**Forest Stand Density: Integration of Trees, Forage (Silvopasture), and Habitat Management**

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**Abstract**

***Context*.** Silvopastoral agroforestry systems seek to integrate the production of timber with livestock grazing and food production. Pre-commercial thinning and nitrogen fertilization are two common practices in such systems which seek to enhance tree production but whose effect on forage production and ecosystem biodiversity are still being studied.

***Aims*.** To examine the effects of pre-commercial thinning and nitrogen fertilization on the ability to produce grazing forage (species abundance) and on the ecosystem’s biodiversity (species richness, species diversity, structural richness, structural diversity).

***Methods*.** Replicate study areas were established in Kelowna, Summerland and the Cariboo. Each study area had 9 units with varying stand densities (250, 500, 1000 and 2000 stems/ha) as well as one fertilized and unfertilized unit for each density. Vegetation samples were taken across transects to estimate volume crown index and species richness.

***Key Results.*** Species richness, species abundance and structural richness were not strongly influenced by forest stand density. Species diversity was higher at higher stem densities and structural diversity was higher at lower stem densities. Species richness, structural richness and structural diversity were not strongly influenced by fertilization. Species abundance increased with fertilization, whereas species diversity decreased with fertilization.

***Conclusions*.** Pre-commercial thinning and fertilization are beneficial for increased productivity of timber and grazing forage of silvopastoral systems, but have mixed effects on the ecosystem’s biodiversity.

***Implications.*** Managers of silvopastoral systems should maintain intermediate levels of both stand densities and nitrogen fertilization in order to maintain and enhance the economic and environmental benefits of these systems.

**Introduction**

Forest plantations of food or timber products rely on overstory productivity for their economic viability. However, the understory vegetation of a plantation might prove valuable if it can be integrated with livestock that will graze upon it (Crouch 1986). This is the basis of silvopastoral systems, where tree and forage production are integrated in a single piece of land. Not only is this system economically beneficial for landholders because of product diversification, but it has been shown that livestock grazing might additionally lead to improved tree growth and reduction in growing costs (Knowles 1991). Under proper management, trees can also provide the necessary microclimatic and nutrient conditions for abundant grazing forage.

These systems, however, have rarely been subject to conventional agricultural inputs since their cost has been considered too high for the consequent low plant response. This has led developed countries to start looking into the potential of silvopastoral systems as modified landscapes capable of harboring substantial biodiversity (Manning et al. 2009). Due to the significant growth, both in size and economic importance, of forest plantations throughout the world (Sedjo 1999) it is important to examine the various ways of designing a silvopasture system capable of effectively providing forage for cattle, timber for harvest and habitat for wildlife species.

Silvopastoral systems rely on the concept of resource sharing-- a spatial coordination of resource pooling between the different components competing for nutrients, light and moisture (Buck 1986). Normally, forest openings due to harvesting or natural disturbances such as forest fires or pests allow light into the understory and lead to the growth of early successional vegetation (also called a ‘transitory rangeland’, where cattle can graze while the forest regenerates). The different stages of succession found in this rangelands are an important source of species biodiversity. But increase in management of silvopastoral systems has led to the development of different techniques in order to increase forage yields as well as the quality and the time that this forage is available. One type of techniques is directed towards managing the natural momentum of the system to move towards a closed canopy, maintaining low densities and therefore decreasing competition for resources. Pre-commercial thinning, the decrease in forest stand density in order to concentrate superior growth on a predetermine number of stems, is an example of these (Cole & Koch 1996). The other type of techniques is directed towards increasing nutrient content, therefore increasing the system’s resource pool. Nutrient fertilization has often been used for this purpose (Abrams 1983; Lindgren et al. 2007; VanderSchaaf et al. 2000).

Studies on the effects of these techniques on pine forests have been performed for various species such as jack pine (Abrams 1983) or douglas fir (He and Barclay 2000; Sharrow 1991; Thysell 2001) and Lodgepole pine (Cole & Koch 1996; Johnstone 1985; Lindgren et al. 2007; Sullivan et al. 2005-2007; Yang 1998). In the Pacific Northwest, Lodgepole pine (*Pinus Contorta)* appears to have the greatest response to both thinning and fertilization (Lindgren et al. 2007; Sullivan et al. 2005-2007).

This report seeks to determine the influence of lodgepole pine tree density and nitrogen fertilization applications on: (1) the abundance of understory vegetation as a measure of forage production for livestock grazing, (2) species diversity and structural diversity of the understory vegetation as a measure of the forest’s ability to provide habitat for wildlife species.

**Method**

Samples were taken from three study areas which were used as regional replicates for data collection. One was 37 km northwest of Kelowna, BC (Montane Spruce biogeoclimatic subzone), another was near Summerland in the Okanagan Valley (Montane Spruce biogeoclimatic subzone) and another one in the Cariboo, 75 km Northwest of Williams Lake, BC (sub-boreal Spruce biogeoclimatic subzone). All of the forest areas were clearcut harvested in the late 1970s, have sandy loam soils and regenerated naturally (although in the Cariboo with some aid from tree-planting) to forests where lodgepole pine is the dominant tree species.

Within each study area, 9 experimental units were established, each one corresponding to different amounts of treatment. One unit was left unthinned, two were thinned to a 250 stems/ha density, two to 500 stems/ha, two to 1,000 stems/ha and two to 2,000 stems/ha. One of the two units corresponding to each density was subject to the application of nitrogen fertilizer at an operational scale through the use of a helicopter flying above the designated area. Due to the costs of fertilizer application, no unthinned unit was fertilized.

Within each unit, vegetation sampling was performed through a 25-m transect with different subplots for trees (5x5m), shrubs (3x3m) and herbs (1x1m) (Figure 1).



Figure 1: Transect Layout for Vegetation Sampling

*Species Richness*

Within each subplot, the number of visible species was recorded and classified as shrubs, herbs or trees.

*Species Abundance*

For each species, a visual estimate of their percentage cover was estimated. This estimate was established to be the area that the shade of the plant would amount to if a source of light was placed directly above it. Herb, shrub and tree species were divided into the following height classes: 0-0.25, 0.25-0.50, 0.50-1.0, 1.0-2.0, 2.0-3.0, and 3.0-5.0 m. The measures of percentage cover and their height classes were used to calculate the the volume of a cylindroid representing the space occupied by the plant in the community, also referred to as crown volume index. These volumes were averaged for each species within each plot size and then converted to a 0.01-ha base.

*Species Diversity*

The crown volume index and the number of species recorder were used to calculate two different diversity index: Simpson’s Diversity Index and the Shanon-Weiner Diversity Index.

Simpson’s Index shows diversity as inversely related to the probability that two individuals picked at random belong to the same species. For each species, the proportion of the total volume that they occupied in the ecosystem was calculated by dividing the species crown index by the sum of the crown indexes of the complete population. This value was then squared and added up across all species to give a number ranging from 0-1. Subtracting this value from 1 gives the Simpson’s Index, where 0 represents the lowest diversity.

The Shanon-Weiner Diversity Index measures the uncertainty of correctly predicting the species of an individual picked at random. The same measure of proportion was used (individual crown volume/total crown volume) but it was input into the expression p\*(log2(p)), where p represents this proportion. The sum of these calculated values for all individual species gave a number between 0-5, where 0 represents no uncertainty and, therefore, no diversity.

*Structural Richness*

On-site recordings of the divisions between the different height classes were used to calculate structural richness, or the number of different height classes present in the community.

*Structural Diversity*

The measure of structural richness and the Shanon-Wiener measure of diversity were used to calculate structural diversity of the ecosystem.

*Statistical Analysis*

Results were averaged between the three regions (n=3) and the 95% confidence interval was calculated according to these averages.

To determine the effect of stand density, linear regression analysis was performed on the results by segregating fertilized and unfertilized units and graphing the relationship between stand density and the studied ecosystem indicator in a scatter plot. Correlation signs (positive or negative correlation between the stand density and the indicator) were recorded for R2 values above .70.

To determine the effect of fertilization, the difference in the studied ecosystem indicator between unfertilized and fertilized units was recorded for each stand density. A positive number (denominated ∆+) meant the indicator had a higher value in unfertilized stands and a negative number (denominated ∆-) meant the indicator had a higher value in fertilized stands. ∆~ was used to denominate stands that showed no change. The total number of ∆+, ∆- and ∆~ was recorded for each class species (herbs/shrubs) in each study area for the various ecosystem indicators.

Data on unthinned stands was observed as a control sample. However, because of its lack of a discrete stand density unit it was not included in the scatter plots for regression analysis. Due to the lack of a fertilized unthinned unit, it was also not included in the analysis for fertilization effects.

**Results**

*95% Confidence Interval*

The confidence interval calculated by averaging the results (n=3) between the three study areas resulted in wide intervals which resulted in no statistical significance (Table 1). Due to the high intervals of confidence resulting from this calculation, results were analysed individually for subsequent ecosystem indicators.

*Species Richness*

Apart from the unfertilized herbs layer in the Cariboo study area, which showed a strong negative correlation between stand density and species richness (R2=0.9968), no other area appeared to have its species richness affected by the stand density of the forest (Table 2).

**Table 2: Correlation Between Stand Density and Species Richness**

|  |  |  |  |
| --- | --- | --- | --- |
|  | **Kelowna** | **Summerland** | **Cariboo** |
|  | **R²** | **Correlation** | **R²** | **Correlation** | **R²** | **Correlation** |
| **Fertilized** |  |  |  |  |  |  |
| Shrubs | 0.41818 | - | 0.01783 | - | 0.65703 | - |
| Herbs | 0.00017 | - | 0.00679 | - | 0.06189 | - |
| **Unfertilized** |  |  |  |  |  |  |
| Shrubs | 0.01976 | - | 0.67251 | - | 0.37101 | - |
| Herbs | 0.34039 | - | 0.34862 | - | 0.9968 | Negative |

Effects of fertilization were, also, only present in the Cariboo study area, which showed a greater species richness in the unfertilized units than in the fertilized ones (Table 3). The Kelowna and Summerland study areas showed no clear response to fertilization.

**Table 3: Species Richness Responses to Fertilization**

|  |  |  |
| --- | --- | --- |
|  | **∆+** | **∆-** |
| **Cariboo** |  |  |
| Herbs | 4 | 0 |
| Shrubs | 4 | 0 |
| **Kelowna** |  |  |
| Herbs | 2 | 2 |
| Shrubs | 2 | 2 |
| **Summerland** |  |  |
| Herbs | 1 | 3 |
| Shrubs | 2 | 2 |
|  |  |  |

*Species Abundance*

Herbs of unfertilized units appeared to be the only species whose volume was affected by stand density (Table 4). In the Kelowna study area, their volume appeared to increase with stand density whereas, in the Cariboo study area, it appeared to decrease. Species abundance of all other species in the different study areas appeared unresponsive to stand density.

**Table 4: Correlation Between Stand Density and Species Abundance**

|  |  |  |  |
| --- | --- | --- | --- |
|  | **Kelowna** | **Summerland** | **Cariboo** |
|  | **R²** | **Correlation** | **R²** | **Correlation** | **R²** | **Correlation** |
| **Fertilized** |  |  |  |  |  |  |
| Shrubs | 0.11946 | - | 0.33744 | - | 0.51255 | - |
| Herbs | 0.55841 | - | 0.00868 | - | 0.11371 | - |
| **Unfertilized** |  |  |  |  |  |  |
| Shrubs | 0.02715 | - | 0.33689 | - | 0.24605 | - |
| Herbs | 0.94447 | Positive | 0.33689 | - | 0.82553 | Negative |

The Cariboo and Kelowna study areas showed a strong response to fertilization, with higher species abundance in fertilized units (Table 5). This, however, was unclear in the Summerland study area.

**Table 5: Species Abundance Responses to Fertilization**

|  |  |  |
| --- | --- | --- |
|  | **∆+** | **∆-** |
| **Cariboo** |  |  |
| Herbs | 0 | 4 |
| Shrubs | 0 | 4 |
| **Kelowna** |  |  |
| Herbs | 0 | 4 |
| Shrubs | 1 | 3 |
| **Summerland** |  |  |
| Herbs | 2 | 2 |
| Shrubs | 3 | 1 |

*Species Diversity*

Both the Shanon-Weiner and Simpson’s Index of diversity show a strong positive correlation (R2=0.95694 and R2=0.95547 respectively) between increased density stand and species diversity in the herbs layer of the unfertilized units of the Cariboo study area. All other layers in the different study area appeared unresponsive to stand density, apart from some weak positive correlations (R2~0.7) in some of the fertilized units of other study areas (Tables 6 and 7).

**Table 6: Correlation Between Stand Density and Shanon-Weiner Diversity Index**

|  |  |  |  |
| --- | --- | --- | --- |
|  | **Kelowna** | **Summerland** | **Cariboo** |
|  | **R²** | **Correlation** | **R²** | **Correlation** | **R²** | **Correlation** |
| **Fertilized** |  |  |  |  |  |  |
| Shrubs | 0.00184 | - | 0.70524 | Positive | 0.2543 | - |
| Herbs | 0.01739 | - | 0.09217 | - | 0.07492 | - |
| **Unfertilized** |  |  |  |  |  |  |
| Shrubs | 0.09052 | - | 0.09113 | - | 0.32344 | - |
| Herbs | 0.5589 | - | 0.24749 | - | 0.95694 | Positive |

**Table 7: Correlation Between Stand Density and Simpson’s Diversity Index**

|  |  |  |  |
| --- | --- | --- | --- |
|  | **Kelowna** | **Summerland** | **Cariboo** |
|  | **R²** | **Correlation** | **R²** | **Correlation** | **R²** | **Correlation** |
| **Fertilized** |  |  |  |  |  |  |
| Shrubs | 0.70318 | Positive | 0.02627 | - | 0.31815 | - |
| Herbs | 0.04141 | - | 0.71143 | Positive | 0.04209 | - |
| **Unfertilized** |  |  |  |  |  |  |
| Shrubs | 0.01299 | - | 0.03124 | - | 0.40296 | - |
| Herbs | 0.07168 | - | 0.01739 | - | 0.95547 | Positive |

There was a strong response in species diversity to fertilization, as most units appeared to have a lower species diversity in fertilized units according to both diversity Indexes (Tables 8 and 9). These results were not as strong in the Summerland study area.

**Table 8: Shanon-Weiner’s Diversity Index**

 **Responses to Fertilization**

**Table 9: Simpson’s Diversity Index**

 **Responses to Fertilization**

|  |  |  |
| --- | --- | --- |
|  | **∆+** | **∆-** |
| **Cariboo** |  |  |
| Herbs | 4 | 0 |
| Shrubs | 4 | 0 |
| **Kelowna** |  |  |
| Herbs | 4 | 0 |
| Shrubs | 3 | 1 |
| **Summerland** |  |  |
| Herbs | 3 | 1 |
| Shrubs | 1 | 3 |

|  |  |  |
| --- | --- | --- |
|  | **∆+** | **∆-** |
| **Cariboo** |  |  |
| Herbs | 4 | 0 |
| Shrubs | 4 | 0 |
| **Kelowna** |  |  |
| Herbs | 4 | 0 |
| Shrubs | 3 | 1 |
| **Summerland** |  |  |
| Herbs | 2 | 2 |
| Shrubs | 2 | 2 |

*Structural Richness*

The Kelowna study area appeared to be the only one whose structural richness responded to changes in stand density. In its fertilized units, higher stand density was associated with lower structural richness. In its unfertilized units, higher stand density was associated with higher structural richness. These correlations, however, were not significantly strong (R2=0.83768 and R2=0.70435 respectively) and other study areas showed no response at all (Table 10). The fertilized units of the Summerland study area had a constant structural richness (6 height classes) throughout the different stand densities tested.

**Table 10: Correlation Between Stand Density and Structural Richness**

|  |  |  |
| --- | --- | --- |
|  | **R²** | **Correlation** |
| **Fertilized** |  |  |
| Kelowna | 0.83768 | Negative |
| Summerland | N/A | - |
| Cariboo | 0.21739 | - |
|  |  |  |
| **Unfertilized** |  |  |
| Kelowna | 0.70435 | Positive |
| Summerland | 0.35072 | - |
| Cariboo | 0.14203 | - |

There was no clear response in structural richness to fertilization (Table 11).

**Table 11: Structural Richness Responses to Fertilization**

|  |  |  |  |
| --- | --- | --- | --- |
|  | **∆+** | **∆-** | **∆~** |
| **Cariboo** | 1 | 1 | 2 |
| **Kelowna** | 1 | 2 | 1 |
| **Summerland** | 0 | 3 | 1 |

*Structural Diversity*

Structural Diversity appeared to respond significantly to stand density, showing a strong negative correlation in almost all units across all study areas (Table 13.)

Responses to fertilization were varied: higher structural diversity was found in fertilized units in the Cariboo study area, but in unfertilized units in the Summerland study area. The Kelowna study area showed no clear pattern (Table 12).

**Table 12: Structural Richness Responses to Fertilization**

|  |  |  |  |
| --- | --- | --- | --- |
|  | **∆+** | **∆-** | **∆~** |
| **Cariboo** | 1 | 3 | 0 |
| **Kelowna** | 1 | 2 | 1 |
| **Summerland** | 3 | 1 | 0 |

**Table 13: Correlation Between Stand Density and Structural Diversity**

|  |  |  |
| --- | --- | --- |
|  | **R²** | **Correlation** |
| **Fertilized** |  |  |
| Kelowna | 0.77461 | Negative |
| Summerland | 0.90044 | Negative |
| Cariboo | 0.82703 | Negative |
|  |  |  |
| **Unfertilized** |  |  |
| Kelowna | 0.71992 | Negative |
| Summerland | 0.93471 | Negative |
| Cariboo | 0.66121 | - |

**Discussion**

*Species Richness*

According to this study, neither pre-commercial thinning or applications of fertilization generally hamper the ecosystem’s ability to host a variety of wildlife species. Results from other studies (He and Barclay, 2000; Stone and Wolfe, 1996; Sullivan et al., 2007) have supported the lack of correlation between stand thinning and fertilizing and species richness in ecosystems. The results found in the Cariboo, however, suggest that these practices might, under some circumstances, have a significant effect in certain areas, especially when conditions are similar to those of a sub-boreal spruce biogeoclimatic zone. In this cases, thinning might actually contribute to the number of species that are hosted in an ecosystem. A similar study conducted by Thysell and Carey (2001) also found that there was an increase in species richness after pre-commercial thinning. Fertilization, however, might actually interfere with the ecosystem’s biodiversity. But there are conflicting results on this topic across the literature. For example, Kellner and Marshagen (1991) found that fertilization actually led to the establishment of new species.

*Species Abundance*

According to these study’s results, pre-commercial thinning is compatible with silvopastoral systems, as it will not affect the abundance of forage for grazing. A strong variety of literature, however, says that not only is it compatible, but it will also enhance its growth (Abrams, 1983; Hawke 1991; Johnstone 1985; Lindgren et al. 2006; Nadkami and Haber, 2009; Sharrow, 1991; Stone and Wolfe, 1996). The main idea behind this is that a decrease in competition (Abrams, 1983) and the creation of microclimates (Nadmaki and Haber, 2009) leads to an increased production of understory vegetation. Other research (He and Barclay, 2000; Sullivan, 2007) coincide more precisely with these studies’ findings of no enhanced growth. Sullivan et al. (2007) found that the mean density of understory vegetation is similar in thinned and old-growth stands and that mean abundance of herbs and shrubs are unaffected by stand density.

The study also shows fertilization as beneficial for silvopastoral systems by increasing the abundance of understory grazing vegetation. Studies by Sullivan et al. (2007), Abrams (1983) and Lindgren (2007) support these results. But VanderShaaf et al. (2000) mentions that the effects of tree stand density end up being more significant than those caused by fertilization.

*Species Diversity*

According to these study’s results, it appears as though the practices of pre-commercial thinning and fertilization contribute negatively to the ecosystem’s ability to host a wide variety of wildlife species. When pre-commercial thinning decreases tree density, it reduces the trees abilities to perform certain roles that contribute to biodiversity, such as providing safe spots for animal seed dispensers and contributing to seedbanks in their associated soils through the decomposition of their canopy layers (Nadkami and Haber, 2009). However, other studies suggest that thinning might be beneficial for biodiversity, as it creates the ‘succession mosaic’ (Sullivan, 2016) that creates the perfect environment for different varieties of wildlife. For example, Stone and Wolfe (1996) found that it is actually at intermediate levels of tree stand density that biodiversity peaks.

The negative response of species diversity to fertilization can be attributed to the fact that high fertilization has been found to increase tree mortality (Yang 1998), leading to a decrease in the abundance and number of species that are found within an ecosystem. These results are also supported by the findings of Sullivan et al. (2007).

*Structural Richness and Diversity*

Although this report found no relationship between stand density and structural richness, it did have strong results on structural diversity relationships. Thinning, in this case, appears to be beneficial for the ecosystem’s structural diversity. This is supported by Thysell and Carey (2001), who explain thinning as a technique to restore the complexity of the vegetative cover. These results have also been supported by studies such as that of Lindgren et al. (2007), who found that thinning resulted in an increased structural richness of the tree layers. This report dealt only with herb and shrub data, explaining why some insight on structural richness might have been overlooked.

*Confidence Intervals*

The widely-varying results can be attributed to differences in biogeoclimatic zones, altitude and topography between the three regions, causing individual study to provide more insight into the effects of these techniques.

**Management Implications**

Managing biodiversity while still maintaining high productivity of timber and grazing forage is a great challenge for silvopastoral systems. This study suggests that managers of this systems do not cease practices of pre-commercial thinning or fertilization, as they significantly contribute to their yields and, therefore, to the maintenance of these systems and the environmental and economical benefits associated with them.

This study advises managers not to maintain high stand densities, as this intensifies resource competition and, therefore, hampers both biodiversity and production efforts. On the other hand, maintaining low standing densities will compromise the benefits that come from both producing forage grazing and hosting biodiversity in an ecosystem surrounded by canopy trees. An intermediate thinning density is advised.

This same principle applies to fertilization. Fertilizing small areas and in controlled quantities will increase productivity and might even increase the abundance of rare species, but will not risk an increase in species mortality, which would be both economically and environmentally undesireable.

**Literature Cited**

Abrams, M.C. and D.I. Dickmann. 1983. Response of understory vegetation to fertilization on mature and clearcut Jack pine sites in northern lower Michigan. Am. Midl. Nat. 110: 194-200.

Buck, M.G. 1986. Concepts of resource sharing in agroforestry systems. Agro. Syst. 4: 191.

Cole, D,M. & Koch, P. 1996. Managing lodgepole pine to yield merchantable thinning products and attain sawtimber rotations*.* Res. Pap. INT-RP-482. USDA Forest Service Intermountain Research Station.

Crouch, G.L. 1986. Effects of thinning pole-sized lodgepole pine on understory vegetation and large herbivore activity in central Colorado*.* Res. Pap. RM-268. U.S. Forest Service, Rocky Mountain Research Station.

Hawke, M.F. 1991. Pasture production and animal performance under pine agroforestry in New Zealand. For. Ecol. Manage. 45: 109.

He, F. and H.J. Barclay. 2000. Long-term response of understory plant species to thinning and fertilization in a Douglas-fir plantation on southern Vancouver Island, British Columbia. Can. J. For. Res.30: 566-572.

Johnstone, W.J. 1985. Thinning lodgepole pine. Lodgepole Pine: the Speciesand its Management. Pages 253-262 *in* D. M. Baumgartner, R. G. Krebill, J. T. Arnott & G. F. Weetman (eds.). Washington State University Cooperative extension, Spokane, Washington, USA, and Vancouver, B C, Canada.

Kellner, O. and M. Marshagen. 1991. Effects of irrigation and fertilization on the ground vegetation in a 130-year-old stand of Scots pine. Can. J.For. Res. 21: 733-738.

Knowles, R.L. 1991. New Zeland experience with silvopastoral systems: A review. For. Ecol. Manage. 45: 251.

Lindgren, P.M.F., D.B. Ransome, D.S. Sullivan, and T.P. Sullivan. 2006. Plant community attributes 12 to 14 years following pre-commercial thinning in a young lodgepole pine forest. Can. J. For. Res. 36: 48-61.

Lindgren, P.M.F., T.P. Sullivan, D.S. Sullivan, R.P. Brockley, and R. Winter. 2007. Growth response of young lodgepole pine to thinning and repeated fertilization treatments: 10-year results. Forestry 80: 187-211.

Manning, A.D., P. Gibbons, and D.B. Lindenmayer. 2009. Scattered trees: A complementary strategy for facilitating adaptive responses to climate change in modified landscapes? Journal of Applied Ecology 46: 915-919.

Nadkarni, N.M. and W.A. Haber. 2009. Canopy seed banks as time capsules of biodiversity in pasture-remnant tree crowns. Conservation Biology 23: 1117-1126.

Sedjo, R.A. 1999. The potential of high-yield plantation forestry for meeting timber needs – Recent performance, future potentials, and environmental implications. New Forests17: 339-359.

Sharrow, S.H. 1991. Tree planting pattern effects on forage production in a Douglas-for agroforest. Agro. Syst. 16: 167-175.

Stone, W.E. and M.L. Wolfe. 1996. Response of understory vegetation to variable tree mortality following mountain beetle epidemic in lodgepole pine stands in northern Utah. Vegetatio122: 1-12.

Sullivan, T.P., D.S. Sullivan, P.M.F. Lindgren, and D.B. Ransome. 2007. Long-term responses of ecosystem components to stand thinning in young lodgepole pine forest: IV. Relative habitat use by mammalian herbivores. For. Ecol. Manage. 240: 32-41.

Thysell, D.R. and Carey, A.B. 2001. Manipulation of density of *Pseudotsuga menziesii* canopies: preliminary effects on understory vegetation. Can.J. For. Res. 31: 1513-1525.

VanderSchaaf, C.L., J.A. Moore, and J.L. Kingery. 2000. The effect of multi-nutrient fertilization on understory plant diversity. Northwest Science74: 316-324.

Yang, R.C. 1998. Foliage and stand growth responses of semimature lodgepole pine to thinning and fertilization. Can. J. For. Res.28: 1794-1804.