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Productivity of two Douglas fir/subclover/sheep agroforests compared to pasture and forest monocultures*

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Abstract. Resource sharing between tree and forage plant components in silvopastoral systems includes a complex set of facilitative and competitive interactions. To the extent that facilitation exceeds competition, agroforests are expected to outyield monocultures of their components. Pasture and Douglas fir (*Pseudotsuga menziesii*) tree production of young agroforests was compared to pasture and forest monocultures under both grid and cluster patterns of tree planting near Corvallis, Oregon, USA, during 1983–1987. The height and diameter growth of forest and agroforest trees was similar, regardless of tree planting pattern. Five-year average annual forage production was 6500, 5800, and 2800 kg ha^{-1} on pasture, agroforest, and forest plots, respectively. The total cumulative 1982–1987 above-ground phytomass yield of forage plus trees was similar for pasture and conventional grid forest monocultures. The total productivity of agroforests, however, was over 30% greater than either pasture or forest components grown in monoculture. Approximately 1.6 ha (0.96 ha forest + 0.64 ha pasture) of monocultures would be needed to equal the productivity of 1 ha of agroforest.

Introduction

Agroforestry systems are polycultures incorporating both forest and agricultural components. Phytomass productivity of such systems reflects the nature of resource pool sharing in both time and space (Buck, 1986) as well as involving an often complex set of biotic and abiotic interactions among components. Plants may compete with each other for site resources. They may also facilitate each other's growth (Hunter and Aarssen, 1988). To the extent that facilitation exceeds competition, polycultures are generally expected to outyield monocultures (Horwith, 1985; Vandermeer, 1981). Interspecific and intraspecific plant interactions are functions of both plant density and spatial pattern (Buck, 1986; Sharrow, 1991). Although conifer density effects upon tree/understory interactions in forest stands are well documented (Krueger, 1981; Larson and Wolters, 1983; Percival and Knowles, 1986), tree pattern effects are less well understood. Biological and economic understanding of temperate conifer agroforestry systems is currently limited by a lack of adequate field data representing a range of management alternatives (Thomas,

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1990). The objective of our study was to compare aboveground net productivity of two structurally different silvopastoral systems to forest and pasture monocultures during the period following tree establishment until the first precommercial tree thinning. Two spacial patterns of agroforest and forest were examined: (1) a grid representing conventional forest practice, and (2) clusters of trees that were proposed to reduce tree/pasture competition (Avery and Gordon, 1983; Sharrow, 1991).

Materials and methods

The 3-ha study site was located on the eastern edge of the Coastal Mountain Range, approximately 16 km north of Corvallis, Oregon (latitude 44°30′ N, longitude 123°20′ W). The elevation is 70 m above mean sea level. The soil is a deep, silty-clay loam of the Jory Series (Xeric Haplohumults) which is of average suitability for both timber and agricultural crop production (Knezevich, 1975). The climate is maritime with warm dry summers and cool moist winters. Approximately 70% of the 100 cm mean annual precipitation falls as rain from November to March. Potential evaporation during June through September averages 407 mm, while rainfall is only 91 mm. Douglas fir trees periodically experience moisture stress during this period (Carlson et al., 1994). The frost-free period averages 165–200 days.

Two-year-old bare root Douglas fir (*Pseudotsuga menziesii*) seedlings (2–0 stock) were planted in two replications of two plantation patterns in 1979. Patterns were grid plantations of trees planted 2.5 m apart (1600 trees ha^{-1}) and cluster plantations consisting of groups of five trees evenly spaced on the circumference of a 1.5-m-radius circle with clusters established 7.5 m apart (890 trees ha^{-1}) in a grid pattern. The entire site was shallowly rototilled in September 1982. The original plantations were then split in half, and a randomly chosen half, together with two adjacent pasture plots, was sown with 20 kg ha^{-1} of inoculated subterranean clover (*Trifolium subterraneum*) seed in October 1982. The resulting 10 plots were approximately 0.4, 0.1, and 0.1 ha in size for cluster, grid, and pasture plots, respectively. This combination of treatments provided examples of forest and pasture monocultures that could be compared to joint pasture and forest production (agroforestry) under two forest planting patterns. The entire experimental area was fertilized with 40, 96, 48, and 0.5 kg ha^{-1} of N, P, K and Mo in fall 1982. Annual applications of 36 kg ha^{-1} P and 18 kg ha^{-1} S were broadcast over the entire experimental area each fall during 1983–1987. Only clover-seeded (agroforestry and improved pasture) plots were subsequently grazed. Plots were individually fenced, and grazing began in June 1983. The resulting agroforestry and improved pasture plots were grazed once each spring (April), summer (June–August), and fall (November–December) during 1983–1985 and each spring and summer during 1986 and 1987. A flock of 40–60 sheep was randomly rotated through the grazed plots, remaining in each plot until approximately 50% of the available forage was consumed or until sheep began to consume tree foliage (generally 1–4 days in spring, 2–10 days in summer, and 1–3 days in fall periods). Sheep were allowed free access to trees during all grazing periods in 1983–1985 and in spring 1986–1987. By 1986, pastures had become dominated by tall fescue (*Festuca arundinacea*), a relatively coarse and unpalatable grass. Cluster agroforests were strip-grazed during the 1986 and 1987 summer grazing periods. Portable electric fencing was used to protect trees so that the high levels of grazing pressure required to maintain subclover in competition with this aggressive grass would not be accompanied by unacceptable levels of browsing/debarking damage to trees. Grid agroforests were not grazed in 1987.

Forage production and utilization were estimated for each grazing period using the movable cage technique and before-and-after technique (Brown, 1954) during 1983–1985 and 1986–1987, respectively. Sixteen cages were randomly placed in each cluster plantation and 10 cages in each grid plantation and pasture just prior to sheep grazing in 1983–1985. Immediately after sheep left each plantation, all vegetation inside a 0.2 m^2 quadrant within and another adjacent to each cage were harvested. A sample of 18 randomly placed 0.2 m^2 quadrants per plantation was harvested immediately prior to (before) each grazing period in 1986 and 1987. A second sample of 18 quadrants was harvested just after sheep left each plot. Forage standing crop of both grazed and ungrazed treatments at the end of the growing season was estimated by harvesting 15×0.2 m^2 quadrants per plot in late August–early September each year. Herbage samples were hand-sorted into tall fescue, subclover, annual grass, and other forb components in 1983 and 1984. Herbage harvested on all sampling dates was dried in an oven at 50 °C until weight loss ceased, then weighed. Forage utilization was calculated as the change in herbage mass while sheep were present. The total annual forage production was estimated by the sum of the August standing crop plus the forage removed by sheep during the grazing periods. Forage production estimates are on an actual hectare basis, including the area occupied by trees. The species composition (by canopy cover) of all subplots was estimated in April 1986 and 1987 by point sampling using $20 \times$ ten-point frames (Sharrow and Tober, 1979) per plot.

Approximately 60 trees per grid plot and 120 trees per cluster plot (the largest and smallest tree in each cluster) served as study trees. Tree height to the nearest centimeter and basal diameter at 50 cm above the soil surface to the nearest millimeter, were measured after the onset of fall rains in October–November each year during 1982–1987 using a graduated pole and tree caliper, respectively. Canopy cover of the trees was estimated from radial measurements of canopy diameter of each study tree measured in fall, beginning in 1985. Tree phytomass was estimated from tree diameter using prediction formulas calculated for Oregon Douglas fir by Gholz et al. (1979). Both forest and agroforests were precommercially thinned in 1988.

Data were analyzed within years as a split-plot arrangement of treatments with pattern (grid, cluster) as main plots and management (agroforestry, pasture, forest) as subplots in a completely randomized design with two replications. Means of significant ($P < 0.05$) treatment effects were separated using the Student–Newman–Keuls procedure (Steel and Torrie, 1980).

Results and discussion

The entire study area supported a dense stand of tall fescue prior to cultivation in fall 1982. Tall fescue rapidly reestablished itself from the residual soil seed bank after cultivation, contributing approximately 500, 1500, and 1900 kg ha^{-1} of 1983 forage production to pasture, agroforest, and forest plots, respectively. Subterranean clover, seeded on agroforestry and improved pasture plots, was the major understory plant species on these plots in 1983 (Table 1). Miscellaneous plants in 1983 and 1984 on all plots were predominantly the cool season annual grasses *Vulpia myuros* and *Aira caryophyllea*. By 1986, however, the perennial forb *Hypochoeris radicata* was the principal miscellaneous plant on all plots. Forest plantations had over twice as much cool

Table 1. Percent species composition of herbaceous understory vegetation during 1983–1987 at Corvallis, Oregon, USA.

Year/species	Pasture	Agroforest		Forest		SE
		Gird	Cluster	Grid	Cluster	
1983						
Fear	9^a	18^a	21^a	70^b	75^b	6.4
Trsu	84^a	76^a	67^a	0^b	0^b	6.9
Misc.	7^a	6^a	12^a	30^a	25^a	4.3
1984						
Fear	56^a	65^a	56^a	82^b	89^b	1.8
Trsu	40^a	28^a	41^a	0^b	0^b	3.5
Misc.	4^a	7^a	3^a	18^a	11^a	4.5
1986						
Fear	49^a	41^a	24^a	78^b	92^b	6.3
Trsu	46^a	51^a	75^a	0^b	0^b	6.8
Misc.	5^a	8^a	1^a	22^a	8^a	6.9
1987						
Fear	36^a	86^b	39^a	89^b	91^b	5.5
Trus	61^a	6^b	54^a	0^b	9^b	4.8
Misc.	3^a	8^a	7^a	11^a	9^a	5.5

Fear = *Festuca arundinacea*; *Trsu* = *Trifolium, subterraneum*; Misc. = other herbaceous plants.
Means within a row not sharing a common letter differ ($P < 0.05$).
SE is the standard error of a mean.

season annual grass as pastures or agroforests in 1983. Presumably, this reflects competition from the cool season annual forb, subterranean clover, which contributed most of the plant phytomass on seeded plots in 1983. Tree planting pattern had no effect upon understory plant composition in any year with the exception of agroforests in 1987. Grazing was discontinued after spring 1986 in grid agroforests due to relatively low forage production together with management difficulties encountered in handling sheep in these small, densely timbered plantations. Subterranean clover in our area requires grazing in order to compete with perennial pasture grasses (Sharrow et al., 1981). Low clover content of grid agroforests in 1987, therefore, likely reflected low grazing pressure rather than tree planting pattern *per se*.

Pastures and agroforests produced approximately twice as much forage as forests during 1983–1987 (Table 2). Average tall fescue production during 1983–1987 was similar among treatments, being approximately 2600, 2500, 2500, 2000, and 2100 kg ha^{-1} $year^{-1}$ for pastures, grid agroforests, cluster agroforests, grid forests, and cluster forests, respectively. Increased production of pastures and agroforests relative to forests was primarily due to subterranean clover production that occurred in addition to the base production level of tall fescue. As one might expect, total understory forage production of forests tended to decline relative to pastures as trees grew and began to use more site resources over time. Tree canopy cover of grid agroforests was 19%, 49%, and 74% in 1985, 1986, and 1987, respectively. Forage production of grid agroforests was similar to that of pastures in 1985, then declined from 70% to 40% of open pasture yields during 1986 and 1987, respectively. This pattern of decline is consistent with Krueger's (1981) contention that conifer trees do not substantially decrease understory forage production until tree canopy cover exceeds 35%. Canopy cover of cluster agroforests was only 24% in 1987. Forage yield of cluster agroforests remained high, being 110% and 75% of pasture yield, during 1986 and 1987, respectively. Decreased forage production on grid compared to cluster agroforests likely accrues from both tree pattern and tree density differences between the two plantation types

Table 2. Average total annual forage production (t ha^{-1}) from pastures, forests and agroforests during 1983–1987 at Corvallis, Oregon, USA.

Year	Pasture	Agroforest		Forest		SE
		Grid	Cluster	Grid	Cluster	
1983	5.9^{a}	6.9^{a}	5.6^{a}	2.2^{b}	3.0^{b}	0.36
1984	9.5^{a}	7.7^{a}	9.3^{a}	4.4^{b}	3.7^{b}	0.39
1985	6.2^{a}	6.1^{a}	6.8^{a}	3.6^{b}	3.8^{b}	0.27
1986	5.0^{a}	3.6^{b}	5.5^{a}	1.6^{b}	2.0^{b}	0.18
1987	5.9^{a}	2.5^{b}	4.4^{a}	1.3^{b}	2.0^{b}	0.43

Means within a row not sharing a common letter differ ($P < 0.05$).
SE is the standard error of a mean.

(Sharrow, 1991). Numerically higher 1985 and 1986 forage production of cluster agroforests compared to pastures, although not statistically significant, is interesting in the light of other reports of 10–16% higher forage production under young conifers (Anderson and Moore, 1987; Percival and Knowles, 1986) and *Eucalyptus* (Ralph, 1990) compared to pastures. Trees may increase production of cool season pasture plants by providing thermal cover which reduces frost damage and which extends the growing season farther into summer (Anderson, 1987).

Average forage utilization by sheep during 1983–1987 (Table 3) was similar for pastures and cluster agroforests. However, only about half as much forage was utilized by sheep grazing grid agroforests as cluster agroforests during this period. Differences in forage utilization between cluster and grid agroforests were primarily due to a greater proportion of annual forage production consumed by sheep rather than a greater amount of forage produced on cluster relative to grid agroforests. Averaged over the 5-yr study period, utilization was 57%, 54%, and 24% of forage produced by pastures, cluster agroforests, and grid agroforests, respectively. Lower tree density in our cluster plantations, together with grouping of trees into clumps, provided 6-m-wide alleys between clusters of trees. Livestock management and forage consumption by sheep within these alleys were similar to that practised in open pasture. Tall fescue becomes relatively coarse and unpalatable in summer. Portable fencing was used in alleys between clusters to facilitate high levels of forage use without any risk of associated sheep browsing and debarking damage to trees in summer 1985–1987. Dense, uniform planting of trees in grid agroforests maximized the area covered by tree foliage and provided only narrow (2 m) alleys between trees, thus making use of portable fencing impractical. Problems with animal management increased as trees became larger and forage supply decreased over time, as indicated by the rapid decline of forage utilized in grid agroforests from 1984 to 1986. Rectangular patterns work well for tree monocultures because they minimize competition between adjacent trees while maximizing tree competition with ground vegetation. This

Table 3. Average annual forage utilized (t ha^{-1}) by sheep grazing pastures and agroforests during 1983–1987 at Corvallis, Oregon, USA.

Year	Pasture	Agroforest		SE
		Grid	Cluster	
1983	2.3^{a}	1.1^{b}	1.2^{ab}	0.28
1984	4.6^{a}	3.1^{b}	4.2^{a}	0.20
1985	3.5^{a}	1.5^{c}	5.0^{b}	0.34
1986	4.0^{a}	0.8^{b}	3.5^{a}	0.32
1987	4.2^{a}	0^{b}	3.0^{a}	0.36

Means within a row not sharing a common letter differ ($P < 0.05$).
SE is the standard error of a mean.

encourages rapid tree dominance and concentrates site resources in the tree crop. For these same reasons, they are less suitable for polycultures where both tree and ground vegetation are valued components (Sharrow, 1991). Such increased competition between trees and pasture is suggested by the numerically lower forage production in both grid forests and agroforests compared to cluster plantations during 1986 and 1987 (Table 2).

Cluster trees were approximately 70 cm taller and 11 mm larger in basal diameter than grid trees ($P < 0.05$) at the beginning of the agroforestry study in 1982 (Table 4). Similar numerical differences (77 cm height and 9 mm diameter) were evident between cluster and grid plantations in 1987. Apparently, whatever effect tree pattern had upon tree growth occurred primarily during the 1979–1982 period. Within pattern, agroforest and forest trees grew at similar rates (Table 4). The average height of both forest and agroforest trees increased by approximately 4 m during 1982–1987. During this same period, the diameter of agroforest and forest trees increased by 76 and 78 mm, respectively.

Pasture and conventional forest grid monocultures produced similar ($P > 0.05$) amounts of total phytomass during 1982–1987 (Table 5). The higher tree density in grid agroforests was reflected in the greater total tree phytomass production at the expense of numerically lower forage production compared to cluster agroforests. Tree production in agroforests was 102–103% that of the forest monocultures, while pasture production was 90% that of open pastures. Combined productivity of agroforests was over 30% greater than either of its two components growth in monoculture. Approximately 1.6 ha of monocultures (0.96 ha forest plus 0.64 ha pasture) would be needed to equal the productivity of 1 ha of agroforest. Similar ratios, ranging from 0.7 to 1.7 have been reported in the literature for legume/nonlegume polycultures (Hiebsch and McCollum, 1987). Our value of this ratio, called the Land

Table 4. Average Douglas fir tree height (cm) and basal diameter (mm at 50 cm above the soil surface) for forests and agroforests at the beginning (1982) and end (1987) of the experimental period at Corvallis, Oregon, USA.

Plantation type	1982		1987	
	Height	Diameter	Height	Diameter
Cluster forest	191^a	25^a	606^a	101^a
Cluster agroforest	170^a	22^a	551^a	97^a
Grid forest	107^b	13^b	503^a	88^a
Grid agroforest	102^b	12^b	500^a	92^a
SE	8	1	29	3

Means within a column not sharing a common letter differ (Student–Newman–Keuls' procedure, $P < 0.05$)
SE is the standard error of a mean.
Each mean contains data from approximately 240 and 120 trees for cluster and grid plantations, respectively.

Table 5. Components of cumulative aboveground phytomass production (t ha^{-1}) during 1983–1987 at Corvallis, Oregon, USA.

Component	Pasture	Agroforest		Forest		SE
		Grid	Cluster	Grid	Cluster	
Tree	0^a	18.7^c	9.4^b	18.3^c	9.1^b	2.20
Forage	32.5^a	26.7^a	31.7^a	13.1^b	14.5^b	1.68
Total	32.5^b	45.5^c	41.2^c	31.4^b	23.4^a	1.49

Means within a row not sharing a common letter differ ($P < 0.05$).
SE is the standard error of a mean.

Equivalency Ratio (LER: Vandermeer, 1981), is relatively high, being within the top 5% of the 506 forage polycultures reviewed by Hiebsch and McCollum (1987). Our LER of 1.6 compares favorably to the LER of 1.18–1.35 calculated from data included in Anderson's (1987) review of pine/subterranean clover pasture agroforestry research in Australia. The relatively high LER achieved by agroforests compared to that reported for agronomic polycultures, may reflect greater opportunities to select plant components that differ in vertical structure, season of growth, nutrient requirements, and rooting depth when trees are combined with perennial and annual herbaceous plants than when selection is limited to herbaceous field crops.

Conclusions

Agroforests in our study produced substantially more total aboveground phytomass than did either forest or pasture monocultures. Increased productivity of agroforests compared to forest plantations accrued from a greater understory herbaceous plant production (primarily subterranean clover) obtained without any apparent reduction in agroforest tree growth. The greater phytomass production of agroforests suggests a higher photosynthetic efficiency (i.e. a greater proportion of incoming solar radiation fixed into plant tissue) and a greater potential for early carbon sequestering compared to either forest or pasture monocultures. This likely reflects effective site resource sharing in time and space, resulting from differences in seasonal growth together with the multiple canopy and root layers of vegetation components (tree, grass, clover) present in young agroforests.

Cluster agroforests were generally preferable over grid agroforests because the wider alleys between clusters facilitated livestock handling and slowed the decline of forage production as trees grew. Douglas fir agroforest production models (Sharrow, 1991) suggest that plantations with trees planted densely along widely spaced rows may be superior to cluster plantings in both of these respects. Preliminary data from current field trials (Sharrow, 1995) generally support this supposition.

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