MODELING LODGEPOLE PINE SILVOPASTURES IN SOUTH CENTRAL BRITISH COLUMBIA

by

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Abstract

Silvopasture systems within lodgepole pine stands in British Columbia are not widely implemented because knowledge is lacking on profitability, appropriate tree and cattle stocking standards, and the suitability and potential of understory forage species in silvopasture systems. In order to compare total timber and forage production values of single-crop tree plantations with those of silvopasture systems, this study consists of: 1) a theoretical economic model (the Lodgepole pine Silvopasture Economic Model) that predicts revenues expected for tree-only, pasture-only, and both uniform- and clumped-tree distribution silvopasture systems, and 2) a screening of native and agronomic forage species under simulated shade conditions to compare forage quantity and quality for grazing beef cattle. The Lodgepole pine Silvopasture Economic Model relies on a constant supply of mean production values projected into the future to estimate and compare the yield and value of resource commodities. The objectives of the forage screening component were to compare agronomic and native grass biomass production and forage quality, and study the effects of shading, clipping, and their interaction, on pinegrass and rough fescue, two species native to British Columbia, and the agronomic forages orchardgrass and perennial ryegrass. Some morphological changes under shade were noticed in this study, but the effects were minimal in comparison to differences in biomass production between species. The study clearly demonstrated the high productivity of orchardgrass compared to pinegrass and rough fescue as orchardgrass plants produced a total of 11 and 9 times more total biomass than pinegrass and rough fescue under ambient sunlight, but the differences between species factors tended to decrease with increasing shade. The benefit of improved forage production using agronomic species in clumped distribution lodgepole pine silvopasture systems has the potential to provide sizeable benefits to the ranching industry while diversifying resource commodities in lodgepole pine stands.

Chapter 1. Introduction

Integrating over- and understory crops to diversify crops and enhance production or sustainability is the basis of agroforestry systems. Silvopastures, alley-cropping practices, shelterbelts and buffer strips are all examples of agroforestry systems. Management of these systems is more complex than conventional monoculture practices, but the economic and environmental benefits can offer advantages over traditional systems (Jose 2009). Another potential advantage is the increase in total site productivity in areas characterized by high climatic stress factors such as excessive drought, wind or heat (Nair 2007), as plants grown in integrated systems are able to facilitate growth of competing plants (Hunter and Aarssen 1988). In British Columbia, cyclical timber harvesting forests provides interim range values during the reforestation period as understory forage is released from tree canopy shade, an example of tree and forage resource use coordinated temporally (Buck 1986). Opportunities for increasing forage production on forested range exist in the development of pine silvopastures in order to diversify commodities and simultaneously integrate forestry and grazing practices, with a potential added benefit of greater production on dry, unproductive sites. This study models the economic benefits of altering tree density and distribution in order to integrate cattle grazing with lodgepole pine (*Pinus contorta* var. *latifolia* Engelm) timber production.

Agroforestry applications have been implemented around the globe for centuries, often for purposes beyond diversifying commodities produced on one landbase. Sharrow at et al. (1996) determined that total productivity of Douglas-fir (*Pseudotsuga menziesii* Mirb.) and understory forage was greater in a silvopasture compared to forest and pasture monocultures. Silvopasture systems have been implemented in pine plantations, including long-leaf pine (*Pinus palustris*) (Burner and Brauer 2003), slash pine (*P. elliotti*) (Lewis 1989), and radiata pine (*P. radiata*) (Malajczuk et al. 1996), and studies have quantified forage production in mature, thinned ponderosa pine (*P. ponderosa*) stands (Jameson 1967, Severson and Uresk 1988). Lodgepole pine is a commonly planted conifer in forest plantations in the southern and central interior of British Columbia, Canada. Although few studies have looked at lodgepole pine as a silviculture species intentionally integrated with livestock grazing in a silvopasture system, McLean (1967, 1972) found support for good cattle weight gains from mature lodgepole pine forest grazing utilizing predominantly pinegrass (*Calamagrostis rubescens* Buckl.). Seeding practices in British Columbia have been conducted in cutblocks following the harvest and planting of a new crop of tree seedlings to increase forage and reduce erosion (McLean and Clark 1980). Increased weight gains in cattle have resulted from seeding agronomic pasture species (Sassaman 1972, McLean and Clark 1980, Quinton 1987, Quinton et al. 1991).

The suitability of lodgepole pine in silvopasture systems is not well researched. Previous studies have focused primarily on the effects of thinning treatments on understory vegetation yield (Lindgren et al. 2006), tree crown structure (Sullivan et al. 2006), and timber production (Long and Smith 1992). Lodgepole pine has a history of developing as dense forests following stand-replacing fires (Collins et al. 2010). Pre-commercial thinning can increase the overall productivity of a stand (Sullivan et al. 2006); but few stands have been thinned to densities less than 500 stems per hectare (sph). Exceptions include studies by Sullivan et al. (2007) and Clason et al. (2008) with thinning treatment densities as low as 250 stems per hectare. In the Lodgepole pine Silvopasture Economic Model (Chapter 2), lodgepole pine growth and yield was modeled in various stand designs with integrated forage for livestock grazing. Sawlog production is simulated in monoculture stands as well as both a wide espacement silvopasture and a clumped distribution design. The integrated forage production of forage in the understory, as well as total net present values of various systems of tree planting design provides insight as to the performance of lodgepole pine in these systems.

Cattle grazing in these systems increases the pressure on understory plant to provide adequate, nutritious forage while being able to persist and reproduce under the combined effects of tree growth and grazing pressure. The experimental field study (Chapter 3) compares two native grasses with two commonly seeded agronomic grasses in order to predict future returns in a theoretical silvopasture. An intended outcome is that recommendations can be made regarding the applicability of silvopasturing lodgepole pine stands to include the capacity for livestock grazing of a native or agronomic forage understory.

The projected valuation of forest, pasture, and silvopasture systems requires complex accounting of the costs and revenues due to the interaction between the two crops in the field. A comparison of the financial investments and estimated future returns from the three land use types is required in order to consider tree and forage management systems that best optimizes this dual commodity production. In order to compare differences in commodity values of a single-crop tree plantation with those of a silvopasture, this study consists of two components. First, a theoretical economic model that predicts present and future costs and revenues expected for tree-only, pasture-only, or silvopasture systems (Chapter 2), and second, a screening of native and agronomic forage species under simulated shade conditions to compare forage quantity and quality as summer pasture for grazing beef livestock (Chapter 3). The screening results provide the predictive model with an estimation of the effect of on forage quality indicators due to reduced sunlight under the modeled tree canopy. The goal of the study is to explore and compare the potential future value of forest, pasture and silvopasture systems implemented in theoretical lodgepole pine stands.

Chapter 2. Predictive economic model for lodgepole pine forest, silvopasture, and pasture systems

Introduction

Natural resource scientists and managers have built mathematical models which temporally and spatially describes and define relationships between ecosystem component to compare predicted outcomes and provide feedback information to guide management accordingly. The coupling of economics and ecology in models is evident in many disciplines, such as energy policy considerations (Choi et al. 2010), land and water management (Richardson et al. 2011), and agro-ecosystem development (Yongping et al. 2009). Richardson et al. (2011) argue that the development of a unifying synthetic model is as essential for developing an economic, ecological and social solution to a particular problem as in the physical sciences. Agroforestry systems are often implemented with biological intentions, such as ameliorating understory crop conditions, as well as economic reasons, such as diversifying commodities produced on one landbase. Scientific research is important in developing our understanding of our natural vegetation resources, and simulated modeling is one tool that can be applied to unify the management of trees and forage. Considering this, agroforests are good candidates for modeling approaches.

Several forestry models have been developed to forecast returns on investment into the future and predict what outcomes particular management and silviculture practices may have on both individual trees and forest dynamics. One example is the British Columbia Ministry of Forests, Lands and Natural Resource Operations' TASS (Tree and Stand Simulator), an empirical growth and yield model based on field plot data that is used to develop stand growth and yield predictions in even-age stands (British Columbia Ministry of Forests, Lands and Natural Resources, 2002). Outside of British Columbia, Canada, other models exist, including JABOWA, an early forest simulation model used for eastern North American forests (Botkin et al. 1972), and more recently SORTIE, also based on eastern forests of North America, but with more complex empirical formulas for estimating forest dynamics based on individual tree growth, their location, and competition with neighbouring trees (Pacala et al. 1993, Canham et al. 1994). An example of a rangeland model is the holistic model called SPUR (Simulation of Production and Utilization of Rangelands) that was developed by Wight (1983) to assist both resource managers and scientists in explaining the relationship between range ecology and livestock production. Models continue to be developed and improved as field research furthers our understanding of forest ecosystem dynamics and economic objectives are incorporated into interdisciplinary studies.

Models simulating agroforestry systems have been developed, and often incorporate components of tree and understory crop production with a focus on abiotic and biotic interactions. Examples within agroforestry include: water and nutrient management (Gregory 1996), canopy development, CO_2 balance and carbon exchange of agroforest-grown and pruned trees (Nygren et al. 1996), and light interception and evapotranspiration (McIntyre et al. 1996). Considering the wide range of agroforestry applications, model specificity is often limited to a particular system being simulated. For example, Malajczuk et al. (1996) modeled the financial returns and labour requirements of integrating sheep grazing with pine timber in an Australian Mediterranean-type climate. A similar financial analysis was conducted by Grado et al. (2001)

in a Mississippi *Pinus taeda* stand where cattle grazing and forestry were integrated to compare Land Expectation Values.

I designed a theoretical lodgepole pine model to estimate future crop values and define the production relationships between a lodgepole pine tree crop as it develops and impacts understory forage yield. The model was developed to estimate future returns for simulated forest and silvopasture lodgepole pine stands in south central British Columbia, building on TASS forest modeling approaches by incorporating modeled stand growth and yield with an understory component specific to upland forest grazing. I compare uniform and clumped tree distribution with a conventional timber approach to provide future predicted timber and forage values produced in a theoretical lodgepole pine forest, open pasture, and lodgepole pine silvopasture systems. The model analyzes predicted yields for lodgepole pine trees growing on three site index values, providing a measure of the productivity of a site as an estimation of the height of the tallest tree in a stand at age 50. The model was used to test a variety of land use scenarios incorporating either timber or forage production, or both, in order to put the potential applicability of silvopasture systems in lodgepole pine forest and range lands into perspective with conventional forest and pasture management. I hypothesize that there is no difference in commodity production between conventional lodgepole pine plantations and lodgepole pine silvopasture systems.

Methodology

The silvopasture economic model (Appendix A) was developed in Microsoft Excel 2007 software using imported modeling outputs from TIPSY, the tree growth and yield modeling program developed by the British Columbia Ministry of Forests, Lands and Natural Resources Operations (2001), using simulations from TASS. The model was designed to enable comparisons of timber and forage land-use systems as they would apply to summer grazing in lodgepole pine forests. The model used investment costs and resource prices outlined in Table 1, while incorporating site index (as a measure of site productivity), and tree growth and yield outputs from TIPSY to model the effect of tree growth on understory forage crop quantity and quality. This allows for the comparison of theoretical net present values of lodgepole pine monoculture, pasture and lodgepole pine silvopasture scenarios. Tree growth and yield outputs from TIPSY are incorporated into the model in subsequent worksheets that call on the data depending on input factors chosen currently in the output tables. Scenario net present values were compared over a range of discount rates and site indices to determine the potential for silvopasture applications in lodgepole pine stands. The internal rate of return was also considered as a measure of the economic returns produced from their investment costs. Further investigation of silvopasture techniques with altered tree density and distribution over a range of timber and forage prices identified optimal stand designs that integrate timber and forage management.

Model description

The model was designed for livestock producers and land managers to easily use on most computer platforms running Microsoft Excel. The model contains several functions that were developed for use beyond the scenarios tested in this thesis, but only those employed in this study are explained in this paper. The estimation of future commodity values requires that all costs and revenues over the life of the project are accounted for with an adjustment for inflation to estimate future returns in present-day values, referred to as the net present value (NPV). The discount rate in the model accounts for this, incorporated as a constant rate over the life of an estimated scenario. The principle factor in net present valuation is the discount rate, which predicts future returns at present day valuation, taking into account annual cash flows and costs using the following formula:

$$\text{net present value} = \sum_{i=1}^{n} \frac{\textit{annual costs \& returns}}{(1 + \text{discount rate})^{i}}$$

Net present valuation alters scenario outcomes by reducing future returns on investment as projected time into the future increases. A basic assumption of the discount rate is that money is worth more now than in the future, taking into account compound interest and returns on investment. The weakness of this approach is the comparison of immediate versus long-term revenues. Returns on the investment of planted trees are substantially reduced by the discounting of revenues derived from the tree harvest at the end of the rotation.

This affects the rotation age as the highest valued harvest year occurs when the total revenue reaches its highest NPV before the discount rate becomes large enough to reduce the value of the stand after this point. The same principle applies to revenues for cattle ranchers as the annual return that is received will be larger soon after the establishment of the silvopasture as opposed to further into the future when revenues are reduced by the applied discount rate. Regardless, future discounting is commonly used by economists along with the internal rate of return (IRR) to determine the feasibility of long-term projects and compare the profitability of each scenario. This provides a measure of the output yield expected based on a given investment, such as seeding forage species and planting trees.

Higher discount rates estimate returns to occur sooner, therefore a downfall of this modeling approach is the potential undervaluing of a stand of trees on a low productivity site that could be harvested at a later date. A higher discount rate creates an inherent advantage for forage valuation over tree production as trees harvested in the future are reduced in comparison with immediate annual revenues generated from the sale of forage or livestock. The balance in the system comes from the small annual value of each forage harvest compared to the one-time, high value of the trees at the end of the plantation's lifespan.

Agroforestry studies have used a range of discount rates in a variety of economic analyses; Graves et al (2007) used a rate of four percent in a European silvoarable and forestry study, Ares and Brauer 2006) used higher rates of six and eight percent in a central United States pecan silvopasture study, and an Australian pine and sheep silvopasture study conducted by Malajczuk et al. (1996) used a range of rates between four and nine percent. Modest discount rates of three and four percent were used for comparisons in this study as a rate between the two represent the balance point between selection for returns for immediate (forage) versus delayed (timber) commodity production.

Following the clearcut harvest of a lodgepole pine stand, removing and burning slash and scarification of the soil surface to expose mineral soil during logging and clearing of debris, the modeled scenarios start with the planting of trees (if applicable) followed by the seeding of agronomic forages. Stands grown in tree densities of 250, 500, 750, 1000 stems per hectare (sph) were modeled using TIPSY for use in the silvopasture economic model on site indices 12, 16 and 20. In British Columbia, the site index is a measure of the productivity of a site defined as the height of a tree at age 50. A total of twelve tree growth and percent canopy cover extracts were produced using TIPSY for each combination of site index and targeted tree stocking rate. Field settings used in TIPSY to model tree growth and create output files were selected to model a lodgepole pine stand near the city of Kamloops, British Columbia, Canada with all remaining TIPSY fields left in their default setting.

A complete tree harvest occurs once at the end of each rotation. A uniform tree distribution is used in the modeling of uniform silvopasture systems. A clumped distribution uses the 1000 sph stand with 10 % of the area dedicated to permanent pasture (i.e., not planted with trees). Planting costs were based on 2003 average costs provided by the BC Ministry of Forests, Lands and Natural Resource Operations for the Southern Interior Region. An estimate of $1000 per hectare was used for a 1000 sph stand, and I assumed reduced planting densities at values of $400, $600, and $800 for stands planted at 250, 500, and 750 sph respectively. This assumption is based on the larger per-tree costs associated with planting a reduced number of trees per hectare as transport to and from the site is still required and a larger walking distance between planting spots increases the amount of time a tree planter requires to plant each tree.

Tree canopy cover estimates from TIPSY are used to reduce understory forage yield. When the clumped planting scenario was modeled, the planting cost was reduced proportionally to the reduction in total trees planted. Tree limb pruning was applied to the uniform density stands of 250, 500 and 750 sph, and the same costs as used for tree planting were applied at year ten. Log prices are based on a five year average (2005-2010) and AUM value are based on a long-standing AUM price used for pasture rental in the interior of British Columbia. Fees paid to the government in the form of stumpage ($ per cubic meter) and grazing fees ($ per AUM) are recent values for interior forests and range licenses. Tree growth and yield outputs from TIPSY are incorporated into the model in subsequent worksheets that call on the data depending on input factors chosen currently in the output tables.

The interaction component of the economic model uses TIPSY canopy cover values to reduce forage production and alter forage quality under a growing stand of lodgepole pine in the conventional forest and silvopasture scenarios. When employing TIPSY crown canopy cover estimations, total forage yield was reduced proportionately as canopy cover increased, and eliminated entirely when crown cover reached 50%. This conservative approach was based on forest cover and subsequent range values presented by Jameson (1967).

Scenario descriptions

Three basic land-use scenarios were compared in this study to explore the options available when considering the integration of timber and livestock production practices during reforestation of lodgepole pine plantations. The scenarios examined were: 1) a lodgepole pine forest with and without interim grazing at the juvenile tree stage, 2) a cleared permanent pasture for livestock grazing, and 3) one silvopastoral and two silvopasture systems where tree density or distribution was altered in order to optimize potential land resource value to the benefit of both the timber and ranching industries (Table 2.1).

Table 2.1 Land use scenario descriptions.

Scenario	Description
Tree plantation (timber only)	A lodgepole pine-planted cutblock with no forest grazing
Pasture (forage only)	A cutblock seeded with agronomic forages and not planted to provide forage without the impact of a growing stand of trees
Tree plantation w/ interim grazing	A lodgepole pine-planted forest plantation with a seeded understory of agronomic forage for interim cutblock grazing until tree canopy eliminates forage values.
Uniform silvopasture	A lodgepole pine silvopasture with seeded agronomic forage and trees plant at a density of 250,500 and 750 stems per hectare of uniform distribution
Clumped silvopasture	A lodgepole pine silvopasture with seeded agronomic forage and trees planted in clumps at a density equivalent of 1000 stems per hectare and seeded agronomic forage between planted clumps

The initiation of each scenario occurs with the removal of a stand of lodgepole pine following the salvage harvesting of mountain pine beetle-killed trees. During harvest, it is anticipated that the ground will be disturbed, which encourages germination of a seeded agronomic crop. It is also assumed that remaining coarse woody debris has been piled and burnt, and stumps left behind to provide obstacles to protect planted trees from livestock damage. Livestock values in the model are estimated using the average pasture rental rate for one animal unit month (AUM) in the British Columbia interior. The utilization rate is the amount of the total forage that is removed by the grazing cattle set at 50% for all scenarios. The annual forage yield is divided by the expected consumption of forage by one AUM to determine the number of AUMs the forage is capable of supporting. Forage production was estimated as the mean total annual forage crop produced on the site without the influence of a growing crop of trees. Seeding costs accrued in year 2, and were estimated at $20.00 per hectare for the seed and aerial application. A sawlog price of $44.29 per cubic meter is based on a five year average (2005-2010) and an AUM value of $12.00 per hectare is based on an average AUM price used for pasture rental in the interior of British Columbia.

Resource fees were set at 2011 average rates in the Kamloops Forest District of $6.00 per cubic meter of timber and $2.00 per AUM for grazing. Stumpage is paid at the harvest of the timber, and grazing fees are incurred annually. The final age of each comparison with a combination of discount rate and site index was determined by selecting the mean of ages with the highest total value of those scenarios that include a tree component. The scenarios are described below as they apply to the south and central interior of British Columbia where beef cattle production and forest harvesting activity overlap in lodgepole pine forests.

Tree plantation (timber only) scenario

Tree-only scenarios are designed to theorize conventional lodgepole pine plantations. Scenarios start when tree seedlings are planted into a deforested ‘cutblock’ the spring following the previous autumn harvest of mature trees. Intentional disturbance of understory vegetation and exposure of some mineral soil during the harvesting of trees is prescribed to promote good forage germination and establishment conditions. Seedlings are planted into the cutblock in the first year at a stocking density of 1256 sph. This stocking rate is 25% higher than the targeted stocking of 1000 sph to account for any mortality that may occur during establishment. The targeted stocking of 1000 sph is used to represent a moderately dense lodgepole pine stand with a medium average tree diameter resulting in high stand yields (Middleton et al. 1995).

Other than initial planting, few inputs are expected in these systems. Lodgepole pine plantations can be grown on sites of low productivity with little management intervention, but modeling results indicate low returns on investment as the low productivity does not justify further tree improvement activities. Assuming that potential risks such as catastrophic fire or insect activity do not damage the stand, the targeted endpoint is a stand of trees ready to be sold to harvest as sawlogs for the timber industry.

Pasture (forage only) scenario

For the purposes of the model, the definition of a pasture is an area not replanted with trees in order to remain deforested in the long-term to produce consistent forage for summer grazing livestock. Pasture forage quality is improved with agronomic grass and legume seed applications following the methodology described above. Grazing is prescribed at the forage utilization level of 50% in the same manner as the forest grazing scenarios explained above. The intended pasture use is forage production only; other uses such as storing livestock in pastured sites and hay cutting are outside the valuation methods employed in this study.

Forage seed is applied immediately in the spring following tree planting in order to allow the trees one growing season to establish before introducing forage seeding to limit affects on tree growth and establishment (Powell et al. 1994). Agronomic grass and legume seed are aerially applied at 3 kg ha^{-1} in the spring of year two. The presumed value of forage is based on estimated productivities of seeded lodgepole pine cutblocks in the interior of British Columbia. McLean and Clark (1980) estimate seeded cutblock yields at between 590 and 1540 kg per hectare. By comparison, McLean (1972) found that lodgepole pine under a lodgepole pine forest produced 465 kg per hectare. Pasture yield estimated production values of 700, 1100 and 1500 kg per hectare were used when modeling scenarios with site indices of 12, 16 and 20 respectively. Livestock grazing is introduced to the plantation at a 25% utilization in year 3 to limit any deleterious impacts on forage establishment, and increased to an operational stocking rate in year four. The operational stocking rate is calculated by the economic model as follows: the stocking rate is determined by utilizing 50% of the total forage yield in order to leave 50% of total production as residue to sustain pasture productivity. The stocking rate is determined by applying the Animal Unit Month (AUM) principle, using an AUM value of 453 kg ha-1 of forage consumed by a 450 kg (1200 lb) cow and her suckling calf.

This system provides summer range for cattle producers integrated with lodgepole pine timber production. The two resources are integrated temporally as the scheduling of newly harvested and seeded cutblocks across the landscape unit provides an ongoing supply of annual forage production for livestock producers. Providing that the scheduling system is not interrupted, and that the landscape unit is large enough, resources can be perpetually produced in tandem.

Lodgepole pine silvopasture scenarios

Simulations of lodgepole pine silvopasture were approached in two ways, and compared to a conventional silvopastoral approach of grazing interim forage prior to tree canopy closure. The first silvopasture approach used a reduced planting density to increase forage production. Resulting targeted tree densities of 250, 500 and 750 sph by harvesting age were considered in order to explore silvopasture potential return-on-investment under a range of tree densities. The second approach incorporates a clumped distribution whereby 10% of the area is not replanted and remains non-treed as inter-clump openings or access corridors providing permanent pasture for the life of the stand. A clumped approach has shown promise in maintaining forage production with high tree densities when implemented in a Douglas-fir stand with an aggregated planting design (Sharrow 1991).

Interim grazing is a common practice whereby livestock producers graze beef cattle on forage produced in young tree plantations before trees cast shade over understory forage (McLean and Clark 1980). This is a conventional use of lodgepole pine stands where grazing is temporally integrated by utilizing forage until tree crown cover reaches 35%, beyond which understory grazing potential is greatly reduced (Jameson 1967) and excluded from cattle after the developing tree canopy reaches a value of 50%. A moderate cattle stocking density is assumed in order to mitigate any damage to the tree seedlings as a result of livestock trampling (McLean and Clark 1980, Pitt et al. 1991, Newman et al. 1997). This system has proven successful as plantations provide medium to high herbage yield and moderate growth of lodgepole pine seedlings providing that grazing occurs in the first half of the growing season (Clark and McLean 1979, McLean and Clark 1980). The clumped silvopasture scenarios have an added management activity in the pruning of tree limbs as recommended when crop trees are roughly four meters in height if post-spacing densities fall below 1200 sph (BC Forest Service 2002). Both tree planting and limb pruning costs (where applied) are estimated at $400, $600, $800, and $1,000 per hectare for tree densities of 314, 628, 942 and 1256 sph respectively. When the number of planted trees is reduced in the clumped silvopasture scenarios, planting costs are reduced proportionately to the number of trees planted.

The scenario modeling results were explored both figuratively as estimated net present values of the predicted returns from age zero to 100, and financially as internal rates of rates of return at age 50. Net present valuation results were compared over a range of discount rates and site indices in order to determine the sensitivity of outputs to fluctuations in these two important factors. The internal rates of return were compared across three of site indices to provide an estimate of profitability over a range of site productivities. To further investigate potential returns and silvopasture suitability, a comparison of returns from pasture forage production and five tree densities (0, 250, 500, 750 and 1000 sph) with integrated forage production is also provided. These estimates were compared for each combination of discount rate (using moderate rates of 3% and 4%) and site index (12, 16 and 20). Finally, I compared net present value returns for three potential silvopasture systems over a range of sawlog values ($40, $44 and $48 per cubic meter, constant pasture rental rate of $12.00 per AUM) and a range of pasture rental rates ($10, $12, $14 per AUM, constant sawlog value of $44.00 per cubic meter).

Results

Adjusting the discount rate results in large fluctuations in the estimated net present value of systems that include trees (Figure 2.1). Pasture systems result in positive returns regardless of the discount rate. The estimated net present values of a timber only system (no forage) is similar to that of the clumped silvopasture, and returns on investment are positive at discount rates of 2% or 3%. The uniform distribution silvopasture does not provide returns as high as the tree only and clumped silvopasture systems, nor does it provide positive returns at discount rates of 3% or higher. No system that includes a tree component is profitable at discount rates of 4% or higher.

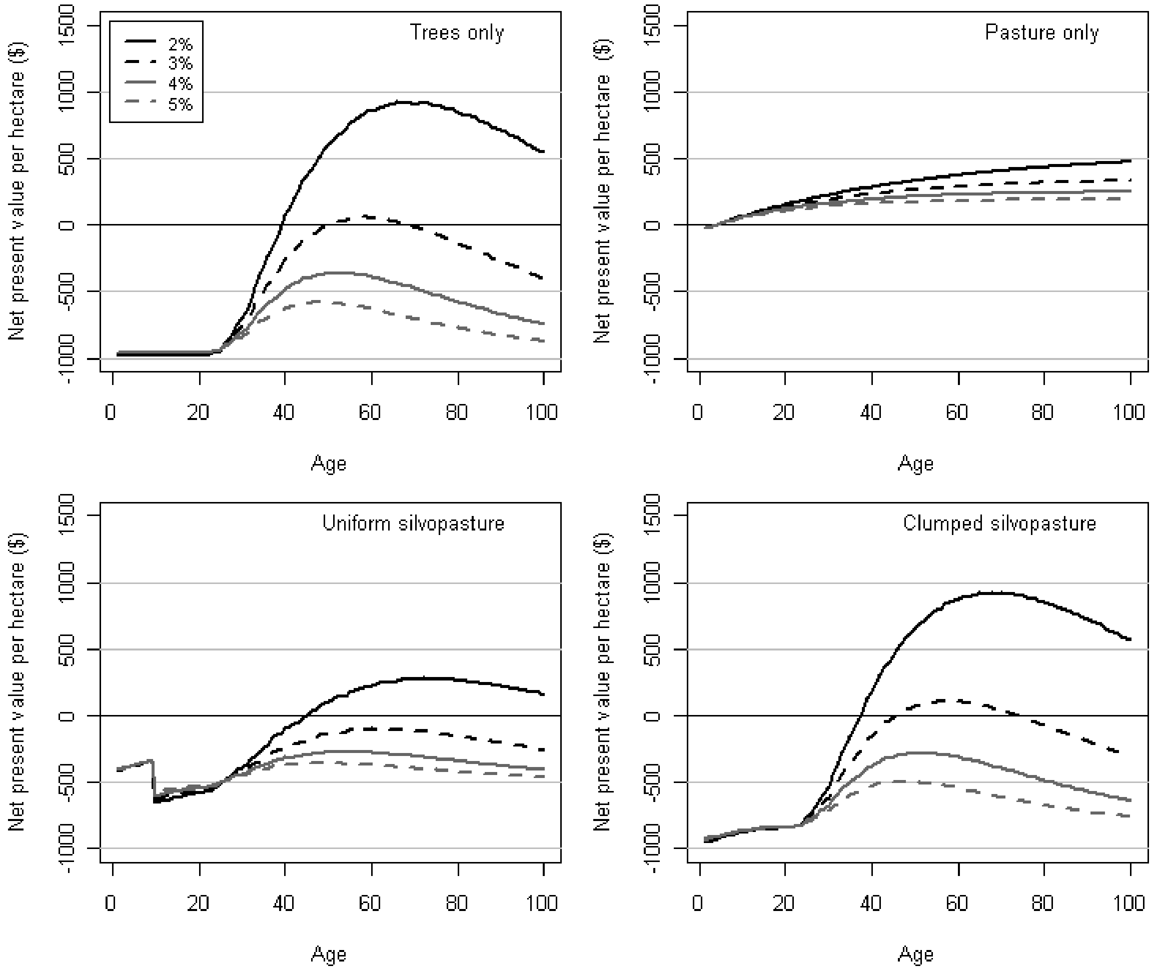

Figure 2.1: Total land net present values for four discount rates (2, 3, 4, 5%) of four scenarios: trees only, pasture only, silvopasture with uniform tree spacing and density of 250 sph, and a clumped silvopasture with tree clump density of 1000 sph and 10% of the stand open to grazing.

The site index has a rather large influence on estimated net present values (Figure 2.2). No system that includes a tree component growing on a site index of 12 results in positive returns. Estimated net present values are similar for the tree-only scenarios and the clumped silvopasture scenarios, as they are both capable of positive returns on a site index of 16, and returns are substantially higher on site indices of 20. The uniform silvopasture scenario provides lower returns, and is not capable of providing positive returns on site indices of 16.

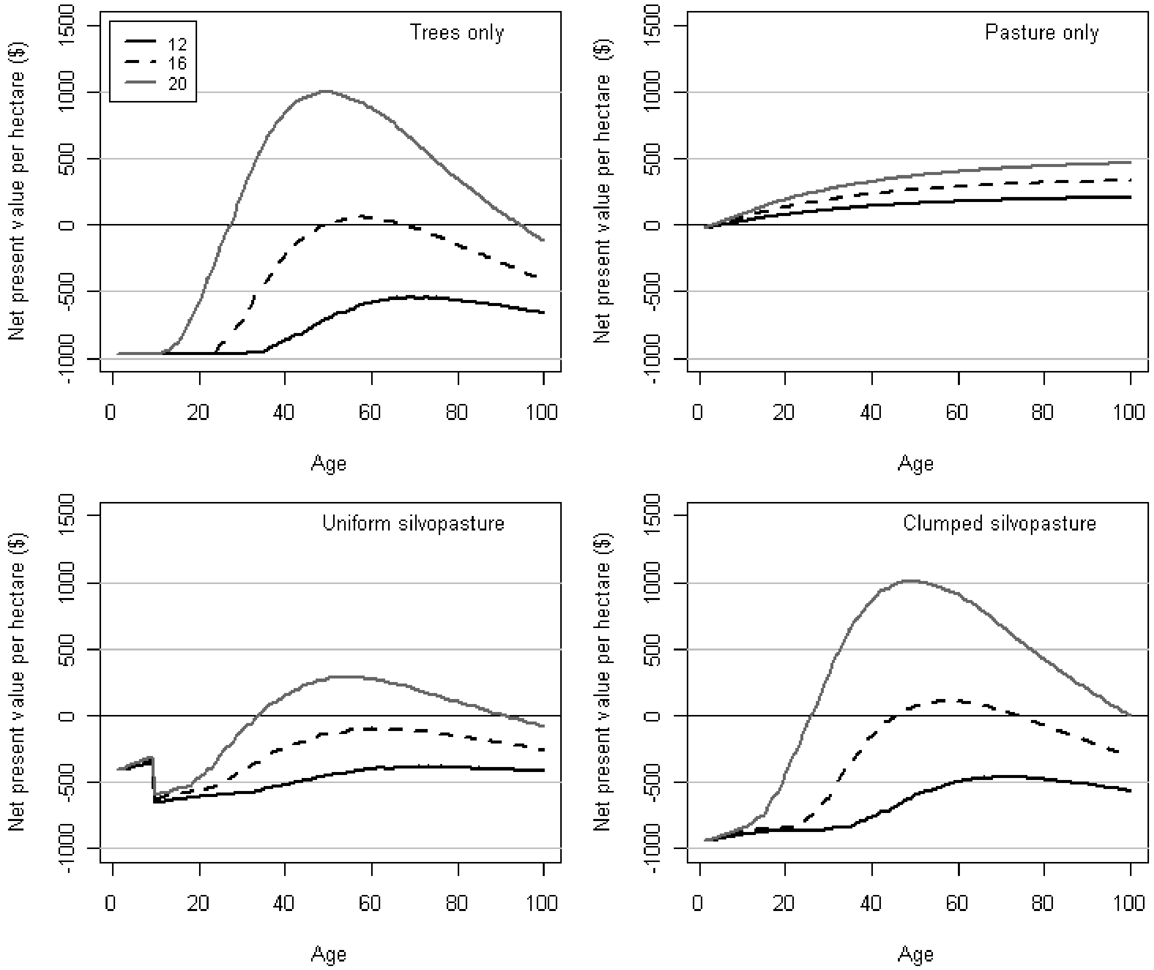

Figure 2.2: Total land commodity production net present values for three site productivities (12, 16, 20) of four scenarios: trees only, pasture only, silvopasture with uniform tree spacing and density of 250 sph, and a clumped silvopasture with tree density of 1000 sph and 10% of the stand allocated to grazing.

The internal rate of return results indicate that pasture-only systems are much more productive than those systems that incorporate trees (Table 2.2). The site index does increase the IRR as investments made into more productive land result in higher growth and larger returns. There is little difference between the tree only, forest with interim grazing, uniform silvopasture and clumped silvopasture systems at site indices of 12 and 16. However, the reduced profitability of the uniform silvopasture on a site index of 20 is evident when compared to the other treed systems. Compared with the Figure 2.1 discount rate alterations, increasing the site index of highly productive sites provides the added benefit of a shortened rotation age, represented by the peak of the net present value curves (Figure 2.2).

Table 2.2: Internal rates of return of scenarios over three site indices (12, 16 and 20) at age 50 using a discount rate of three percent, sawlog value of \$44.29 m^{-3}, and pasture rental of \$12.00 AUM^{-1}.

Scenario	Site Index 12	Site Index 16	Site Index 20
Trees only	5%	10%	16%
Pasture only	27%	38%	47%
Forest w/ interim grazing (tree spaced 1000 sph)	5%	11%	16%
Silvopasture (uniform spacing at 250 sph)	4%	10%	13%
Silvopasture (tree spacing at 1000 sph w/ 10% open canopy for pasture)	5%	11%	16%

The density of trees planted in an integrated forage and timber system results in varied outcomes depending on the site index and discount rate (Figure 2.3). Values are compared over two discount rates (3 & 4 %) and three site indices (12, 16 & 20) using constant sawlog values of \$44.29 m^{-3} and a pasture rental rate of \$12.00 AUM^{-1}. As mentioned previously, only pasture systems result in positive returns at site indices of 12, and the 1000 sph stand with interim grazing results in the highest returns of the treed systems. On sites with an index of 16, pasture systems still produce the highest net present returns, and the 1000 sph stand with interim grazing also provides positive returns of the treed systems. However, on sites with an index of 16 and discount rate of 4%, net present returns from the 250 sph silvopasture are equivalent to that of the 1000 sph stand with interim grazing. High productivity sites result in the 1000 sph stand with interim grazing producing the highest net present values, although less so for discount rates of 4% as little difference exists with the pasture under these conditions. Furthermore, all systems result in positive returns on a site index of 20 with a discount rate of 3%, and the 500 sph uniform silvopasture system results in similar returns than pasture-only systems. No uniform spacing silvopasture provides net present returns at a discount rate of 4% and a site index of 20.

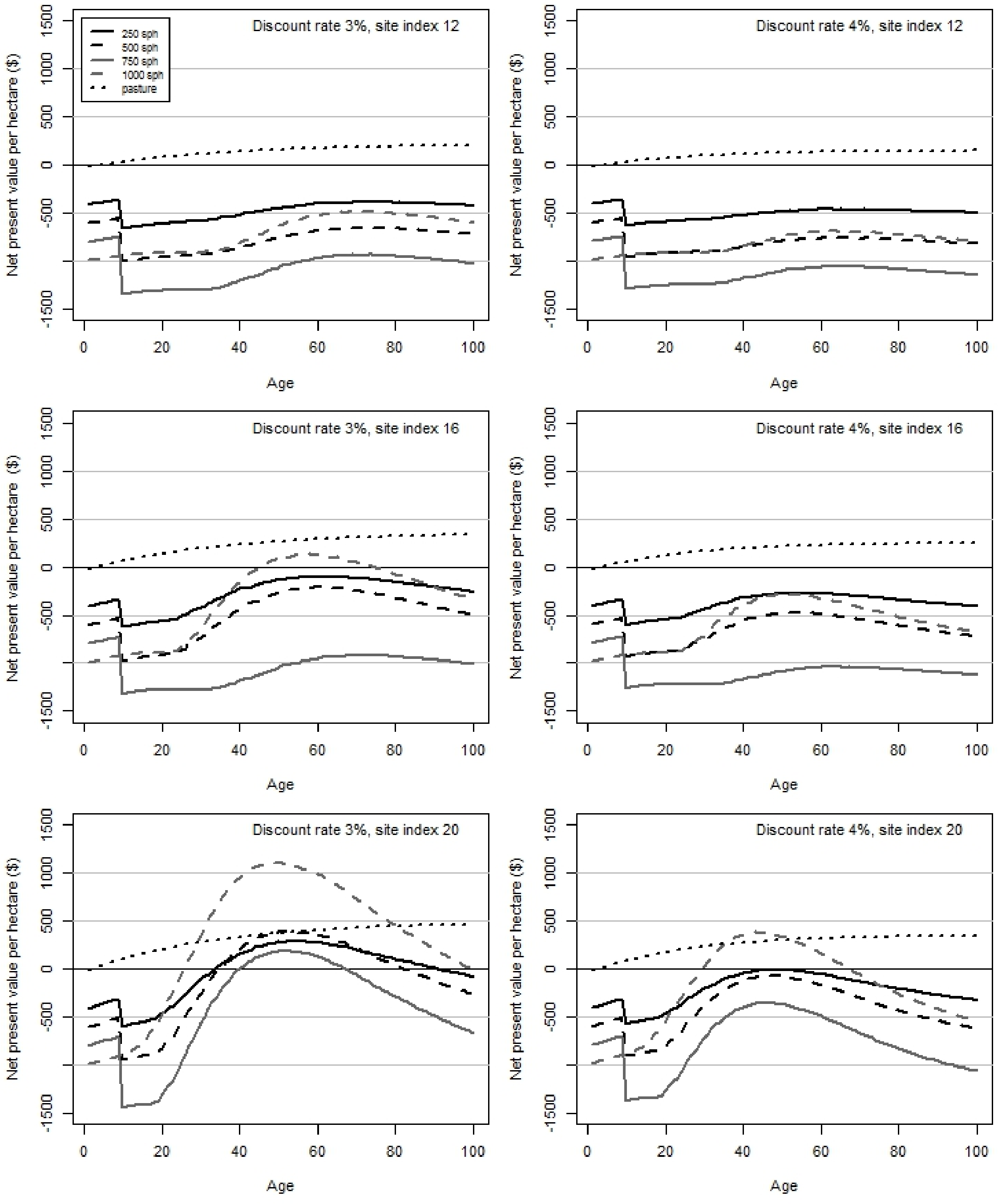

Figure 2.3: Net present value of timber and forage integrated within four stand densities (250, 500, 750 and 1000 sph) in comparison to a forage-only system (pasture).

Commodity prices have an impact on the estimated net present values generated, particularly timber price fluctuations (Figure 2.4). Values are compared over three sawlog values ($40.00, $44.00, and $48.00 m^{-3}) and three pasture rental rates ($10.00, $12.00, $14.00 AUM^{-1}).
The resulting differences in NPV are less pronounced over the range of expected high and low commodity prices than the changes in NPV over the range of discount rates or site indices. The lowest sawlog price does not result in positive net present values in the forest system with interim grazing, or the clumped silvopasture system, and no sawlog value allows for the uniform silvopasture system to break even. Changes in pasture rental rates result in less pronounced changes to the resulting NPV. Overall, little difference in estimated NPV exists between the forest system with interim grazing and the clumped silvopasture system.

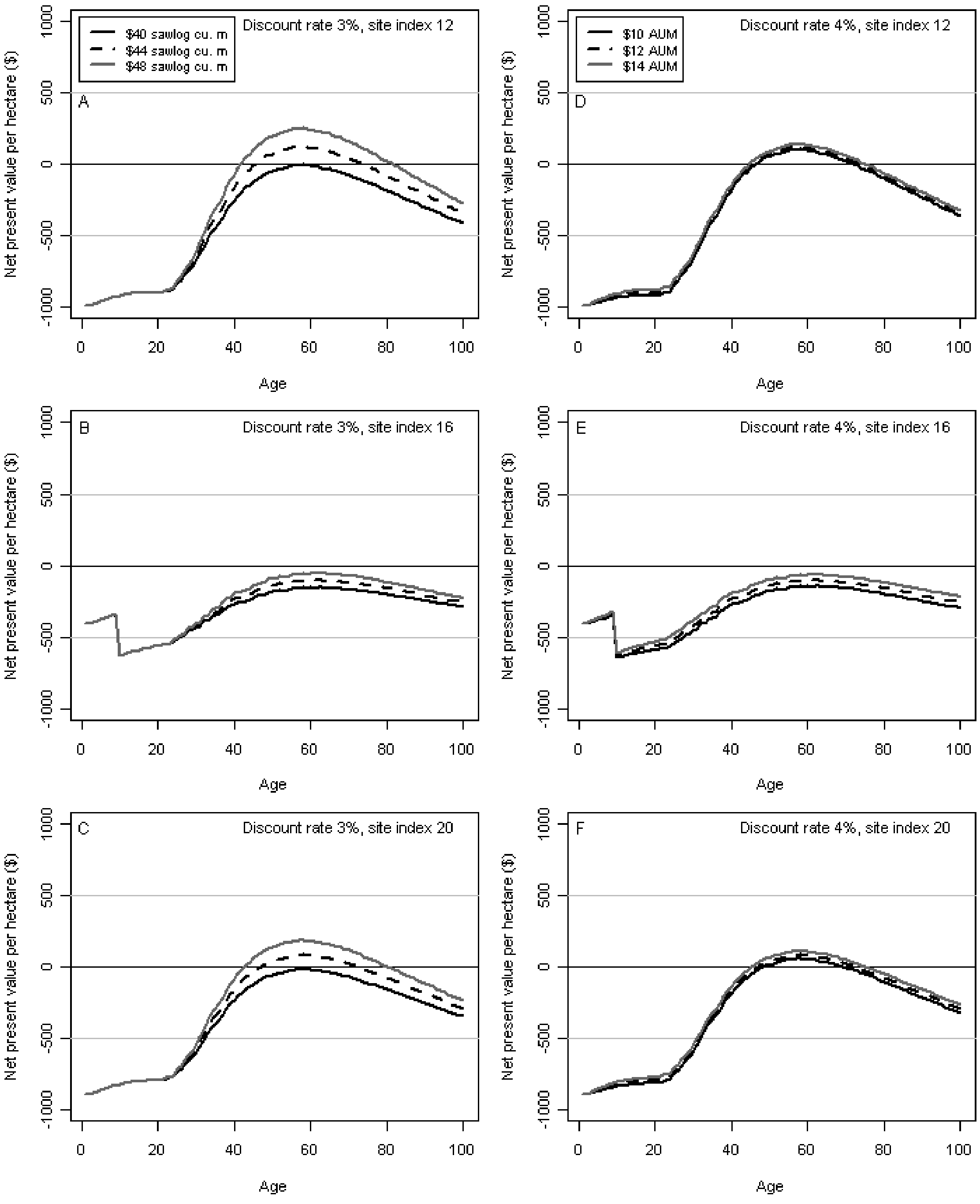

Figure 2.4: Total timber and forage net present values of forst and silvopasture systems over three sawlog prices ($40.00, $44.00 and $48.00 m^{-3}, figures A, B and C) and three pasture rental rates ($10.00, $12.00 and $14.00 AUM^{-1}, figures D, E and F). Three integrated systems presented are: a conventional forest with interim grazing (A and D), a uniform distribution silvopasture with tree density of 250 sph (B and E), and a clumped silvopasture with a tree density of 1000 sph and 10% of the stand allocated to grazing (C and F).

Modeling Discussion

The modeling outputs provide support for the modeling hypothesis that there is no difference between conventional lodgepole pine plantations and clumped lodgepole pine silvopasture systems. Compared to these systems however, the relatively low value resulting from reduced-tree density silvopasture systems indicate that lodgepole pine may not be a species well suited to stands with wider espacement for the allowance of understory forage production. My modeling results indicate that clumped silvopasture systems will meet the basic agroforestry objective of diversified resource commodities when implemented into traditional lodgepole pine plantations. Although Sullivan et al. (2006) reported an increase in individual tree volume in thinned lodgepole pine stands generally, a downfall of this approach is the loss in value of the logs because of reduced clear wood free of knots (BC Forest Service 2002). This information leads me to believe that lodgepole pine may not be suitable for reduced density planting configurations if the stand objective is to produce sawlogs for structural timber, but modeling forage yield under these stands will provide insight into the potential silvopasture applicability of lodgepole pine.

In the scenarios examined, discount rates of 5% or greater resulted in negative returns on investment for any scenario that included trees. Due to the initial cost of tree planting and limb pruning in the spaced-tree silvopasture scenarios, only pasture scenarios result in positive returns from the seeding investment at discount rates of five percent or higher. A minimal discount rate of two percent results in estimated outcomes that are large compared to planting and seeding investments, but this discount rate is realistically too low and outside of the range of other similar studies. Although reducing the discount rate to 2% does increase the anticipated value of systems that include a tree component, it also increases the plantation harvest age. Price (1995) recommends that moderate rates provide an advantage for agroforestry, and my model appears to support this.

In stands with a site index of 16, the seeded pastures have a larger value than the forested stands, however the opposite is true for sites with an index of 20 where the forest scenarios with or without interim grazing both value higher than areas dedicated to forage production (Figure 2.3). Herein lays the importance of site index in interpreting predictive modeling outputs, but simply stating that lower productivity sites are conducive to forage production and higher productivity sites are only suitable for timber production violates the value of diversification as a basic premise of agroforestry implementation. If the wood product market were to change in coming decades, and larger, lower density trees grown in spaced settings are desired, there may be a potential for lodgepole pine use in uniform distribution silvopastures with wider inter-tree espacement. Larger trees are often preferred over smaller trees for greater use of recoverable volume in the production of timber (Rotherham and Mooney 1988), and this would be enhanced should the value of larger trees increase relative to smaller individual trees. This could potentially justify the added management cost of the pruning entry, but again wood product development in the future may forego strength for the sake of biomass production for bioenergy as an example, and therefore an unpruned, larger tree could be of high value.

No spaced-tree silvopasture implemented in a stand with site index of 12 resulted in positive revenue, however the 250 sph system resulted in the least loss on investment of the three systems, and the 750 sph in the highest estimated loss. The reduced-density stand is the highest valued of the three simulations likely because of the relatively high value of the increased forage production under the least shaded conditions in these low productivity systems. Considering the same three silvopasture scenarios implemented on sites with an index of 16, the results are similar, as the lowest density stand resulted in the highest NPV, albeit at a loss on investment, and the 750 sph stand resulted in the greatest loss on investment (Figure 2.3). Slightly different results were shown from modeling spaced-tree stands on a site index of 20. All three spaced-tree silvopastures resulted in positive returns on investment, and the 500 sph stand was the highest valued system (Figure 2.3). Like the silvopasture scenarios in sites of index 12 and 16, the 750 sph system resulted in the lowest NPV for a site index of 20. However, their low value compared to a conventional tree stand or pasture reduces their applicability in real-world situations.

The clumped silvopasture systems were estimated to be the higher valued of the silvopasture systems according to the model. Although the clumped system resulted in negative results for site index of 12, again likely due to the cost of planting trees on site of very low productivity, all clumped silvopasture systems resulted in higher estimated returns than any of the uniform distribution silvopasture systems. The value of these systems was comparable to the conventional forest systems with interim grazing (Figure 2.3). The clumped silvopasture resulted in total net present values of 98 and 94 percent of the total NPV of the conventional system with interim grazing for a site index of 16 and 20 respectively. Furthermore, both clumped systems established on a site index of 16 and 20 resulted in higher future returns than tree-only systems. The clumped-tree silvopasture systems can be used as a tool for forest managers to provide forage for livestock in lodgepole pine forests where planned, semi-annual tree harvesting does not occur. Where consistent interim grazing opportunities are not provided by regular tree harvesting, a clumped silvopasture approach provides a viable management option for the integration of livestock grazing in lodgepole pine stands.

Integrating forage production in British Columbia’s lodgepole pine forest-dominated rangelands requires a small proportion of a range management unit be managed for diversified timber and forage objectives. This is particularly critical for situations where a livestock producer relies on consistent, semi-annual forest harvesting within a defined range management area for a steady supply of cutblocks to support interim livestock grazing. In order to achieve a holistic land-use system, both respective land uses may make relatively small sacrifices when compared to a monoculture crop, but the resulting system can increase the total combined productivity of timber and forage. The longer-term provision of forage in the clumped silvopasture is a key component in forested rangelands that utilize the temporal supply of forage in the cycle of new cutblocks resulting from timber harvesting, particularly during periods of cyclical disruption such as log market price fluctuations and extensive salvage harvesting following bark beetle mortality.

Chapter 3. Forage grass growth, morphology, and nutrient response to simulated shading and grazing

Introduction

Forage species used for livestock production in silvopasture systems should be tolerant of grazing, while capable of persisting and producing palatable and nutritious forage under partially shaded conditions. Persistence of grazed forage grasses under shade is a function of their ability to maintain biomass production and reproductive capability under grazing stress and reduced irradiance. Belesky (2005) has recommended that moderate grazing pressure should not be exceeded for forages grown under shaded conditions in order to maintain long-term productivity and persistence. The ability of a plant to produce carbohydrates for plant growth is often measured by the production of biomass and number of tillers produced (Willms and Fraser 1992, Belesky 2005). The production of flowering parts under shade, an important trait for the persistence of a forage species subjected to understory conditions found in silvopasture systems, is also poorly studied. Agronomic species have been selected with tolerance to heavy removal of leaf area for use in both hay and improved range applications.

Morphological adaptations to shade include increased leaf area to weight ratio (LAR), Allard et al. 1991, Kephart and Buxton 1993, Lin et al. 2001) as plants respond to shade by allocating more energy as structural carbohydrates to allow for foraging of the leaves to capture a greater amount of light (Sanderson et al. 1997). These morphological changes have been shown to affect the nutrient values of forage (Lin et al. 2001, Belesky et al. 2006). The increase in structural carbohydrates is seen as higher hemicellulose and lignin concentrations as physiological processes are altered under shade to enhance the efficiency of carbon utilization (Sanderson et al. 1997). This translates into a decrease in digestibility and uptake by livestock as increased structural carbohydrates reduces intake due to slower rates of digestion. However, protein concentrations can be increased under shade (Kephart and Buxton 1993, Lin et al. 2001, Kesting et al. 2009), resulting in higher animal weight gain. Although applying forage quality indicators to cattle weight gain can be difficult because rumen digestibility and animal weight gain is subject to many interacting factors, the outcomes of the study can be used to make predictions about animal performance.

Pinegrass (*Calamagrostis rubescens* Buckl.) is the most common grass species that dominates the understory of the Interior Douglas-fir zone in British Columbia (Tisdale and McLean 1957) and provides a major contribution to the overall forage supply on forested range (McLean 1967). Pinegrass is not an ideal forage grass because it loses nutritional value for cattle as the growing season progresses resulting in reductions in cattle weight gain (McLean et al. 1969). Rough fescue (*Festuca campestris* Rydb.) is less common than pinegrass due to its mesic site preferences and limited distribution (Hodgkinson and Young 1973), but retains high quality forage throughout the growing season and into autumn and winter months (McLean and Wikeem 1985). Rough fescue is a preferred forage by livestock and wildlife (Willms and Kalnin 1980, Wikeem et al. 1993) and very susceptible to overgrazing (Willms and Beauchamin 1991). As a result, long periods of rest from grazing are required for the adequate recovery of rough fescue (Dormaar and Willms 1990) making annual livestock production challenging unless recommended utilization rates are never exceeded or a high intensity, low frequency grazing regime is implemented.

Orchardgrass (*Dactylis glomerata* L.) is an important agronomic grass to agricultural producers throughout most temperate regions in both the northern and southern hemispheres.
Seeding agronomic species such as orchardgrass and perennial ryegrass *(Lolium perenne* L.) is a once-common practice used to increase the quantity and quality of forage for livestock grazing (McLean and Clark 1980). The high shade tolerance of these species in agroforestry applications has been well researched (Kephart et al. 1992, Kephart and Buxton 1993, Burner 2003). However, few studies have compared the production and morphological development of pinegrass and rough fescue with the developed agronomic forage species orchardgrass and perennial ryegrass under shading and grazing, and the resulting affect on forage quality.

The objectives of this study were to evaluate the effects that shading and clipping have on the growth and morphology of four forage grasses, two native and two agronomic, and to compare the productivity and relative forage value of the agronomic and indigenous species under simulated shaded conditions, as would exist in silvopasture applications. The field experiment tested three hypotheses relating to plant growth under shading and clipping treatments: 1) shading will reduce total tiller production, 2) clipping, as a surrogate for grazing, will reduce tiller production and, 3) the interaction between shading and clipping will have an additive effect to reduce plant tiller production. Also tested were two hypotheses of forage yield and quality attributes: 4) agronomic species will produce greater biomass and higher forage quality than native species, and 5) shading treatments will reduce forage quantity and quality.

Study site and methodology

The field experiment was conducted at the Agriculture and Agri-Food Canada Range Research Unit at Pass Lake, approximately 20 km north of Kamloops, British Columbia, Canada. The study site (120^{o} 28’ 48.4” 50^{o} 50’ 45.8”) was located on a south facing aspect with less than 5% slope. Soil was classified as a Grey Gleysol; the dominant tree species at the site is Douglas-fir and the site falls in the Interior Douglas-fir Biogeoclimatic zone (Lloyd et al. 1990). The understory is dominated by Kentucky bluegrass (*Poa pratensis* L.), Canada bluegrass (*Poa compressa* L.) and pinegrass, and common understory woody species include birch-leaved spiraea (*Spiraea betulifolia* L.) and common snowberry (*Symphoricarpos albus* L.). A 32 by 20 m, 2 m high page-wire fence was erected in the spring of 2009 to enclose the experiment (Figure 3.1) and exclude wildlife and livestock.

Figure 3.1: Pass Lake experiment installation, June 2009 looking west.

The test plants were started from seed in a standard potting soil in individual pots in the greenhouse during the winter of 2009, with the exception of the pinegrass which was started from separated ramets of plants collected near the study site. Rough fescue seed was collected from a site about 5 km southeast of the study site, and orchardgrass and perennial ryegrass seed was purchased from Purity Feeds in Kamloops, British Columbia, Canada. The site was prepared by tilling the site to a depth of 20 cm and raking out sod, rocks and remaining live vegetation. Some leveling of the site was done to homogenize the grade. Glyphosate spot spraying and handpulling was used to kill plants that either emerged from the seed bank or dispersed into the exclosure, and a one meter buffer of glyphosate was applied around the outer edge of the fence to reduce potential effects of plant roots from outside the experiment perimeter. Potted plants were planted out June 26 and 17, 2009. The site was layered with newsprint paper and covered in three to five cm of wood chips in order to reduce weed competition.

A fully randomized factorial design with six replicate plants included four shade treatments: ambient sunlight (control), one layer of shade screen, two layers of shade screen, and complete light blocking canopy to exclude most direct sunlight, x four forage grass species x two clipping treatments (clip to 12 cm or no clip) resulted in a total of 192 grass plant treatment combinations. The experiment site was divided into six blocks for each replicate per factor to take into account the slightly different conditions that may have existed from the previous experiment that covered two of the blocks. The shading treatment was accomplished by placing one or two one meter-squares of window screen with 1 mm mesh openings, or an opaque canopy (produced by Great Lakes Fabrics Inc.) over a frame consisting of a 1.3 m stake supported at a 35 degree angle directly south of the plant (Figure 3.1). One layer of mesh shade cloth was used to provide a shaded reduction in full sun by approximately 44%, and two layers were used to reduce available sunlight by 66%. An opaque canopy material was used to reduce full sunlight by 94% with reflected sunlight likely causing the five percent reading. Sunlight measurements were taken with a LI-COR Light Meter model LI-250 in May, August and October and averaged to provide the shade reductions indicated above. The two corners pulled in front of the plant on either side were pinned down to reduce or block sunlight throughout the growing season.

Figure 3.2: Shade structures covering individual rough fescue plants showing (front row, left to right): one layer of screen (44% shade), two layers of screen (66% shade), and full canopy shade treatments.

In the first week of June, 2009, the grasses were planted in rows 1.5 m apart with 1.5 m spacing between plants, and every second row was laterally offset to maximize the distance between test plants. The plants were grown over two growing seasons with the shade structures removed during the winter. Plants were clipped as a treatment to simulate moderate grazing and to provide samples for forage analysis. Clipping to a height of 12 cm was conducted on July 24th and August 24th of 2009 and June 28th, July 26th, August 24th, and September 22nd in 2010. Clipped samples were dried at 65 °C for 48 hours and the leaves were separated from stems and flowers and weighed. The clipped treatment samples were analyzed for forage quality predictions using a FOSS Infra-xact Near-Infrared Forage Quality analyzer. Where clipped samples were too small to analyze, samples were pooled together within species for each treatment. Tillers were counted from September 13-16, 2010 to measure grass response to the treatment combinations.

Statistical analyses were carried out using R software version 2.9.1 (R Core Development Team 2008). Normality was checked using the Kolmogorov-Smirnov test, and log transformation was used to normalize biomass data. A two-factor ANOVA was done to test the effect that shading and clipping treatments, and their interaction, had on tiller counts. A two-factor ANOVA was used to test the effect that shade and species had on total biomass production. ANOVA tests included the effects of experimental blocking, and were followed with Tukey's honest significant difference test to determine differences among means.

The effects of shade, species and clipping period on the near-infrared (NIR) spectroscopy forage quality predictions acid detergent fiber (ADF), neutral detergent fiber (NDF), lignin, protein, calcium, potassium, magnesium, and phosphorus were tested using a permutational three-factor MANOVA employing 999 permutations. NIR predictions were retested for the June, July, August and September clipping periods of 2010 independently using an ANOVA to test for differences between species, clipping treatments, and their interaction. NIR predictions were reanalyzed by testing the means of all six clipping periods in 2009 and 2010 for differences between shade factor means using a pairwise t test with a Bonferroni correction. Treatment effects were considered significant at $P <= 0.05$.

Results

All orchardgrass plants survived for the duration of the experiment, and pinegrass and rough fescue mortality was limited to four percent of total planted specimens (Table 3.1). Perennial ryegrass survival was low following winter of 2009/2010 with close to 42% mortality and excluded from several of the analyses due to replicate limitations.

Table 3.1: Mean values and number of subject plants per shading treatment remaining by October 2010 of the 12 seedlings initially planted (6 clipped / 6 unclipped).

Species	control	1 screen	2 screens	Full canopy
pinegrass	6 / 6	5 / 6	6 / 6	5 / 6
orchardgrass	6 / 6	6 / 6	6 / 6	6 / 6
rough fescue	6 / 6	6 / 6	5 / 6	6 / 5
perennial ryegrass	4 / 4	3 / 6	2 / 3	2 / 4

Tiller response to shading and clipping

Tiller counts decreased with both shading and clipping treatments (Table 3.2). Mean pinegrass tiller counts were reduced by 50% under full shade without clipping, and 75% under full shade with clipping while orchardgrass tiller reductions were slightly less at 56% and 66% respectively

(Table 3.2). Rough fescue showed a similar response to full shade with a 43% reduction in mean tiller counts from the control, but appeared to be least effected by shade and clipping with 30% of tillers when compared to ambient sunlight (Table 3.3). Apart from pinegrass under one layer of shade screen, tiller counts were fewer under clipping for all combination of factors. Tukey's Honestly Significant Difference post-hoc test revealed no differences among grass species means within factors for any of the means that were declared significant by ANOVA.

Table3.2: ANOVA results table for tillers counts under shade and clipping treatments, and their interaction.

Species	Factor	Df	F value	Probability
pinegrass n = 45	Shade	3	5.3020	0.00442 ***
	Clipping	1	5.4353	0.02619 ***
	Blocking	5	1.2778	0.2976
	Shade*Clipping	3	1.0809	0.3711
orchardgrass n = 47	Shade	3	7.6155	0.00050 ***
	Clipping	1	13.1077	0.00095 ***
	Blocking	5	3.3938	0.01358 *
	Shade*Clipping	3	0.6791	0.5709
rough fescue n = 47	Shade	3	1.8723	0.1529
	Clipping	1	2.5429	0.1200
	Blocking	5	0.4741	0.7929
	Shade*Clipping	3	0.2389	0.8686

Signif. codes: 0 '*' 0.001 '**' 0.01 '*' 0.05 '^' 0.1 ' '**

Table 3.3: Mean count values (and std. dev.) of total tillers produced per plant as of September, 2010.

	clipping	control	1 screen	2 screens	full canopy
pinegrass	no clip	421.0 (126.09)	293.7 (251.39)	382.5 (40.97)	206.7 (127.3)
	clipped	325.0 (131.74)	305.0 (181.50)	174.5 (105.60)	81.4 (56.78)
orchardgrass	no clip	474.8 (267.02)	481.7 (240.46)	302.8 (153.97)	209.0 (130.27)
	clipped	361.7 (199.66)	181.8 (134.0)	125.7 (38.06)	121.8 (68.32)
rough fescue	no clip	614.5 (318.77)	583.5 (334.45)	400.0 (273.51)	347.7 (199.31)
	clipped	381.3 (182.21)	478.2 (376.17)	325.2 (88.72)	266.2 (119.76)

Treatment effects on biomass production and forage quality

Total biomass production differed among species and decreased with increased shading (Table 3.4). Orchardgrass consistently produced more biomass at each clipping time than each of the other species and there were few differences in total biomass among the remaining three species (Figure 3.). Orchardgrass was also the most affected by shade with a 72% reduction in total biomass, compared to 64% for pinegrass and 40% for rough fescue (Table 3.5). Although perennial ryegrass produced more total biomass over the life of the experiment than pinegrass or rough fescue under ambient sunlight, one layer of screen and opaque canopy, most perennial ryegrass production can be accounted for by the first season before winter mortality reduced survival on many perennial ryegrass plants.

Table 3.4: ANOVA/MANOVA results table for total biomass production and forage quality predictions from monthly clipping periods June and July 2009 and June through September 2010.

Measurement and analysis (excluding ryegrass)	**factor**	**Df**	**F value** * approximated for MANOVA	**Probability**
Log of total biomass (g)	Shade	3	8.1317	0.0001***
All species	Species	3	44.6467	<0.0001***
Two-factor ANOVA	Blocking	5	3.0652	0.0157
n = 81	Shade*Species	9	1.163	0.3353
Forage quality	Shade	3	4.378*	<0.0001***
prediction	Species	2	65.472*	<0.0001***
MANOVA	Clipping period	5	22.232*	<0.0001***
n = 319	Species*Shade	6	1.898*	<0.0001***

Signif. codes: 0 '*' 0.001 '**' 0.01 '*' 0.05 '^' 0.1 ' '**

Table 3.5: Total mean plant biomass clipped above 12 cm grams/plant (and std. dev.) from monthly clipping periods June and July 2009 and June through September 2010.

Species	**control**	**1 screen**	**2 screens**	**canopy**
pinegrass	27.9 (8.12)	24.3 (9.11)	23.2 (15.76)	10.1 (13.26)
orchardgrass	331.8 (133.66)	236.6 (125.21)	154.3 (82.82)	94.4 (39.07)
rough fescue	35.6 (17.70)	38.5 (26.31)	27.45 (12.04)	21.4 (6.09)
perennial ryegrass	117.1 (82.46)	42.3 (25.28)	22.1 (25.81)	46.2 (59.36)

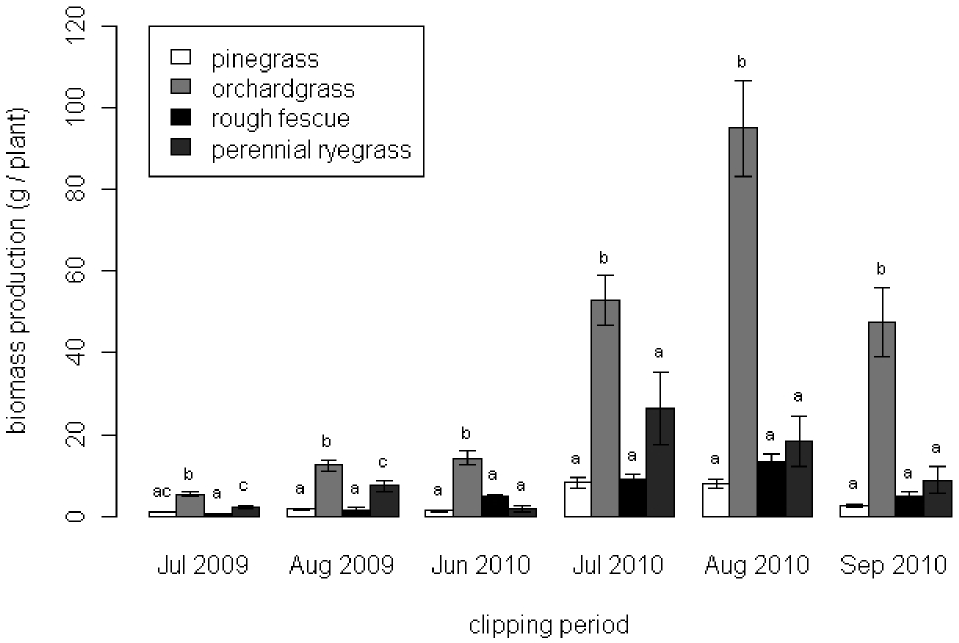

Figure 3.3: Biomass production by time of clipping and species (in g/plant). Significant differences between the log of biomass production by species in each clipping period is indicated by unique letters as determined using Tukey's Honest Significant Difference test.

Forage quality was affected by shade, and differences existed among species (Table 3.6); time as a blocking factor was also significant. A significant interaction between shade and species was also noted (Table 3.6). Mean forage quality predictions by species over the life of the experiment from NIR spectroscopy are displayed in Table 3.7, and forage quality predictions are further broken down by species for each of the four clipping periods in 2010 (Table 3.7). Orchardgrass was the only species that responded to shade with noted increases under full shade for ADF, NDF, lignin and potassium when compared to the control. ADF increased under full shade from the control for pinegrass and orchardgrass by 8.3 and 8.9%, and rough fescue showed no response. Mean NDF for pinegrass did not respond to shade , although increases in NDF under full shade occurred in orchardgrass and pinegrass by 16.3 and 6.5 %. Mean NDF in orchardgrass was the only predictor that was larger under 44% shade treatment with an increase of 9.3%. Orchardgrass was the only species that responded to 64 and 94% shade with an increase in mean lignin of 9.9% and an increase in mean potassium under full shade of 9.5%. Protein, calcium, phosphorus or magnesium did not respond to shading for any grass species.

Differences in forage quality predictions for 2010 existed between species in all clipping periods for ADF, NDF, lignin, protein, calcium and potassium (Table 3.7). Differences between species also occurred for phosphorus in July, August, and September, while magnesium was only different among species in June. ADF and NDF was affected by shade in August and September, and July, August and September, respectively while shade affected protein in July and August only. Some differences in micronutrients exist due to shade treatments as calcium was affected in June and August and potassium and phosphorus was altered in June.

Table 3.6: ANOVA results for NIR forage quality predictions by species, shade and their interaction: acid-detergent fiber (ADF), neutral-detergent fiber (NDF), lignin, protein, calcium, potassium, phosphorus, and magnesium; clipped June, July, August and September 2010.

Forage quality prediction	Factor	June		July		August		September	
		F value	Prob.	F value	Prob.	F value	Prob.	F value	Prob.
ADF	Species	14.3671	<0.00001***	22.7925	<0.00001***	20.2062	<0.00001***	10.1462	0.00024***
	Shade	0.5717	0.6367	1.8320	0.1539	3.0858	0.0353*	3.8336	0.01596*
	Species*Shade	1.1165	0.3688	0.4491	0.8420	0.3084	0.9297	0.8660	0.5273
NDF	Species	37.7848	<0.00001***	17.2424	<0.00001***	12.8021	<0.00001***	24.8418	<0.00001***
	Shade	0.7774	0.5130	3.7899	0.01613*	5.4690	0.002454 **	5.7155	0.00215**
	Species*Shade	0.8209	0.5599	0.4755	0.8231	0.1884	0.9787	1.4691	0.2110
lignin	Species	5.4198	0.00796**	3.7292	0.03123*	20.2800	<0.00001***	25.0824	<0.00001***
	Shade	1.8538	0.1518	7.5431	0.00031***	0.5138	0.6746	3.0601	0.0379*
	Species*Shade	1.0573	0.4027	0.2260	0.9663	0.6572	0.6842	1.5640	0.1804
protein	Species	12.3262	<0.00001***	6.5763	0.00299**	24.6712	<0.00001***	6.6538	0.00299**
	Shade	0.8947	0.4517	4.1875	0.01034*	3.7183	0.01706*	1.0886	0.3639
	Species*Shade	0.6344	0.7019	0.5781	0.7459	1.5387	0.1846	1.1028	0.3761
Ca	Species	69.9299	<0.00001***	85.9322	<0.00001***	24.8123	<0.00001***	43.7012	<0.00001***
	Shade	7.9149	<0.00026***	0.8933	0.4515	5.5734	0.002194 **	2.1050	0.1132
	Species*Shade	1.3724	0.2475	0.8046	0.5714	0.8424	0.54324	0.3158	0.9253
K	Species	53.0670	<0.00001***	25.3720	<0.00001***	14.8272	<0.00001***	9.3352	0.000412***
	Shade	1.2955	0.2882	7.9432	0.00021*	1.1675	0.33124	0.2114	0.8880
	Species*Shade	1.2535	0.2988	1.2930	0.2785	2.1910	0.05892^	0.5574	0.7616
P	Species	2.0506	0.1411	19.2970	<0.00001***	13.0412	<0.00001***	4.1474	0.0224*
	Shade	1.9799	0.1312	8.8692	<0.00001***	0.2011	0.8952	0.9283	0.4350
	Species*Shade	1.2341	0.3080	0.7948	0.5786	3.3541	0.00731**	2.3469	0.0472*
Mg	Species	16.4456	<0.00001***	2.8767	0.06608	1.0680	0.3513	13.5613	0.00003***
	Shade	3.7598	0.01749*	2.2596	0.09346	2.0236	0.1222	1.0497	0.3801
	Species*Shade	0.5572	0.76165	1.0030	0.43447	1.7451	0.1295	0.7717	0.5963

Signif. codes: 0 ‘***’, 0.001 ‘**’, 0.01 ‘*’, 0.05 ‘^’, 0.1 ‘ ’

Table 3.7: Mean (and std. dev.) of all NIR forage quality predictions: acid-detergent fiber (ADF), neutral-detergent fiber (NDF), lignin, protein, calcium, phosphorus, potassium, and magnesium, by species and shade treatment. Significant differences between shade treatment means within rows, are indicated by unique letters.

Mean forage quality prediction	Species	Control	1 screen	2 screens	canopy
ADF	pinegrass	26.74 (2.92) **ab**	26.60 (2.38) **a**	27.97 (2.87) **ab**	29.14 (3.15) **b**
	orchardgrass	27.05 (3.72)	29.40 (3.44)	29.31 (4.43)	29.70 (4.5)
	rough fescue	30.26 (4.03)	31.17 (3.31)	32.12 (3.70)	31.45 (3.06)
NDF	pinegrass	52.62 (4.92)	52.18 (3.20)	53.43 (4.82)	54.95 (4.04)
	orchardgrass	43.29 (5.46) **a**	47.74 (5.08) **ab**	49.25 (4.87) **bc**	51.73 (5.58) **c**
	rough fescue	55.33 (4.18) **a**	56.66 (3.11) **ab**	58.42 (4.49) **b**	59.19 (2.87) **b**
lignin	pinegrass	4.98 (0.82)	4.94 (0.79)	5.08 (0.67)	5.13 (0.60)
	orchardgrass	5.02 (0.71) **a**	5.26 (0.64) **ab**	5.53 (0.54) **b**	5.57 (0.69) **b**
	rough fescue	5.49 (0.98)	5.66 (0.75)	5.83 (0.86)	5.74 (0.63)
protein	pinegrass	19.54 (2.96)	19.51 (2.11)	19.14 (2.68)	19.57 (2.55)
	orchardgrass	19.01 (3.59)	18.44 (3.64)	19.32 (3.66)	19.16 (3.37)
	rough fescue	17.93 (3.35)	17.90 (2.77)	17.20 (2.78)	16.99 (2.18)
Ca	pinegrass	0.49 (0.12)	0.51 (0.12)	0.50 (0.08)	0.48 (0.07)
	orchardgrass	0.63 (0.14)	0.59 (0.11)	0.59 (0.12)	0.58 (0.12)
	rough fescue	0.36 (0.11)	0.32 (0.09)	0.35 (0.13)	0.33 (0.07)
K	pinegrass	3.33 (0.38)	3.44 (0.26)	3.54 (0.35)	3.68 (0.30)
	orchardgrass	3.89 (0.42)	3.95 (0.48)	4.11 (0.36)	4.00 (0.33)
	rough fescue	3.32 (0.51)	3.33 (0.35)	3.21 (0.42)	3.27 (0.31)
P	pinegrass	0.35 (0.05)	0.34 (0.04)	0.36 (0.05)	0.38 (0.05)
	orchardgrass	0.38 (0.03)	0.39 (0.04)	0.40 (0.03)	0.38 (0.03)
	rough fescue	0.39 (0.05)	0.42 (0.04)	0.39 (0.04)	0.39 (0.03)
Mg	pinegrass	0.19 (0.02)	0.20 (0.015)	0.19 (0.02)	0.19 (0.02)
	orchardgrass	0.20 (0.02)	0.20 (0.016)	0.20 (0.02)	0.20 (0.02)
	rough fescue	0.19 (0.02)	0.19 (0.02)	0.19 (0.02)	0.19 (0.02)

Screening discussion

Plant productivity under shade and clipping

Effect of shade on tiller count

The study showed support for the first plant screening hypothesis that tiller counts would be decreased under shaded conditions; there was a reduction in tiller counts under shade for both pinegrass and orchardgrass, however it did not appear that shade affected tiller counts in rough fescue. The latter response could be due to the large number of tillers that comprise each rough fescue plant in comparison to the other two species tested. The high number of morphologically smaller-sized tillers, and high variance in the data, could also have resulted in the insignificant results, although there did appear to be a general trend towards reduced tiller production in both clipped and unclipped rough fescue plants. Considering tiller counts as a proxy for overall productivity, it would appear that production was compromised by shade. Maximum photosynthetic capacity is reduced under shade (Allard et al 1991) as leaves acclimated to reduced solar radiation develop to maximize light absorption under a range of light environments (Evans 1989). This tradeoff in primary productivity reduces total carbohydrate production under shade. Wan and Sosebee (1988) noted reduced tiller response to reduced photosynthetically-active radiation in *Eragrostis curvula*, a subtropical grass species, which is consistent with my findings in pinegrass and orchardgrass. Simulated shade, as a surrogate of the conditions found in heavily shaded-silvopasture systems, reinforces evidence of the effect of shade on understory forage production.

Effects of clipping on tiller count

The response of tiller count to clipping treatments supported my second hypothesis that clipping would reduce tiller counts, with similar results to that of the shade treatments. The treatment effects were significant for pinegrass and orchardgrass, but not rough fescue. This could also be attributed to the high number and variability in tiller counts of rough fescue plants. However, there did appear to be a trend towards reduced tiller production in rough fescue resulting from clipping which supports findings by Willms and Fraser (1992). Field studies have shown that this species provides lower mean annual yields when subjected to continuous defoliation (Dormaar and Willms 1990). Results were consistent with findings by others with respect to Pinegrass (Stout et al. 1980), and orchardgrass (Volesky and Anderson 2007), and similar results were noted in perennial ryegrass (El Hassan and Krueger 1980). As a proxy for overall production, reductions in tiller counts as a result of clipping was expected as photosynthetic material was removed therefore reducing the ability to produce carbohydrates. As a surrogate for grazing, clipping reduces forage production, and applying this response to forage systems results in reductions in plant vigor and deterioration of range and pasture systems.

Shade and clipping treatment interaction on tiller counts

The third hypothesis stated that there will be an additive effect on tiller counts as a result of both shade and clipping treatments which is supported by the lack of interaction, as noted by Table 3.2. This is most evident in pinegrass as tiller production is reduced by 40% under full shade, and 19% under both full shade and clipping. These results are very similar for orchardgrass, while rough fescue remains consistent with its response to shade and clipping separately in appearing to best tolerate the combination of shade and clipping. Using tiller production as a proxy for the ability to produce forage the results suggest that rough fescue is best suited to the shaded conditions created in silvopasture conditions of the three species discussed here. Although rough fescue is tolerant of repeated grazing at moderate utilization rates similar to the clipping height applied in this experiment, the susceptibility of diminished rough fescue performance to repeated grazing (Dormaar and Willms 1990, Willms and Fraser 1992), applying these results to silvopasture systems should be considered with caution. It is surprising that tiller production in orchardgrass was not as tolerant to shade and clipping compared to rough fescue, but no studies have compared the two species directly. The suitability of orchardgrass for use in silvopasture systems has been previously documented (Devkota et al. 1997, Peri et al. 2007), as well as the ability of pinegrass to provide for forest grazing values (McLean 1967, 1972). In addition to these species I conclude that rough fescue is a suitable candidate for silvopasture systems as well, for those areas where rough fescue currently exists.

Forage production and quality under shade

Comparison of agronomic and native forages

I find support for my fourth hypothesis that the agronomic species produce more forage than native species. I found that orchardgrass produced a significantly greater amount biomass compared to pinegrass and rough fescue. Under ambient sunlight, orchardgrass plants produced a total of 11 and 9 times more total biomass than pinegrass and rough fescue over the life of the experiment, but the differences were reduced under increasing shade. Orchardgrass biomass production under full shade decreased more than pinegrass and rough fescue relative to control. Rough fescue appeared to be slightly more productive than pinegrass under continuous clipping. Perennial ryegrass produced more total biomass than rough fescue or pinegrass but a large majority of this was accounted for in the first season before winter mortality reduced the number of surviving individuals, and only a few of those remaining were healthy enough to produce any significant amount of biomass. Perennial ryegrass has been shown to be intolerant of freezing temperatures (Xiong et al. 2007), and the mortality observed at the Pass Lake suggests that this species is not suited to higher elevation forested range in the interior of British Columbia.

With smaller decreases in biomass production under full shade, it would appear that rough fescue and pinegrass were more shade tolerant than orchardgrass. Studies that have screened growth of orchardgrass against other species such as tall fescue (*Festuca arundinacea* Shreb.), smooth brome (*Bromus inermis* Leyss.), and browntop (*Agrostis capillaris* L.) under shade (Kephart et al. 1992, Lin et al. 2001, Belesky et al. 2006, Peri et al. 2007) all noted the high production potential and tolerance to shade of orchardgrass, but no previous studies have compared it to pinegrass or rough fescue.

Effects of shade on forage quality

I find support for my final hypothesis. Responses to decreased ambient sunlight were positive for mean ADF and NDF in orchardgrass indicating decreased digestibility under full shade. Differences in mean ADF between full shade and the control are significant for pinegrass yet not rough fescue, and the opposite is true for mean NDF. This could suggest that rough fescue and pinegrass have varied morphological responses to reduced irradiance as pinegrass may invest more carbohydrate energy into lignin and undigestible cellulose than rough fescue. This is supported by a decrease in digestible dry matter under full shade for pinegrass but not rough fescue. This is consistent with characteristics of pinegrass noted by McLean (1967) as palatability is decreased typically by August, coinciding with a drop in nutritive value due to late summer senescence (McLean et al. 1969). The significance of the time of clipping is explained by effects on ADF and NDF as each growing season progressed as there was a trend towards higher indications of digestibility in the first clipping of each season. This is supported by research of Belesky et al. (2006) on orchardgrass that analyzed forage quality over the growing season and found decreasing total digestible nutrients under shade.

I expected to see an increase in lignin as the proportion of indigestible, structural carbohydrates increased, but pinegrass results did not reflect this. Only orchardgrass lignin concentrations responded positively to increased shade. I also noted increased lignification under shade which supports similar findings in the literature (e.g., Samarakoon et al. 1990) and there was an effect on lignin concentrations in July and September sampling periods. There were no alterations of lignin under shade in rough fescue. Protein was not affected by shade in any of my independent species analyses, although there was an effect on protein over all species in July and August. This lack of response is not consistent with previous studies that have found an increase under shade in protein concentrations of orchardgrass (Allard et al. 1991, Lin et al. 2001, Koukoura et al. 2009). Soil water content in the experiment appeared to be greater under the wood chip mulch than outside conditions (data not shown). The site was well watered until June 20th to encourage high plant survival during the establishment phase, and the wood chip mulch maintained soil moisture effectively to eliminate drought throughout the remainder of 2009. Furthermore, higher than normal precipitation for 2010 resulted in relatively wet soil conditions throughout the second growing season. This lack of drought is not characteristic of conditions found in the Interior Douglas-fir zone that often experiences annual drought in the summer months (Tisdale and Mclean 1957), and results could have differed if the added stress of water deficits were added to the experiment. The high water content in the soil of the experiment likely allowed growing conditions to continue for all species and treatments longer than would regularly be expected. As a result the forage quality was likely maintained longer in the growing season and therefore the effects from treatments may not have been as substantial.

Screening conclusion

Reduced irradiance decreased forage production of all species in our study, regardless of clipping. However, the high productivity of orchardgrass compared to pinegrass and rough fescue clearly overshadows the relatively minor effects imposed by reduced ambient sunlight. This was particularly apparent when the plants were clipped as orchardgrass is an improved agronomic forage grass that has been developed to provide high production with good forage quality well suited as an agricultural pasture and hay species. Many studies have expressed the high tolerance of orchardgrass to shaded conditions such as those found in silvopasture applications, and although both pinegrass and rough fescue appear to be more tolerant of shade, their capacity to produce large amounts of high quality forage does not compare to the fast-growing nature of orchardgrass and its continued production under regular removal of leaf tissue. These traits support the use of orchardgrass to significantly improve the production of forage in improved range and silvopasture applications, and consider the potential in other agronomic species to dramatically improve forage production.

Chapter 4. Thesis discussion

Predicting resource economics beyond fifteen years into the future is difficult due to climate and market uncertainty and unforeseen circumstances. As the mountain pine beetle outbreak in British Columbia has shown, long-term timber planning is easily disrupted by forest health factors, and a changing climate could further exacerbate insect and disease problems. Studies and applications of agroforestry systems are implemented for an increase in productivity potential of multiple integrated crops, as compared to single crop systems. In the case of lodgepole pine forests in British Columbia, the unpredictable nature of the many forest pests that use this species as a host can result in extensive stand mortality. Therefore diversifying commodities produced in these forests reduces the risk of losing extensive crops, and provides a second commodity to stabilize incomes during times of poor market prices and pest and disease outbreaks. Regular tree harvests provide steady income for the forest industry, as well as a regular supply of cutblocks for livestock grazing for several years until planted trees reduce understory vegetation production and cattle are drawn to freshly harvested cutblocks for forage.

Environmental stochasticity challenges this traditional use of lodgepole pine forests when disturbance events such as pest outbreaks and wildfire impacts disrupt regular harvesting schedules. The subsequent rotational supply of forage produced when forest management activities remove forest cover and release the growth of understory vegetation is eliminated as regular semi-annual tree harvesting does not provide for interim grazing following a continuous supply of freshly harvested cutblocks. However, disruptions to the normal cycle of harvesting can result in forage shortfalls during downturn periods in logging if the grazing unit of reference is too small or the proportion of salvage harvesting area is too large. This can occur if specific pastures with allocated forage requirements are harvested, and regenerating trees reduce available forage below the required carrying capacity. Although the two resource commodities are diversified on the landscape so as to support both the timber and livestock industries, the diversification relies on regular harvesting intervals, and the creation of roadsides, landings and other disturbed areas to be seeded for forage production. Providing areas specifically for forage production within a conventional forest is not a common practice, therefore livestock grazing is limited to marginal areas. The benefits if this, apart from an increase in forage availability to cattle, include the ability to draw cattle into improved areas in order to limit their impacts on areas where undesirable damage may occur such as riparian areas, sensitive soils, and tree plantations managed solely for timber regeneration. The weakness of this system can only be corrected by providing adequate permanent forage within the livestock producer's summer range area within a lodgepole pine forest.

With potentially enhanced pest activity in a changing climate resulting in unseen forest ecosystem dynamics, new approaches are needed to manage these forests (Seastedt et al. 2008) that are susceptible to extensive mortality. For extensive interior lodgepole pine plantations established in areas providing summer range, silvopasture systems offer an opportunity to provide an immediate annual return due to grazing values, and a permanent supply of both tree and forage resources for the two industries that rely on them. The mountain pine beetle epidemic in B.C. will result in an estimated 65% pine volume killed by the year 2016 (BC Ministry of Forests, Lands and Natural Resource Operations 2010). This catastrophe highlights the opportunity to incorporate diverse commodity values in order to reduce the risk of large losses to single-crop systems. Silvopasture systems manage these risks by integrating land use objectives for, in the case of this study, lodgepole pine plantations and forage production for cattle grazing.

Lodgepole pine evolved as a coniferous pioneer species that reproduces and germinates readily under a wide array of environmental conditions (Koch 1996). Following a stand-replacing fire event, the natural recruitment of lodgepole pine can result in high stand densities and crowded restocking (Koch 1996). As a result, this species has evolved to tolerate dense conditions and self-prunes readily as individual tree crowns become narrow and limited to the upper portion of the stem only while maintaining similar stand timber volumes in both moderate and high density stands. (Sullivan et al. 2006). This strategy opposes that of Ponderosa pine (*Pinus ponderosa*) that performs poorly under crowded stand conditions (Sabo et al. 2008). In conclusion, lodgepole pine is not suitable for open silvopasture designs of reduced tree densities. Although a larger canopy will result in large individual trees and relatively lower overall volume per stand (Smith and Long 1989), the potential for poor wood quality exists as trees will have crowns that develop over a larger proportion of the bole resulting in more knots and lower timber value. Pruning the lower branches can be applied to reduce the number of knots which results in an increase knot-free bole and stronger wood (Long 1985) and a higher value timber product (Jozsa and Middleton 1994). Moderate densities with moderate growth rates have the ability to efficiently produce stemwood (Smith and Long 1989), and self prune to eliminate pruning costs, both of which are characteristics that could work in a clumped silvopasture design.

In other pine silvopasture systems of species with large crown attributes and an even distribution of well-spaced trees, pruning boles would be appropriate. However, the ability of lodgepole pine to tolerate some crowding makes it a better candidate in a clumped distribution of tree islands. Tree density within the islands set at conventional plantation densities to maximize wood production would likely keep livestock between islands thereby reducing tree damage due to cattle rubbing and trampling. Clumping trees together can encourage more self-pruning resulting in higher wood value (Koch 1996), while providing openings and corridors of improved pasture to increase forage. Accessibility to tree islands through pasture corridors is an added benefit which would be convenient for harvesting islands, salvaging those with pest damage, or removing infested trees in islands capable of spreading to other islands. The role of shade as it affects forage quality is removed in this system, as pastures between tree clumps (apart from those experiencing the edge effect of the trees) are free from the competition for light and soil water and nutrients. This requirement of canopy-free pasture within the silvopasture was recommended by Dodd et al. (1972) in order to maintain range values, and therefore the minimal alteration of forage quality due to tree shading and its effect on livestock performance is expected to be negligible.

Forage quality predictions averaged over the life of the experiment for each shading treatment and species all met minimum nutrient requirements for protein as well as Calcium and Potassium (National Research Council 2000). We expected forage quality results to be low, particularly for pinegrass which has been well studied for its decrease in forage value as the growing season progresses and drought factors limit growth (McLean et al. 1969). The high soil water content likely allowed the growing season to continue with no summer drought impacts as indicated by biomass production at all clipping periods throughout the life of the experiment. The very favourable growing conditions allowed for the comparison of plants in their best form.

Applications in operational silvopastures would be much different in the interior of British Columbia as forage would likely experience common summer drought (Tisdale and McLean 1957) and the onset of grass senescence resulting in reduced productivity and forage quality. We might be safe in making the same assumption that orchardgrass would increase forage production in summer-grazed silvopastures experiencing partial drought stress, and Hayes et al. (2010) support the use of drought tolerant orchardgrass cultivars to provide nutritious forage in these environments. A further benefit of incorporating agronomic forages within silviculture activities is the maintenance of long-term soil productivity that can be lost due to clearcutting and site preparation treatments (Thompson et al. 1999). The benefits of improved forage production and annual forage availability in these modeled silvopasture settings has the potential to provide regular forage availability to the ranching industry, and incorporating agronomic forage species into lodgepole pine vegetation communities is key to optimizing silvopasture commodity production.

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