SOIL NITROGEN MINERALIZATION UNDER BLACK WALNUT INTERPLANTED WITH AUTUMN-OLIVE OR BLACK ALDER[1]

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Abstract.-- Seasonal changes in soil nitrogen (N) mineralization rates were estimated *in situ* at two locations in plots of black walnut interplanted with N_2-fixing autumn-olive or black alder. Soil N mineralization rates were highest in most plots at both sites in late summer. N mineralization rates in plots containing actinorhizal autumn-olive or black alder were higher throughout the growing season than in pure walnut plots. It was estimated that plots containing actinorhizal interplantings produced as much as 236 kg ha^{-1} yr^{-1} of net mineral N in the upper 20 cm of soil, which is higher than values previously reported for hardwood forest soils in North America. Plots containing actinorhizal interplantings produced 118 to 236 kg of net mineral N per ha per yr in the upper 20 cm of soil, compared to only 65 to 90 kg ha^{-1} yr^{-1} in the pure walnut plots. Plots which had high N mineralization also had the largest walnut trees. Soils at both sites were acidic (pH 4.1 and 6.5) and low in extractable P (1.4 and 0.7 mg kg^{-1} dry mass). Mineralization of N proceeded through the nitrification process in all plots at both plantations throughout the growing season despite low pH and low extractable P concentrations, which are generally believed to inhibit nitrification.

INTRODUCTION

Black walnut (*Juglans nigra* L.) is one of the more valuable timber species of the central hardwood forest region of North America. Management practices that increase the merchantable yield and quality of black walnut make it an even more attractive tree species for forest managers. Fertilization, particularly with N, is one way of achieving increased walnut growth (Phares 1973). However, N fertilization can be expensive and stimulate weed growth. One alternative is to interplant walnut with N_2-fixing plants that add N to the soil and help control weed competition through shading at the same time.

Woody nurse crops which are associated with N_2-fixing actinomycetes of the genus *Frankia* have been used to improve the growth of several hardwood species (Dawson 1986). Apart from improving N fertility, additional benefits of woody nurse crops include: wind protection; weed control; promotion of self-pruning, straighter boles, and faster height growth in crop trees; and an additional source of wood fiber (Burke and Williams 1973, Melillo and Aber 1979, Schlesinger and Williams 1984, Van

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Sambeek et al. 1985). Several hardwood species, including black walnut, have shown improved growth and stem form when interplanted with black alder (Alnus glutinosa(L.) Gaertn.) or with autumn-olive (Elaeagnus umbellata Thunb.) (Plass 1977, Funk et al. 1979, Schlesinger and Williams 1984, Van Sambeek et al. 1985).

Soil total N levels have been found to be higher under tree plantations containing Frankia and Rhizobium-nodulated plants than in stands lacking the N_2-fixing component (Tarrant 1961, Tarrant and Miller 1963, Bollen et al. 1967, Borman and DeBell 1981, Hansen and Dawson 1982). N accumulation rates ranging from 60 to 209 kg ha^{-1} yr^{-1} have been estimated on sites with Alnus spp. (Tarrant 1968). On sites lacking N_2-fixing plants there is little or no net accumulation of soil N (Dawson 1983).

However, net accumulation of soil N does not necessarily result in increased availability of N to plants. In order to estimate the amount of N that is available for plant growth, it is necessary to assay for soil N mineralization. At the Ambeer Creek site used in this study, Ponder (1980) showed that soil total N and soil NO_3^--N levels were higher at one point in time under mixtures of black walnut and autumn-olive than under pure black walnut.

Friedrich and Dawson (1984) found that soils of interplantings of walnut with black locust (Robinia pseudoacacia L.) and autumn-olive at the Ambeer Creek site had the highest total N concentrations, followed by soils under black alder interplantings and pure walnut control plots at the same site. However, walnut basal area was not strongly correlated with soil total N concentration, suggesting that differences may exist in soil N mineralization among interplantings.

In order to further our understanding of N fertility in black walnut interplantings with actinorhizal plants, we examined seasonal NO_3^--N and NH_4^+-N availability in actinorhizal interplantings where improved walnut growth has been reported. In so doing, we hoped to obtain a more accurate measure of the contribution of actinorhizal plants to soil N fertility in black walnut interplantings with actinorhizal (Frankia-nodulated) plants than has been previously obtained using soil total N measures or single samples of soil mineral N status. The specific objectives of our study were to estimate differences in N mineralization associated with site, season, and interplanted species. Additional objectives included estimating total annual N mineralization in soils of the interplantings and relating N mineralization rates to soil pH, total N, total organic C, and extractable P.

STUDY SITES AND METHODS

Our study was conducted on the Ambeer Creek (AC) and Hogthief Creek (HC) plantations established in 1969 in southern Illinois by the United States Forest Service for the purpose of evaluating the effects of various N_2-fixing nurse crops on black walnut growth and stem quality. Both plantations are located on bottomland soils which had been agricultural fields in the past (table 1). Two plots each of walnut with autumn-olive, of walnut with alder, and of pure walnut (controls) were established at each site. Plots were arranged in a randomized complete block design. Within each plot 24 walnut trees were planted in 6 rows (3.7 m apart) with walnut spacings within rows of 9.8 m. Three alder trees or autumn-olive shrubs were planted at a spacing of 2.4 m between walnuts in a row, giving an overall spacing of 2.4 by 3.7 m. Border rows of pure walnut were planted around the perimeter of each plot. Weeds were controlled for the first 5 years after plantation establishment and missing trees were replaced after the second and fourth years.

Soil N mineralization was measured in situ using soil cores incubated in polyethylene bags (Eno 1960). In each plot, three soil cores were extracted at randomly selected points and separated into 0-10 and 10-20 cm depth increments. Intact soil cores were placed into 0.04 mm thick polyethylene bags and replaced in their original locations in the soil for an incubation period of 35 days in the spring and early summer of 1987, 60 days in late summer and fall, and 150 days over the winter of 1987-88. At the beginning of each incubation, adjacent soil cores were removed to determine the initial levels of NH_4^+-N and NO_3^--N.

Fresh and incubated soil cores were brought to the laboratory on ice where a 5 g subsample was extracted with 75 ml of 1 N KCl for 1 hr. Samples were equilibrated overnight at 3° C and then filtered (Whatman #42 filter paper) and stored at -20° C until analysis. Filtrates were analyzed using a Wescan Ammonia Analyzer. Net N mineralization was estimated as the sum of

Table 1.--Location, edaphic characteristics and precipitation of the two plantation sites.

	Site	
	Ambeer Creek(AC)	Hogthief Creek(HC)
County	Alexander	Hardin
Location	Lat.37° 14'N,Long.89° 19'W	Lat.37° 30'N,Long.88° 17'W
Soil	Haymond silt loam, Typic Udifluvent	Belknap silt loam, Aeric Fluvaquent
Soil drainage	well drained	somewhat poorly drained
Walnut suitability[1]	suitable	questionable
Mean annual precipitation[2]	1159mm	1165mm
Study period precipitation[3]	995mm	1146mm

[1]Losche et. al. 1980.
[2]NOAA 1983.
[3]NOAA personal communication.

ammonification (net change in NH_4^+-N) and nitrification (net change in NO_3^--N) for each soil sample during the incubation period.

Three additional samples were collected in each of the six plots at both sites at the 0-10 cm and 10-20 cm depths in the late summer to be analyzed for soil pH, total nitrogen (Bremner and Mulvaney 1982), extractable P (Olsen and Sommers 1982, Robarge and Fernandez 1986), total organic carbon (Nelson and Sommers 1982), and bulk density. Soil pH was measured using the 0.01 M $CaCl_2$ method described by Robarge and Fernandez (1986). Walnut survival, diameter at 1.07 m, and total height were determined after the 18th growing season during which N mineralization was measured.

RESULTS

Nitrogen mineralization

Seasonal variation in N mineralization occurred at both sites with most of the peak values in net N mineralization occurring in August (fig. 1). NO_3^--N was the most abundant form of mineral N found in the incubated soil cores. In some cases NO_3^--N yield exceeded net N mineralization due to an apparent net loss of NH_4^+-N during incubation of soil cores. Net loss of NH_4^+-N is possible when NH_4^+-N pools are initially large at the beginning of an incubation and nitrification proceeds faster than ammonification (Nadelhoffer et al. 1984) or where NH_4^+-N is immobilized in incubated cores. Net NO_3^--N yields were generally high throughout the growing season in all plots.

General seasonal patterns in N mineralization were similar for the sites and interplantings studied. However, the total annual amounts of mineral N produced at the two sites and in the various interplantings differed considerably (table 2). Soils beneath autumn-olive interplantings showed the highest production of mineral N (138 to 236 kg ha^{-1} yr^{-1}) followed by alder (118 to 185 kg ha^{-1} yr^{-1}) then controls (65 to 90 kg ha^{-1} yr^{-1}). Values obtained for the total annual production of mineral N in the controls were consistent with those reported in similar studies by Pastor et al. (1984) and Nadelhoffer et al. (1985) for hardwood stands in Wisconsin. Soils beneath autumn-olive and alder interplantings, particularly at AC, showed annual N mineralization levels that are higher than or at the high end of other reported values for forests and tree plantations in North America (Pastor et al. 1984, Nadelhoffer et al. 1985).

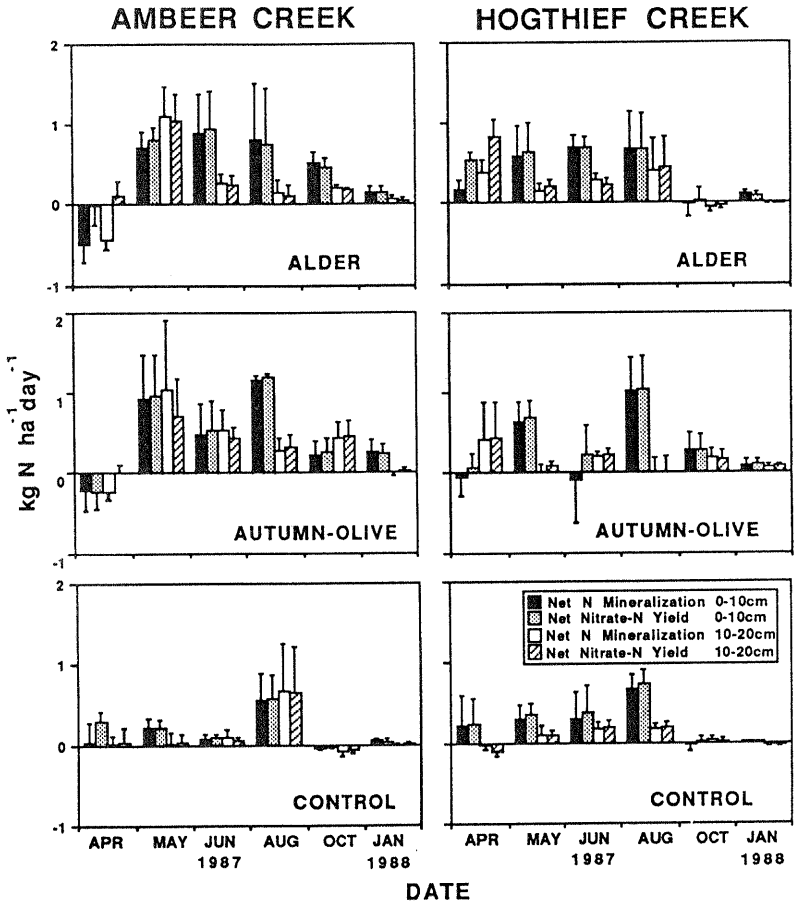

Figure 1. Seasonal patterns of soil NH_4^+-N and NO_3^--N production in the 0-10cm and 10-20cm soil layers in black walnut plots interplanted with autumn-olive, black alder, and pure walnut plots at the Ambeer Creek (AC) and Hogthief Creek (HC) plantations (kg N ha^{-1} day^{-1}+ 1 SE of the mean).

Table 2.--Total annual production of mineral N during the study period (kg ha^{-1} yr^{-1}) and percentage of the soil total N pool mineralized during the 1 year experiment.

Site	Interplanting	Depth(cm)	NH_4^+-N	NO_3^--N	Total net mineralized N	%N Mineralized
AC	alder	0-10	-9.25	146.04	136.09	9.8
AC	aut.-olive	0-10	-0.67	178.28	177.62	13.5
AC	control	0-10	-9.41	61.00	51.59	3.3
AC	alder	10-20	-2.55	51.21	48.66	4.5
AC	aut.-olive	10-20	-10.94	69.45	58.51	5.8
AC	control	10-20	-8.63	46.98	38.35	2.7
HC	alder	0-10	-11.05	97.60	86.55	4.7
HC	aut.-olive	0-10	-40.12	139.28	99.17	5.7
HC	control	0-10	-17.13	73.76	56.63	2.9
HC	alder	10-20	-13.57	45.22	31.65	2.6
HC	aut.-olive	10-20	-9.28	48.61	39.33	3.8
HC	control	10-20	-3.67	12.07	8.40	0.8

The percentage of the soil total N pool mineralized during the year in each plot ranged from 2.9 to 13.5% in the upper 10 cm and from 0.8 to 5.8% in the lower 10 cm (Table 2), with the highest percentages occurring in autumn-olive interplantings (7.2%), followed by alder (5.4%), then controls (2.4%).

Walnut Growth

Black walnut growth in both 18-year-old plantations was greatest in the autumn-olive interplantings (table 3). Walnut growth was greater in the alder interplanting than in the pure walnut controls at Ambeer Creek (AC), but not at Hogthief Creek (HC). The differences between locations in the growth of walnut interplanted with alder is probably due to death of alders at HC as described by Rietveld et al. (1983). In general, the black walnut growth differences that we measured at 18 years of age follow the same patterns that Schlesinger and Williams (1984) reported at age 13 years in these same interplantings.

Soil pH

Soil pH values indicate very slightly acid to strongly acid soils at HC, and very strongly acid soils at AC. Soils under autumn-olive interplantings were more acidic than under alder or controls at both sites (table 4).

Soil Phosphorus

Soil extractable P levels ranged from 0.4 to 0.8 mg kg^{-1} dry mass at HC and from 0.6 to 2.3 mg kg^{-1} dry mass at AC (table 4). Due to the unusually low values of P found in all plots, these soils would have to be regarded as being deficient in available P (Stevenson 1986). Levels of P were highest in the 0-10 cm depth and showed little variation between interplantings, except in the autumn-olive interplantings at AC where P levels in the upper 10 cm of soil were considerably higher than in the upper 10 cm of soil in the alder interplantings or controls.

Organic Carbon and Total Nitrogen

Soil total organic C levels varied from 13,841 to 21,836 kg ha^{-1} in the upper 10 cm, and from 996 to 1403 kg ha^{-1} in the lower 10 cm (table 4). Soil total N values ranged from 1317 to 1928 kg ha^{-1} in the upper 10 cm and from 996 to 1403 kg ha^{-1} in the 10-20 cm depth. Total N and organic C in the upper 10 cm were both higher at HC and were lowest in autumn-olive interplantings at both sites. Values for total N and organic C in the 10-20 cm depth were more uniform for interplantings and sites. C:N ratios were all low, ranging from 10:1 to 14:1 in the upper 10 cm and from 8:1 to 11:1 in the 10-20 cm layer. C:N ratios were always higher in the upper 10 cm and

Table 3.--Dimentions and estimated biomass of 18-year-old black walnut trees interplanted with alder and autumn-olive at two sites (plot means, n=2).

Site	Interplanting	dbh(cm)	Height(m)	Mortality(%)	Total estimated walnut above-ground dry biomass[1] (kg $plot^{-1}$)
AC	alder	14.2	10.1	9	1219
AC	autumn-olive	18.9	11.9	2	2554
AC	control	11.7	7.6	73	78
HC	alder	13.6	7.3	18	759
HC	autumn-olive	19.4	12.8	7	2538
HC	control	12.4	7.0	11	742

[1]biomass = $5.40056 + 0.02307d^2h$ where d = dbh(cm) and h = height(m). From Rietveld et al. 1983.

Table 4. Measured soil properties at the two study sites. Mean values and (standard errors).

Site	Inter-planting	soil depth (cm)	n	pH	extractable P (mg kg^{-1})	total N (kg ha^{-1})	Organic C (kg ha^{-1})	C:N
AC	Alnus	0-10	6	4.16(0.02)	1.0(0.2)	1388(124)	19715(3744)	14
AC	Elaeagnus	0-10	6	3.85(0.10)	2.3(0.5)	1317(123)	13841(1054)	11
AC	none	0-10	6	4.37(0.05)	1.0(0.1)	1558(207)	16114(1184)	10
AC	Alnus	10-20	6	4.19(0.05)	0.8(0.1)	1074 (65)	9134 (422)	9
AC	Elaeagnus	10-20	6	4.19(0.08)	1.2(0.1)	1005 (45)	9492 (603)	9
AC	none	10-20	6	4.47(0.04)	0.6(0.1)	1403(170)	11135 (364)	8
HC	Alnus	0-10	6	6.97(0.11)	0.8(0.1)	1855(181)	20523(1582)	11
HC	Elaeagnus	0-10	6	5.59(0.43)	0.6(0.1)	1727(288)	18268(2606)	11
HC	none	0-10	6	6.85(0.17)	0.8(0.1)	1928(103)	21836(1051)	11
HC	Alnus	10-20	6	6.69(0.13)	0.5(0.0)	1226 (66)	11307 (420)	9
HC	Elaeagnus	10-20	6	5.29(0.29)	0.4(0.1)	1039(119)	9832 (771)	9
HC	none	10-20	6	6.21(0.24)	0.4(0.1)	996 (78)	10834 (473)	11

showed little variation between sites and treatments (table 4). These soil C:N ratios are at the lower end of values reported in the literature and are in a range where N mineralization would be favored.

DISCUSSION

N mineralization was found to have seasonal pulses, indicating that sampling must be done throughout the year in order to quantify annual mineralization. Other researchers using the buried bag technique have found similar seasonal variation (Nadelhoffer et al. 1984, Pastor et al. 1984). Because N mineralization is a microbial reaction, temperature and moisture are important controlling factors. Estimated total annual production of mineral N in soils beneath these actinorhizal interplantings was high when compared to similar studies in hardwood forest stands in the temperate region of North America (Pastor et al. 1984, Nadelhoffer et al. 1985). The greater production of mineral N occurred in plots with the best walnut growth, whereas lower production of mineral N occurred in plots with poor walnut growth. This indicates a stronger relationship between walnut growth and N input into soils than has been previously reported (Friedrich and Dawson 1984). These results indicate that N_2-fixation is probably important in increasing walnut growth in these mixed plantings, although other benefits to walnut growth from interplanting such as weed suppression and sheltering are difficult to segregate from the effects of improved N fertility (Friedrich and Dawson 1984).

The idea that forest trees primarily take up NH_4^+-N, particularly in acidic soils, has been widely promoted (Keeney 1980) However, it is now known that some tree species preferentially take up NO_3^--N. Studies by Krajina et al. (1973), Bigg and Daniel (1978), and Van den Driesche (1978) have shown that some tree species attain better growth on sites where a particular form of mineral N predominates. Our results indicate NO_3^--N is the major form of mineral N available to black walnut interplanted with actinorhizal N_2-fixers and supports the emerging view that nitrification may be a more important process in temperate forest soils than was previously thought.

A review of the literature by Keeney (1980) indicates that many authorities assumed that the acidity of most forest soils inhibits autotrophic nitrification. Alexander (1977) reported that nitrification typically decreased below pH 6.0 and is negligible below pH 5.0, except where acid adapted strains of heterotrophic nitrifiers were present. Our observation of high nitrification rates at pH values as low as 3.85 indicates the presence of acid-tolerant nitrifiers in these plantations.

In addition to pH, P supply is believed to regulate nitrification. Purchase (1974) and Pastor et al. (1984) have suggested that P deficiency can restrict nitrification in forest plantations. The low soil P concentrations in late summer at both HC and AC did not seem to restrict

nitrification. The seasonal availability of P was not determined, therefore, the relationship between available P and nitrification could not be determined.

At the AC plantation, Ponder (1980) found soil total N levels in autumn-olive interplantings to be higher than in pure black walnut plots (3890 vs. 2491 kg ha^{-1}) at the 0-20 cm depth. Our study found soil total N levels in late summer at the 0-20 cm depth at AC to be lowest in autumn-olive interplantings (2322 kg ha^{-1}) and highest in pure walnut plots (2961 kg ha^{-1}). These discrepancies in soil total N in autumn-olive interplantings at AC could be due to analytical errors, methodological differences, or actual changes in the soil total N pool. Given the percentage of the soil total N pool estimated by us to be mineralized in the autumn-olive interplanting during the year of our study, it seems that the latter is true. Of the soil total N pool, 7.2% was mineralized in one year in the upper 20cm of the autumn-olive interplantings as compared to 5.4% in one year for alder and 2.4% for pure walnut in our study. Thus the soil total N pool in the actinorhizal interplantings may be declining faster than the soil total N pool in the control plots - suggesting that the input of N-rich litter from actinorhizal plants may have a priming effect on N mineralization. Although these N mineralization percentages are high, we feel that they are not unreasonable given the low C:N ratios. It should also be noted that the N content of litter is not included in the soil total N estimates. The turnover of N rich litter from the actinorhizal interplantings could also have resulted in the high values obtained for net N mineralization as a percentage of the soil total N pool where the litter component is excluded.

In the alder interplantings at HC N_2-fixation most likely ceased after plantation age 13 due to extensive alder mortality (Rietveld *et al.*, 1983); however, mineralization rates at plantation age 18 are still higher for mixed alder plots than for controls.

Apparently, soil total N pools had been built up over a number of years by N inputs exceeding mineralization. In recent years the inputs in the autumn-olive interplantings and alder interplantings, where alder mortality is high, may have decreased even as high N mineralization rates occurred, thus reducing the soil total N pools to levels comparable to the controls.

The component of black walnut growth improvement due to increased availability of mineral N in the autumn-olive interplantings will probably decline in the future although the benefits of N_2-fixation and interplanting are likely to extend well beyond the life of the autumn-olive. Alder trees not killed by black walnut's allelochemical juglone have growth rates comparable to black walnut on these sites and should continue to provide N to the walnut trees. However, the benefits of improved N fertility afforded by alder trees are probably offset to some extent by their competition with walnut for light, water and nutrients.

In summary, we have shown annual N mineralization rates to be high in mixed plantings of black walnut with actinorhizal plants. Net NO_3^--N production far exceeded the yield of NH_4^+-N, even though soil pH and soil available P were low. Mineralization rates varied seasonally and annual rates were highest in the autumn-olive interplantings where the largest walnut trees also occurred. These results confirm the importance of N input from N_2-fixing actinorhizal plants in promoting black walnut growth. They also illustrate the complexity of relationships of actinorhizal plant development and mortality with soil N mineralization.

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