub layer are a critical factor for determining their responses to restoration treatments [62]. It also showed that despite their sizes, each study had a limited set of shrub conditions that prevented researchers from detecting this pattern. Across the three studies, the restoration treatments resulted in a significant reduction in areas with already existing high shrub cover, likely due to the physical damage during harvesting operations [60]. The shrub layer recovered slowly and barely reached control levels within a decade on these sites [14]. In contrast, in areas with little understory vegetation, the restoration treatment shrub cover increased very quickly after restoration treatments. In contrast, the herbaceous layer generally was unaffected or responded positively due to increases in early seral species [63]. Mosses were negatively affected by heavy thinning but showed little response to lighter thinnings [56].

4. Conclusions

The results and discussions above highlight the wide range of vegetation responses to restoration treatments, both in terms of direction and development speed. Despite finding these trends, our experience showed that the only general rule that applies in such restoration settings is that simple, general rules do not exist. First, the small-scale spatial variability in pre-treatment vegetation and environmental conditions is likely to result in highly variable outcomes, even if restoration treatments are applied homogenously. Restoration efforts may therefore be more effective if they take advantage of this spatial variability by designing treatments that vary as a function of the range of initial conditions encountered. For example, thinning prescriptions could target a range of residual densities, whereby the specific density choice in any location is a function of the presence or absence of advanced regeneration. Other examples include felling and skidding patterns that protect areas with advanced regeneration or with an existing shrub layer. Second, even when starting with homogenous conditions, the various structural components and associated ecosystem processes respond at different time scales, and sometimes even in contrasting directions (Figure 4). Thus, foresters may be better off viewing restoration objectives not as a single structural goal, such as restoring "old-growth" or late successional habitat. Instead, our results suggest that a better approach is to view restoration goals as a collection of interacting, yet individual, structural features and processes. Such an approach would have to include setting priorities about which features and processes are more important in the short versus long term. Treatments prescription and expectations could then be managed to account for different response patterns, trade-offs, and synergies (as highlighted in Figure 4, see also [64]). As an alternative to compromising when achieving multiple structural and compositional goals simultaneously, foresters may explore options to spatially separate specific restoration goals within stands and across the landscape. This separation of goals, in combination with the utilization of the variability in small-scale initial conditions and other logistic aspects, such as access or markets, would greatly enhance the efficiency of restoration efforts.

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Conflicts of Interest: The authors declare no conflict of interest.

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