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Carbon and nitrogen storage in agroforests, tree plantations, and pastures in western Oregon, USA

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Abstract

Pastures store over 90% of their carbon and nitrogen below-ground as soil organic matter. In contrast, temperate conifer forests often store large amounts of organic matter above-ground in woody plant tissue and fibrous litter. Silvopastures, which combine managed pastures with forest trees, should accrete more carbon and nitrogen than pastures or timber plantations because they may produce more total annual biomass and have both forest and grassland nutrient cycling patterns active. This hypothesis was investigated by conducting carbon and nitrogen inventories on three replications of 11 year-old Douglas-fir (*Pseudotsuga menziesii*)/perennial ryegrass (*Lolium perenne*)/subclover (*Trifolium subterraneum*) agroforests, ryegrasss/subclover pastures, and Douglas-fir timber plantations near Corvallis, Oregon in August 2000. Over the 11 years since planting, agroforests accumulated approximately 740 kg ha^{-1} year $^{-1}$ more C than forests and 520 kg ha^{-1} year^{-1} more C than pastures. Agroforests stored approximately 12% of C and 2% of N aboveground compared to 9% of C and 1% of N above ground in plantations and less than 1% of N and C aboveground in pastures. Total N content of agroforests and pastures, both of which included a nitrogen-fixing legume, were approximately 530 and 1200 kg ha^{-1} greater than plantations, respectively. These results support the proposition that agroforests, such as silvopastures, may be more efficient at accreting C than plantations or pasture monocultures. However, pastures may accrete more N than agroforests or plantations. This apparent separation of response in obviously interrelated agroecosystem processes, points out the difficulty in using forest plantation or pasture research results to predict outcomes for mixed systems such as agroforests.

Introduction

Carbon and nitrogen are major constituents of plant and soil organic matter. As such, they play a fundamental role as nutrients within the tropic food web. Carbon and nitrogen are released when organic matter is biologically or chemically deconstructed. Recent concerns about the potential role of anthropogenic emissions of carbon as a contributor to global warming and nitrogen as a major source of eutrophication in streams and lakes has focused attention on the earth's carbon and nitrogen cycles. Oxidation of soil organic matter together with application of inorganic nitrogen fertilizers tend to make conventionally tilled agricultural systems net sources of both nitrogen and carbon emissions (Cambardella and Elliott 1994; Davidson and Ackerman 1993). Grasslands (Adger et al 1992; Potter et. al.1999), young growing forests (Thuille et al 2000) and agroforests (Kaur et al. 2000; Maikhuri et al. 2000), in contrast, tend to accrete organic matter over time. Forests are often favored for carbon sequestration because of their ability to accumulate large amounts of organic matter in woody biomass and decay resistant litter. Grasslands may accrete equivalent amounts of organic matter as forests (Corre et al. 2000), but their contribution is often under emphasized because most storage is in soil organic matter rather than in aboveground biomass (de Groot 1990). Data on carbon content of major world ecosystems presented by Taylor and Lloyd (1992) suggest that temperate grasslands and forests are essentially equal in their role as carbon sinks, but differ fundamentally in how carbon is stored within each ecosystem. Most carbon in temperate grasslands is stored as soil organic matter while mature forests contain over half of their stored carbon as woody biomass with the remainder in soil organic matter. Estimates presented for undisturbed Pacific Northwest USA ecosystems by Houghton and Hackler (2000) suggest that while coniferous forests contain approximately 60% of their stored carbon in aboveground biomass, grasslands store approximately 90% of their carbon in soil organic matter. The residence time of carbon in temperate grassland soils is long (60 years) compared to temperate forest soils (23 years – Taylor and Lloyd 1992)). However, aboveground grassland vegetation decays quickly (1 year residence) while fibrous forest detritus persists for long periods (30 year residence – Taylor and Lloyd 1992). Below-ground carbon pools of terrestrial ecosystems are frequently poorly quantified in carbon assessments, perhaps because of the difficulty in measuring them. This places grasslands and pastures at a disadvantage relative to forests when their potential to accrete carbon is considered (de Groot 1990). In fact, total carbon accretion by pastures may equal or exceed that of adjacent forests (Lugo and Brown 1993).

Potentially, agroforests may accrete more carbon and nitrogen than forests or pastures. More efficient sharing of site resources between tree and pasture plants together with nitrogen fixation by forage clovers and microclimate modification by trees may significantly increase overall net production of phytomass available for storage. Sharrow et al. (1996), for instance, reported that 10-year-old Douglas-fir/grass-clover pasture/sheep agroforests produced 1.6 times as much phytomass as did pastures or forests of the same age, on the same site. Agroforests could have efficient carbon and nitrogen sequestering over time because they have both forest and grassland storage patterns active. This would manifest itself as below ground storage by a vigorous grassland component in very young agroforests being gradually augmented by storage in long residence time woody material and semi-decomposed soil surface organic matter (duff) in older agroforests. Availability of established, 11-year-old forest plantations, pastures, and agroforests on the same site and with a common previous history of use, allowed us to test this hypothesis by inventorying carbon and nitrogen stored in above-ground and below-ground compartments within each system.

Methods and materials

This study was conducted in the eastern foothills of the Coastal Mountain Range near Corvallis, Oregon, USA (Latitude 44 N, Longitude 123 W) during April through August 2000. Elevation is approximately 120m. Climate is Mediterranean with cool moist winters and warm dry summers. Average daily maximum/minimum temperature is 7.3/3.9 °C in January and 27.1/18.1 °C in July. Approximately 70% of the 1024 mm annual precipitation falls as low intensity rains from November through March, with less than 100 mm of precipitation received during the summer dry period from June to September. Soil is a Philomath silty clay (Vertic Hyploxeroll), mostly less than 45 cm deep, developing from fractured basalt rock.

The experimental site occupies the southeastern face of a hill with a 4-6% slope. It was managed as a single pasture that was grazed by sheep each spring-summer from the 1950's until 1977. Grazing pressure was moderate with approximately half of each year's 2000 to 3000 kg ha^{-1} annual herbage production consumed by sheep. Pasture vegetation was primarily naturalized annual grasses together with planted perennial pasture species, such as tall oatgrass (*Arrhenatherum elatius*, L, Presel.), perennial ryegrass (*Lolium perenne* L.), and burnet (*Sanguisorba minor*, Scop.). The entire site was plowed and used to grow winter wheat during 1978 and 1979. Approximately 150 kg ha^{-1} of N as ammonium nitrate fertilizer was applied to the wheat crops in 1978 and again in 1979. It was allowed to return to pasture in 1980, but grazing by sheep was light and infrequent. By 1988, cool season annual grasses, tall oatgrass, and burnet again dominated the site.

Three blocks of pasture, forest plantation, and agroforest treatments were established in 1988-1989. Treatment plots were randomly assigned within upper-, mid-, and lower-slope blocks. Each forest and pasture was approximately 0.3 ha, while agroforests were 0.6 ha in size. Pastures and agroforests were planted with 9 kg ha^{-1} of *Rhizobium* inoculated subclover (*Trifolium subterraneum* L. var. *Nangeela*) in September 1988. Forests and agroforests were planted with 570 two-year old (2-0) bare root Douglas-fir (*Pseudotsuga menziesii* (Mirbel Franco) seedlings ha^{-1} in March 1989. Forest trees were planted 4.2 m apart within the standard rectangular grid pattern commonly used in commercial forestry plantations. Agroforest trees were planted 2.5 m apart within rows that were 7 m apart, as recommended for silvopastures by Sharrow (1992).

Pasture and agroforest plots were individually fenced with electric fencing in March 1990. They were grazed twice each year during 1990-2000, once in April to early-May when forage standing crops exceeded 1500 kg ha^{-1} and again in mid-June to early-July when forage standing crops exceeded 3000 kg/ ha^{-1}. Grazing was timed to end in July, when stored soil moisture is exhausted and forage growth on hill pastures ends. Sufficient ewes were introduced in each plot to consume approximately half of the forage standing crop within 2-5 days. This generally resulted in stocking densities of 200-400 sheep ha^{-1} and residue stubble heights of 2-5 cm.

Species composition of ground vegetation, based upon canopy cover, was assessed in April each year from point sampling using 20 ten-point frames (Sharrow and Tober 1979) per plantation, agroforest, and pasture plot. Forage standing crop and its utilization by sheep was estimated by clipping fifteen 0.2 m^2 quadrats per plot to ground level immediately prior to grazing and a second set of 15 quadrats immediately after each grazing event. Total annual forage production for each plot was calculated by adding its final standing crop in August to the amount of forage removed from it by sheep grazing. Above-ground mass of herbaceous vegetation, litter, and manure at the end of the pasture growing season in August were estimated by harvesting fifteen 0.2 m^2 quadrats each from all treatment plots. Plant standing crop and litter were collected to mineral soil. All fragments of manure were carefully collected and separated by donor species. All material was dried in a 50 °C oven prior to weighing. Like material from each plot was then ground, thoroughly mixed, and a subsample removed for chemical analysis.

Soil samples were obtained for the top 15 cm and 15-45 cm depths in August using a closed bucket auger. Three samples were randomly collected from each of the 9 treatment plots. Because of the greater spatial variability introduced by tree pattern in agroforests and forests compared to pastures, agroforest samples contained 3 sub samples each and forest samples two sub samples each, while each pasture sample was a single sub sample. Soils collected for each sample and depth were thoroughly mixed, placed in paper bags, and dried in a 50 °C oven prior to weighing. The three dry samples for each plot were then combined, thoroughly mixed, ground with a mortar and pestle to pass a 1mm mesh sieve, and 250 grams withdrawn for chemical analysis. The soil contained very little rock. Small rock fragments encountered during grinding were collected and weighed so that chemical analysis could be corrected back to a field basis.

Douglas-fir foliage, branch, root, and stem samples for laboratory analysis were obtained during August. One random twig was collected from each of 25 randomly selected trees per forest and agroforest replication. Branches from 5 randomly selected trees per treatment were removed, the tree cut down approximately 20 cm above the soil surface, and a 1 cm thick cross section removed. A 5-8 cm wide strip of bark was then collected immediately below the cut. Root samples were obtained by total excavation of two forest trees, and from tree roots encountered during soil sampling. Root excavations extended radially out from the stem until no additional roots were visible and downwards to bedrock. All material was dried in a 50 °C oven, ground, and stored in air tight containers until chemical analysis.

Height and DBH (diameter at 137 cm height) of Douglas fir trees were measured in August using a calibrated tree pole and a caliper, respectively. Mass of tree foliage (r^2 = 0.86), branches (r^2 = 0.92), stem (r^2 =0.99), bark (r^2 = 0.99), and roots (r^2 = 0.96) were estimated allometrically from DBH using equations published for western Oregon Douglas-fir plantations (Gholz et al. 1979).

Carbon and nitrogen concentrations (g kg^{-1}) of plant and soil samples were determined in the Oregon State University Central Analytical Lab using a Carlo Erba NA 1400 CNS analyzer. Mass (kg ha^{-1}) of carbon and nitrogen stored in forage, litter, manure, soil, and tree compartments was estimated by multiplying their measured mass by their nutrient content.

Data were analyzed statistically using analysis of variance procedures with the 3 individual plantations, agroforests, and pastures serving as replications in a randomized complete block design. Means of significant treatments ($P < .05$) were compared by the Student-Newman-Keuls' procedure (Steel and Torrie 1980).

Table 1. Species composition of western Oregon, USA pasture, agroforest, and plantation plots in April 2000, based upon relative canopy cover

Species[1]	% of total canopy cover			
	Pasture	Agroforest	Plantation	SE
Perennial ryegrass	15a	16a	1b	3.8
Tall oatgrass	1a	5a	48b	5.9
Meadow foxtail	9a	3a	2a	3.0
Other perennial grasses	2a	8a	4a	3.1
Annual grasses	18a	21a	15a	2.8
Sub clover	40a	30b	1c	1.4
Burnet	3a	6a	11a	7.7
Other forbs	12a	11a	18a	2.6

Means within a row not sharing a common letter differ (Student-Newman-Kehuls' procedure, $P < .05$)

Table 2. Mean biomass contained in various compartments of western Oregon, USA pasture, agroforest, and plantation plots in August 2000

Compartment		kg ha $^{-1}$			
		Pasture	Agroforest	Plantation	SE
Tree		0	23,705a	13,636b	2,689
	Foliage	0	1,814a	1,274b	145
	Bark	0	4,372a	2,413b	527
	Branches	0	2,182a	1,361b	214
	Stem	0	12,362a	6,973b	
				1,443	
	Roots	0	2,972a	1,640b	358
Understory		2,271a	2,674a	4,818b	336
	Forage	1,424a	1,407a	2,786a	213
	Litter	9a	221a	1,832b	166
	Manure	837a	914a	19b	186
TOTAL		2,271a	26,379b	18,454b	3,318

Means within a row not sharing a common letter differ (Student-Newman-Kehuls' procedure, $P < .05$).

Results and discussion

Understory species composition of pastures and agroforests was approximately half grass and half forbs in early spring 2000. Forb cover was primarily the seeded clover (Table 1). Although not planted, perennial ryegrass was the major perennial grass in grazed plots. Subclover and perennial ryegrass commonly co-occur on Western Oregon hill pastures because subclover is a low growing annual which does not compete well with taller perennial grasses. Perennial ryegrass is a relatively short growing, grazing tolerant grass with a high nitrogen requirement. The close grazing commonly used to control grass competition to promote growth and seed set in subclover, along with nitrogen fixation by clovers, also favors perennial ryegrass. The inability of subclover to persist in competition with taller grasses without grazing is evident in its almost total absence from plantation plots despite the seed source from nearby pastures and agroforests. Tall oatgrass, which appears to have low grazing tolerance, dominated plantation plots. Small pockets of meadow foxtail (*Alopecurus pratensis,* L.*)* occurred in the moister lower slope block plots, while burnet occupied the drier upper slope block plots, regardless of land management treatments. Commonly encountered forbs included wild carrot (*Daucus carota*, L.), catsear, (*Hypochaeris radicata,* L.), and vetch (*Vicia sativa* L.). The most common annual grasses were rattail fescue (*Festuca myuros* L.), soft brome (*Bromun mollis* L.), and ripgut brome (*Bromus rigidus* Roth.).

Approximately one third of the 4900 $\pm$ 240 kg ha^{-1} of forage produced by pastures and the 4100 $\pm$ 170 kg ha^{-1} by agroforests during the 1999-2000 growing season remained on the plots in August (Table 2). Sheep consumed approximately 2500 kg ha^{-1} of forage, leaving behind 800-900 kg ha^{-1} of manure. This suggests a forage digestibility of approximately 70%, which is similar to that reported for western Oregon subclover/perennial ryegrass pastures by Motazedian (1984). Total aboveground herbaceous standing crop in the ungrazed plantations was approximately 90% greater at the end of the growing season than that of pastures or agroforests. Pastures and agroforests contained little manure or forage residue from previous years. In contrast, plantations contained most of the current year's herbaceous production plus a substantial accumulation of old weathered grass stems (litter) from the previous 1-2 growing seasons. Plantation trees were too young to have accumulated more than a few fallen needles under their canopies. Fallen seed cones contributed most of their non-grass litter. Although plantations were not grazed by sheep, they did provide habitat for brush rabbits (*Sylvilagus bachmani*) and black-tailed deer (*Odocoileus hemionus*), which contributed a small amount of manure.

Douglas-fir trees in agroforests averaged 10.5 cm DBH and 516 cm height, compared to 8.4 cm DBH and 460 cm height for trees in plantation plots. The 25% greater diameter and 12% greater height of agroforest trees contributed to their 74% greater total biomass compared to plantation trees (Table 2). The more shallowly rooted pasture plants growing in agroforests, together with grazing that reduced pasture leaf area and root areas, and nitrogen fixation by subclover likely all contributed to greater tree growth in agroforests compared to plantations. Approximately 88% of total tree biomass in both plantations and agroforests occurred aboveground, mostly in the tree trunk. Of the 10, 000 kg ha^{-1} difference in tree biomass between plantations and agroforests, only 1300 kg ha^{-1} was below ground. Total plant above-ground standing crop (trees plus forage) was dominated by tree biomass, which comprised approximately 90% of the total standing crop in agroforests and 74% in plantations. Pastures, which lacked trees, contained only about 1/10th as much biomass standing crop as plantations or agroforests.

Carbon and nitrogen concentrations of tree components were similar ($p > .05$) for plantation and agroforest trees. Tree foliage, bark, branches, stems, and roots all contained 510-530 g kg^{-1} carbon. Nitrogen content of tree components varied, averaging 11.8, 5.7, 3.7, 1.3, and 4.2 g kg^{-1} N for foliage, bark, branches, stems, and roots, respectively. Manure in agroforests and pastures averaged 420 g kg^{-1} C and 22 g kg^{-1} N. Forage and litter carbon concentration varied between treatments ($P < .05$), with agroforest and pasture litter having slightly less (420 g kg^{-1} C) carbon and more nitrogen (12 g kg^{-1}N) than plantation litter (450 g kg^{-1} C, 8 g kg^{-1} N), perhaps reflecting the more fibrous nature of old weathered tall oatgrass stems compared to the more leafy ryegrass litter present in pastures and agroforests. Pasture and plantation current year's forage had similar ($P > .05$) carbon (460 g kg^{-1}) and nitrogen (10 g kg^{-1}) content, but agroforest forage contained slightly less ($P < .05$) carbon (440 g kg^{-1}) and more nitrogen (14 g kg^{-1}).

Overall, differences in carbon and nitrogen content of biomass components had relatively little influence on total storage compared to the relative amount of mass contained in each compartment. Soil, however, because of its great mass and similar bulk density ($P < .05$) between treatments (Table 3), was strongly influenced by treatment differences in percentage carbon and nitrogen content, especially near the soil surface. Nitrogen content of the upper 15 cm of pasture soil was significantly higher ($P < .05$) than that of agroforests or plantations, which were similar. Soil carbon followed the same numeric trend as nitrogen. However, treatment differences between pasture and agroforest were not statistically significant ($P > .05$). Percentage carbon and nitrogen of soil below 15 cm did not differ between treatments ($P > .05$).

Table 3. Mean soil attributes of western Oregon, USA pasture, agroforest, and plantation plots in August 2000

Attribute	Pasture	Agroforest	Plantation	SE
Bulk Density g cc^{-1}				
Top 15cm	0.97a	0.98a	0.93a	0.025
15-45 cm	1.46a	1.43a	1.34a	0.031
N g kg^{-1}				
Top 15 cm	0.25a	0.21b	0.20b	0.008
15-45 cm	0.15a	0.14a	0.14a	0.006
C g kg^{-1}				
Top 15cm	2.9a	2.6ab	2.5b	0.170
15-45 cm	1.7a	1.7a	1.8a	0.096

Means within a row not sharing a common letter differ (Student-Newman-Kehuls' procedure, $P < .05$)

Table 4. Mean carbon contained in various compartments of western Oregon, USA pasture, agroforest, and plantation plots in August 2000

Compartment		kg ha $^{-1}$			
		Pasture	Agroforest	Plantation	SE
Tree		0	12,239a	6,949b	1,388
	Foliage	0	768a	486b	57
	Bark	0	2,335a	1,262b	281
	Branches	0	1,112a	694b	110
	Stem	0	6,490a	3,660b	758
	Roots	0	1,534a	847b	185
Understory		1,003a	1,168a	2,231b	183
	Forage	649a	624a	1,299b	98
	Litter	4a	95a	832b	79
	Manure	350a	383a	8b	79
	Cones	0a	66a	92a	55
Soil		102,520a	95,886ab	91,939b	3,044
	Top 15cm	40,980a	37,150ab	34,148b	1,299
	15-45 cm	61,540a	58,766a	57,791a	2,136
TOTAL		103,523a	109,293b	101,119a	2,721

Means within a row not sharing a common letter differ (Student-Newman-Kehuls' procedure, $P < .05$)

As hypothesized, both amounts of total carbon (Table 4) and nitrogen (Table 5) stored and carbon distribution between storage compartments differed among the three land management systems. Soil was the predominant storage area for C and N in all three systems. Pastures, however, stored amost all of their C and N in soil organic matter, with relatively little present in above-ground vegetation and litter. Less

Table 5. Mean nitrogen contained in various compartments of western Oregon USA pasture, agroforest, and plantation plots in August 2000

Compartment		kg ha $^{-1}$			
		Pasture	Agroforest	Plantation	SE
Tree		0	83a	50b	7.0
	Foliage	0	21a	15b	1.6
	Bark	0	25a	14b	2.3
	Branches	0	8a	4b	0.6
	Stem	0	16a	9b	1.4
	Roots	0	12a	7b	1.1
	Understory	36a	43a	38a	5.5
	Forage	18a	19a	21a	3.4
	Litter	0a	3a	16b	1.4
	Manure	19a	22a	1b	4.2
Soil		8,879a	8,097a	7,600a	635
	Top 15cm	3,629a	3,085b	2,817b	186
	15-45 cm	5,249a	5,012a	4,783a	454
TOTAL		8,915a	8,223ab	7,688b	442

Means within a row not sharing a common letter differ (Student-Newman-Kehuls' procedure, $P < .10$)

than 1% of total pasture C and N storage was above-ground. While young plantations also stored 99% of their N in soil, 9% of their total C was stored above-ground. Approximately 7% of total plantation carbon and 0.6% of total N was in trees, with 2% C and 0.5% N in understory vegetation and litter. Approximately 8000 kg ha^{-1} more carbon and 52 kg ha^{-1} more N was stored aboveground in plantations than in pastures. Pasture soils, however, contained approximately 10,000 kg ha^{-1} more carbon and 1230 kg ha^{-1} more N, making total carbon stored in pastures similar to that of plantations and total N 16% greater than for plantations. Carbon storage patterns in agroforests were similar to plantations, with 11% of total carbon and 1% of the nitrogen contained in trees, 1%C and 0.5%N in understory vegetation and litter, and 88% of the C and 98% of the N in soil organic matter.

The total amount of carbon stored in agroforests (Table 4), was approximately 5800 kg ha^{-1} greater than for pastures and 8000 kg ha^{-1} greater than plantations. The amount of carbon contained in agroforest trees was approximately 5000 kg ha^{-1} greater than that contained in plantation trees, primarily due their larger average size. Roughly similar amounts of carbon were stored in understory components of pastures and agroforests. The total amount of carbon stored in the soil of agroforests was intermediate between plantations and forests, being numerically 6000 kg ha^{-1} less than pastures but 4000 kg ha^{-1} greater than plantations. This pattern may be explained by examining pasture production and its use by sheep over the 11-year lifetime of the experiment. Total herbaceous production during 1990-2000 was 55,500, 48,200, and 36,100 kg ha^{-1} for pastures, agroforests, and plantations, respectively. Sheep consumed a total of 30,500 kg ha^{-1} of forage in pastures and 22,000 kg ha^{-1} of forage in agroforests, depositing approximately 9,000 kg ha^{-1} and 7,000 kg ha^{-1} of manure in pastures and agroforests, respectively. Perennial ryegrass root growth in intensively grazed pastures roughly equals that above ground and is largely confined to the top 15 cm of soil depth (Motazedian 1984). So, total mass of herbage plants and manure potentially available for decomposition was approximately 90,000, 81,000, and 72,000 kg ha^{-1} containing 40,800, 37,200, and 32,500 kg ha^{-1} of C in pastures, agroforests, and plantations, respectively. This represents approximately 3,600 kg ha^{-1} more carbon potentially available for storage as soil organic matter in pastures than agroforests, and 4700 kg ha^{-1} more carbon available in agroforests than in plantations, which roughly approximates the treatment differences observed in C stored in the upper 15 cm soil layer. Similar to the surface horizon, soil carbon stored in the 15-45 cm layer was numerically highest in pastures, followed by agroforests and then plantations. However, the differences between treatments were much less pronounced and were not statistically significant. When the relative thickness of the two layers is considered, treatment effects on soil carbon stored in the top 15 cm layer are approximately 4 times those observed in the lower 15-45 cm layer. This difference probably reflects the shallow rooting depth of grazed subclover/perennial ryegrass stands, and the relatively low predicted mass of tree roots present in agroforests and plantations.

Total nitrogen stored in agroforests (Table 5) was numerically 500 kg ha^{-1} more than in plantations and 700 ha^{-1} less than in pastures. Subclover growing in Mediterranean climates such as western Oregon has been observed to fix over100 kg N ha^{-1} year^{-1} (Dear et al. 1999). Using Dear et al.'s (1999) observation that subclover fixes 23-34 kg N t^{-1} of shoot biomass produced, we estimate that clover in our pastures and agroforests fixed $42 - 62$ kg N ha^{-1} year^{-1}. This is remarkably similar to the average 45-65 kg N ha^{-1} year^{-1} that accumulated in pastures and agroforests relative to plantations during the course of this experiment. Grazing also may have played a role in increasing availability of nitrogen in agroforests and pastures. Sheep only retain approximately 3% of forage N consumed. Approximately 70% of the N ingested is quickly returned to the soil nutrient pool as urine (Smith and Frost 2000). Based upon our measurements of forage utilization, this amounts to an average annual urine deposition rate of 45 kg N ha^{-1} in agroforests and 60 kg ha^{-1} in pastures. Increased nitrogen availability resulting from grazing as well as the larger total N pool in agroforests probably contributed to greater tree and herbaceous vegetation growth compared to forests. Greater available soil N, either from nitrogen fixation or fertilizer application, is associated with greater soil carbon in forests. In his literature review, Johnson (1992) concluded that the presence of N-fixing plants increases soil C and N content by 20-100%. Inorganic fertilizer application also increases soil carbon storage, but is generally not as effective as nitrogen fixation (Johnson 1992).

The rate of carbon accretion in agricultural and forestry systems currently has potential economic significance because of the possibility of selling "carbon credits" to offset the carbon emissions associated with burning of fossil fuels (Cathcart 2000; Swisher and Masters 1992). No pre-treatment carbon or biomass data are available for the research site. Therefore, the absolute rate of carbon accretion cannot be easily determined. The entire research site was managed as a single large unit prior to its subdivision into treatment plots. Therefore, relative rates of carbon accretion between land management treatments can be quantified. Averaged over the 11 years since treatments were established, pastures and young forest plantations accreted similar amounts of carbon. Agroforests, however, accreted approximately 500 kg ha^{-1} $year^{-1}$ more carbon than pastures, and 740 kg ha^{-1} year $^{-1}$ more carbon than plantations. Although young forests may be net carbon sources, this is largely the result of soil and vegetation disturbance associated with harvesting the previous forest, and the accompanying changes in microclimate (Cropper and Ewel 1984; Johnson 1992), neither of which apply to the same degree to afforestation. Mid- to late-rotation forests are generally net carbon sinks (Cropper and Ewel 1984). It is reasonable to assume that agroforests and plantations will display this same general pattern of increasing rate of carbon accretion in woody biomass and soil litter into middle age. Substantial amounts of carbon may be accumulated in the "duff" layer of semi-decomposed needles under old stands of conifer trees (Alban 1982). Our trees were just beginning to shed sufficient needles for this layer to begin to accumulate. Since needle production in young Douglas-fir stands is exponentially related to tree size (Gholz et al 1979), needle fall should become an important carbon sink in both our agroforests and plantations in future years. Since conifers grow proportionately to their initial size, greater current tree size in agroforests relative to plantations should increase differences in net carbon accretion both in tree mass and in needle fall in the future.

Conclusions

Although both carbon and nitrogen are major constituents of plant and soil organic matter, they responded differently to land management systems. In general, our data suggest that pastures and young forest plantations store similar amounts of carbon. Pasture carbon storage is almost entirely below-ground. While young plantations and agroforests also store most of their carbon as soil organic matter, above-ground accumulation of litter and tree biomass are also important storage compartments, together accounting for 12% and 9% of total carbon stored in agroforests and plantations, respectively. As hypothesized, 11 year-old agroforests, which have greater total biomass productivity than pastures or plantations, and which have both pasture below-ground and tree above-ground carbon cycles active, accrete more carbon.

In contrast to carbon, the total amount of nitrogen present in pastures was greater than in plantations. Pattern of nitrogen storage did not vary between pastures, agroforests, and plantations. Approximately 99% of total N was stored below ground regardless of treatment. Estimated N fixation by subclover in pastures and agroforests was very similar to the observed increase in the amount of N stored relative to plantations. This suggests that subclover was a significant N source and that a substantial proportion of the N fixed was captured and stored.

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