SOIL AND FOLIAR NITROGEN AFTER FERTILISER TREATMENT OF PONDEROSA PINE

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ABSTRACT

A mature ponderosa pine (*Pinus ponderosa* Dougl.) forest located on the eastern slopes of the Cascade Mountains of the Pacific Northwest, USA, was treated with three different nitrogen fertilisers to compare their relative ability to increase extractable soil-nitrogen, pine foliar-nitrogen, and basal area. Fertilisers tested were urea, ammonium nitrate, and biosolids (a domestic sewage sludge). Urea and ammonium nitrate were applied at a rate of 220 kg N/ha, and biosolids at 11 Mg/ha (which was assumed to provide 240 kg available-N/ha in the first year). All fertilisers increased extractable soil-nitrogen in the first year after application but not always significantly; levels dropped to those of the control soil by year 2. Foliar concentration of nitrogen was increased by all fertilisers; however, urea did not increase foliar concentrations until the second year after application. Biosolids continued to increase foliar nitrogen through year 5, and caused the highest levels of foliar nitrogen. Basal area was not increased by any fertiliser over the 5-year period. Soil solutions showed increases in ammonium (NH_4^+) and nitrate (NO_3^-) in the upper profile, but increases in solution nitrogen at the base of the soil profile were found only with the urea treatment.

Keywords: nitrogen; fertiliser; foliar nitrogen; extractable soil nitrogen; urea; biosolids; *Pinus ponderosa*

INTRODUCTION

In many parts of the world, low nitrogen availability is the most common limiting factor for optimal timber productivity. In north-western United States, nitrogen limitation occurs throughout much of the area (Brockley *et al.* 1992). Soils in this region are typically young with thin surface organic layers, thus mineral nitrogen exists in most soils in relatively small amounts. Inputs of nitrogen to the soil come from nitrogen-fixing plants, atmospheric deposition, and fertilisers. Forests in this area have increasingly been treated with fertiliser to enhance productivity (Harvey *et al.* 1994; Mika *et al.* 1992). Nitrogen can be applied in chemical forms (normally urea or ammonium nitrate) or in combined forms such as in municipal or industrial wastes.

Once nitrogen is applied to a soil, a number of losses or transformations can occur. Ideally, the majority of nitrogen will be converted into tree biomass; however, large amounts of

nitrogen can be lost to the atmosphere via ammonia volatilisation and denitrification, thereby reducing the amount of nitrogen available for plant uptake (Nason & Myrold 1992). Losses from forest soils have been reported from 5% to as high as 40% (Marshall & DeBell 1980). At the location of this study, atmospheric losses were towards the low end of this range (Henry & Zabowski in prep.). Nitrate leaching can also be a major cause of loss (Nason & Myrold 1992), especially in areas where rainfall exceeds evapotranspiration (Henry *et al.* in prep.); however, leaching losses are usually limited in low-rainfall areas. Lastly, immobilisation of nitrogen in the soil and uptake by understorey plants can reduce nitrogen available for tree uptake (Nason & Myrold 1992); soil immobilisation can range up to 1000 kg N/ha after fertiliser application (Henry 1991).

Although a significant amount of research with nitrogen fertiliser has been conducted on Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) forests (Cochran *et al.* 1986) and younger ponderosa pine stands (Youngberg 1975; Powers *et al.* 1988), little work has been done for mature ponderosa pine. Economic fertiliser responses have been obtained with mature Douglas-fir stands in western Washington State (Miller & Webster 1981). Mature ponderosa pine stands are common low-elevation forests of the eastern Cascade Mountains in Washington and Oregon States. Where water is not limiting, nitrogen has been the limiting element (Powers *et al.* 1988); in other areas volume increases as great as 100% with application of nitrogen fertiliser to ponderosa pine have been documented (Cochran *et al.* 1981). Deficiencies are evident in ponderosa pine at foliar nitrogen concentrations below 1.1%, and foliar concentrations of pines are typically increased by fertiliser when below this level (Powers *et al.* 1988) but optimal levels can change with stand age (Miller *et al.* 1981). This study was designed to investigate the effect of urea, ammonium nitrate, and biosolids application on soils, soil solution, foliage, and basal area growth response of a mature interior ponderosa pine stand.

MATERIALS AND METHODS

Site and Treatments

The study site was located in a mature ponderosa pine stand on the eastern slopes of the Cascade Mountains in Washington State. The area had an elevation of 600 m, average annual temperature of 8°C, and average annual precipitation of 960 mm. Precipitation was highly variable during the study period—960, 790, 1600, 1000, 810, and 630 mm for the years 1988 to 1993, respectively. The study area was on an outwash plain near the headwaters of the Wenatchee River (48°50′N, 120°45′W), on soil classified as Goddard series, sandy skeletal, mixed, Frigid Andic Xerochrept, with parent materials consisting of ash over outwash (Beieler 1968). The pine forest was approximately 70 years old, and was thinned at around age 60. The stand was almost entirely ponderosa pine and even-aged, with few Douglas-fir and grand fir (*Abies grandis* (Dougl.) Forbes) trees present. The understorey was mostly pine grass (*Calamagrostis rubescens* Buckl.), ceanothus (*Ceanothus velutinus* Dougl.), elk sedge (*Carex geyeri* Boott), and lupin (*Lupinus sericeus* Pursh), but with a variety of other minor herbaceous species.

Five replicate 0.04-ha plots were established in 1988 for each treatment and control; plots were blocked to allow for a possible moisture gradient and differences in number of trees per plot. All plots were sampled in 1988 prior to fertiliser application and fertilisers were applied in April of 1989. Urea and ammonium nitrate were applied at a rate of 220 kg N/ha. Biosolids

were obtained from the City of Wenatchee (domestic sources), contained 6.5% solids, and were applied at a rate of 11.4 dry Mg/ha. With a total nitrogen content of 6.5%, it was estimated that this application would provide 240 kg available-N/ha within 1 year (U.S. EPA 1983).

Sampling and Analyses

Foliar samples were collected from the upper third of the canopy of three randomly selected trees in each plot for a total of 15 samples per treatment in autumn of 1988 (year 0), 1989 (year 1), 1990 (year 2), and 1993 (year 5). Branches were dried at 75°C, and needles were separated into current- and 1-year-old growth. Samples from years 1, 2, and 5 were ground and analysed for total nitrogen.

Soil solutions were collected from the O, A, Bw, and BC horizons from fall of 1988 to spring of 1990. Solutions were collected using tension lysimeters (10 kPa tension) installed in three of the five replicate plots in summer of 1988. Lysimeters were placed at the base of each horizon; plates were evacuated using a hand pump, and solutions were collected monthly or as moisture permitted. Three collections were made prior to fertiliser application for background levels of nitrogen, and eight collections were made during the first year after treatment. Solutions were filtered to 0.2 μm, and analysed for pH, ammonium, and nitrate (Keeney & Nelson 1982).

Soil samples, from the O, A, and Bw horizons from the plots where lysimeters were installed, were collected and air dried. Potassium chloride extractions were done on air-dried <2-mm soil to compare relative nitrogen availability between treatments (Keeney & Nelson 1982). Solutions were analysed for ammonium and nitrate; total soil nitrogen was determined on whole ground soil samples from each major horizon for years 1, 2, and 5.

Measurements of tree diameter at breast height were made in the fall of year 0 and year 5. Basal area of each plot was determined by measuring tree diameter at breast height, calculating basal area, and summing basal area of all pine trees per plot. Trees were measured prior to treatments and at the end of the fifth growing season. Basal area increment was determined by calculating the difference between total initial basal area and total basal area of all live trees from each plot at year 5.

RESULTS

Soil and Soil Solutions

Soil solution concentrations of ammonium-nitrogen and nitrate-nitrogen, and solution pH from the O, A, Bw, and BC horizons before and during the first year after fertiliser application are given in Table 1. Soil solution pH was increased in the O horizon by both urea and biosolids application, but there was little change in the mineral horizons; ammonium nitrate application had little effect on solution pH. Solution concentration of ammonium-nitrogen was increased in the O horizon after all fertiliser treatments, but was highest with urea; maximum concentrations occurred during April/May after application (maximum concentrations were 19, 6.4, 3.9, and 0.23 mmol NH_4-N/ℓ with urea, ammonium nitrate, biosolids, and control treatments respectively). Concentrations of ammonium-nitrogen changed little in lower horizons. There did not appear to be any noteworthy leaching losses of ammonium-nitrogen with any fertiliser application.

TABLE 1–Soil solution ammonium-nitrogen and nitrate-nitrogen concentrations and pH from soil horizons before and after treatment. Concentrations are averages of three collections prior to fertiliser application (year 0) and eight collections after (year 1); average value of n is 2 for year 0 and 4 for year 1. Blanks indicate no solution collection.

Horizon	Urea		Amm. nitrate		Biosolids		Control	
	Year 0	Year 1	Year 0	Year 1	Year 0	Year 1	Year 0	Year 1
				mmol NH_4-N/ℓ				
O	0.01	4.85	0.01	1.07	0.01	1.14	<0.01	0.04
A	0.01	0.02	<0.01	0.03	0.01	<0.01		0.01
Bw	<0.01	<0.01		0.02	0.01	0.05		<0.01
BC	0.02	0.03	<0.01	0.02	<0.01	0.05	<0.01	<0.01
				mmol NO_3-N/ℓ				
O	<0.01	0.01	<0.01	1.86	<0.01	0.01	<0.01	<0.01
A	<0.01	0.01	<0.01	<0.01	<0.01	<0.01		<0.01
Bw	<0.01	0.01		<0.01	<0.01	<0.01		<0.01
BC	<0.01	0.16	<0.01	0.08	<0.01	0.01	<0.01	<0.01
				pH				
O	5.3	6.8	5.5	5.5	5.5	6.0	5.7	5.4
A	5.9	6.4	6.1	6.5	6.3	5.6		6.5
Bw	6.3	6.6		6.7	6.6	6.7		6.4
BC	6.2	6.6	6.0	6.4	6.3	6.4	6.5	6.7

Concentrations of nitrate-nitrogen were increased in the O horizon only with the ammonium nitrate application. Increases in nitrate-nitrogen were also seen in the BC horizon with both chemical fertilisers, suggesting that some nitrogen could be lost by nitrate leaching from these soils. Average nitrate-nitrogen was below recommended maximum drinking water levels (i.e., 10 mg/ℓ for U.S.A.) with the ammonium nitrate application, and reached a maximum concentration of 10 mg/ℓ with the urea application during the first year. Biosolids did not increase soil solution nitrate in any horizon. These results suggest that none of these fertilisers is likely to contaminate drinking water with a single application at the rates used in this study; however, either ammonium nitrate or biosolids might be prefered to ensure groundwater purity on similar soils.

Extractable soil ammonium-nitrogen and nitrate-nitrogen are given in Table 2 for the first, second, and fifth years after fertiliser application. All fertilisers increased extractable ammonium and nitrate in the O and A horizons in the first year after treatment, but increases were significant only in the O horizon (using ANOVA with p=0.05). The largest increase occurred with urea. Increases were no longer apparent in any horizon in years 2 and 5, and no increases were significant. There was a significant treatment effect in the Bw horizon, with ammonium nitrate causing the highest extractable ammonium. Increases in the Bw horizon suggest that some ammonium was leached into the lower profile with this treatment. Differences between years were significant for ammonium.

Year-since-application was a significant factor for nitrate (p=0.05). Although both the urea and biosolids treatments showed increased nitrate levels in the O horizon in the first year after application, treatment effects were not significant owing to the high variability. The high variability in extractable nitrogen in control plots is evident between all study years in Table 2. Differences in extractable nitrate by year may have been affected by environmental

TABLE 2–Extractable ammonium-nitrogen and nitrate-nitrogen from O, A, and Bw horizons from the first, second, and fifth growing seasons after fertiliser application. Values are averages of three samples per treatment. Standard deviations are given in parentheses.

Horizon	Year 1				Year 2				Year 5			
	Urea	Am.nit.	Biosol.	Control	Urea	Am.nit.	Biosol.	Control	Urea	Am.nit.	Biosol.	Control
						μmol NH_4-N/g						
O	140	79	120	51	6.4	5.2	11	4.1	4.8	6.9	4.9	4.1
	(15)	(29)	(71)	(14)	(4.5)	(2.7)	(6.6)	(2.2)	(3.9)	(2.4)	(4.5)	(1.4)
A	18	11	15	3.1	2.1	2.8	0.14	0.71	3.3	4.4	0.43	7.9
	(12)	(3.2)	(15)	(5.1)	(1.6)	(2.7)	(0.12)	(0.53)	(4.1)	(0.68)	(0.30)	(6.2)
Bw	0.07	4.7	0.53	0.31	1.9	0.86	0.37	0.59	1.9	2.6	0.59	2.5
	(0.00)	(1.9)	(0.80)	(0.42)	(2.0)	(0.78)	(0.52)	(0.90)	(1.5)	(1.1)	(0.90)	(2.9)
						μmol NO_3-N/g						
O	21	1.1	14	0.86	0.57	0.37	0.86	0.36	0.27	0.24	0.18	0.20
	(22)	(0.92)	(9.5)	(0.26)	(0.19)	(0.10)	(0.10)	(0.19)	(0.07)	(0.05)	(0.11)	(0.06)
A	16	3.4	9.3	4.6	0.36	0.71	0.31	0.42	0.07	0.07	0.07	0.04
	(13)	(1.8)	(7.3)	(3.3)	(0.06)	(0.59)	(0.06)	(0.19)	(0.02)	(0.02)	(0.01)	(0.02)
Bw	4.4	3.8	4.0	1.4	0.04	0.51	0.16	0.29	0.06	0.05	0.06	0.05
	(1.4)	(1.6)	(2.9)	(0.11)	(0.03)	(0.06)	(0.04)	(0.03)	(0.01)	(0.00)	(0.01)	(0.03)

factors—precipitation was highly variable throughout the study, with both 1989 (year 1) and 1993 (year 5) below average, and 1990 (year 2) almost twice that of normal.

Total soil nitrogen (Table 3) did not change significantly by treatment or year. In Table 4 extractable nitrogen is expressed as a percentage of total nitrogen in the soil. Substantial increases were evident in the percentage of extractable relative to total nitrogen in the urea and biosolids treatments in the first year, and in all horizons. The percentage of extractable soil nitrogen also increased with ammonium nitrate, but to a lesser extent.

Foliar Nitrogen and Basal Area

Nitrogen concentrations in current- and 1-year-old foliage are given in Fig. 1. Before treatment, current-year foliage was below the critical 1.1% level recommended by Powers *et al.* (1988). In the first and second years after treatment, ammonium nitrate significantly increased current-year foliar nitrogen levels above foliar concentrations in trees of the control plots (ANOVA with p=0.05). No further increases in foliar nitrogen were evident, and by year 5 concentrations were no longer significantly higher than those of controls. Although biosolids did not significantly increase nitrogen content in current-year foliage during years 1 or 2, foliar concentrations did rise. By year 5, foliar concentrations had

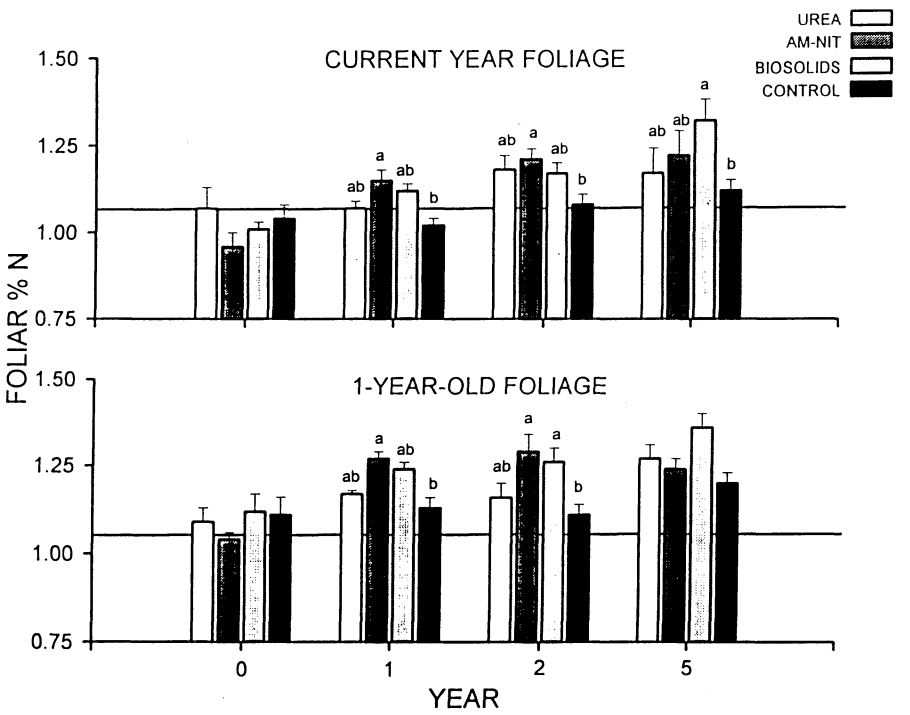

FIG. 1–Nitrogen concentration (%) of current and 1-year-old year foliage of ponderosa pine. Concentrations are averages of three samples taken from the upper third of the canopy of three different trees from each of five replicate plots. Standard errors are indicated by bars. Means that are significantly different (p=0.05) within a year are indicated by different letters; no letters indicate that no treatments were significantly different.

TABLE 3–Total soil nitrogen (%) from O, A, and Bw horizons from the first, second, and fifth growing seasons after fertiliser application. Values are averages of three samples per treatment.

Horizon	Year 1				Year 2				Year 5			
	Urea	Am.nitrate	Biosolids	Control	Urea	Am.nitrate	Biosolids	Control	Urea	Am.nitrate	Biosolids	Control
O	1.3	1.2	1.3	1.1	1.1	1.0	1.3	1.0	0.8	1.2	1.2	1.1
A	0.39	0.26	0.41	0.26	0.29	0.30	0.20	0.27	0.28	0.29	0.26	0.27
Bw	0.15	0.18	0.20	0.18	0.15	0.17	0.16	0.18	0.16	0.22	0.17	0.18

TABLE 4–Extractable nitrogen expressed as a percentage of total soil nitrogen in the O, A, and Bw horizons from the first, second, and fifth growing seasons after fertiliser application.

Horizon	Year 1				Year 2				Year 5			
	Urea	Am.nitrate	Biosolids	Control	Urea	Am.nitrate	Biosolids	Control	Urea	Am.nitrate	Biosolids	Control
O	18	9	15	7	2	1	1	1	1	1	1	1
A	12	8	8	4	1	2	<1	1	2	2	<1	4
Bw	4	7	3	1	2	1	<1	1	2	2	1	2

exceeded those measured with the other fertilisers; biosolids produced the only significant increase evident in year 5. Even though urea increased current-year foliage nitrogen concentration by year 2, increases were not significant. Needle size was not measured but there were no evident changes in needle size after fertiliser application.

Results for the 1-year-old foliage show a similar pattern to that of the current-year foliage. Foliage was at the critical nitrogen level prior to fertiliser application and all fertilisers increased foliar nitrogen during the 5-year period, but increases were significant only in some treatments. Analysis of the 1-year-old foliage showed that application of ammonium nitrate caused the fastest increase in foliar nitrogen, biosolids had the greatest increase but a slower effect (not significant until year 5), and urea did not significantly increase foliar nitrogen concentration. Although the nitrogen content of current-year foliage was usually lower than 1-year-old foliage, a t-test of current-year foliage and 1-year-old foliage by treatment and year showed no significant differences in nitrogen percentage ($p=0.05$) for samples from the same tree.

The 5-year basal area increment is compared with the initial basal area of each plot in Fig. 2. Little effect of treatment can be seen in the comingled data of the fifth-year results. An ANOVA of fertiliser effects using initial basal area as a covariate showed no significant effect of treatment on stand basal area. Although control levels are generally lower than those of both ammonium nitrate and biosolids treatments (as indicated by the regression lines), these effects are not statistically significant.

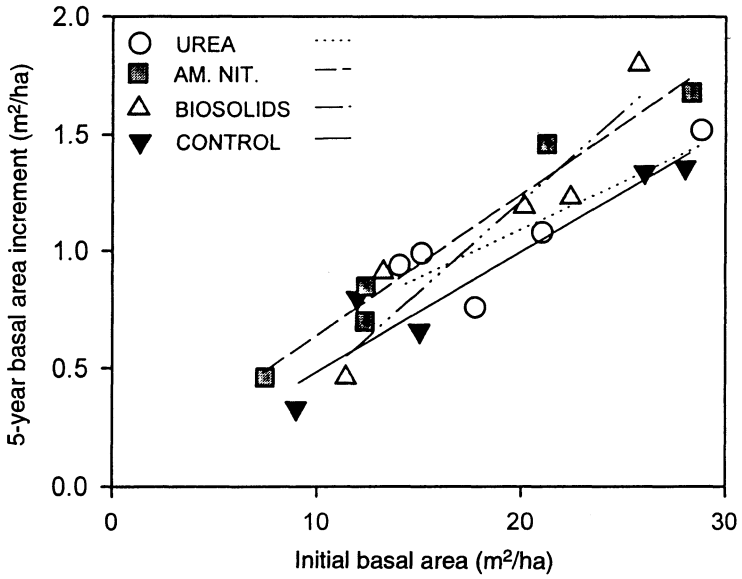

FIG. 2–Five-year basal area increment of ponderosa pine compared with initial basal area, by treatment.

DISCUSSION

Some responses to fertiliser were observed in the extractable soil nutrients in the first year after application, and there were increases in foliar concentrations of nitrogen for several

years afterward. Although there was an immediate increase in extractable soil nitrogen with urea, significant foliar increases occurred only with ammonium nitrate, and later with biosolids. Despite these increases in foliar concentrations, there was no significant increase in basal area of the ponderosa pine. Other factors may have contributed to the lack of increased tree growth. Several studies have reported that fertiliser responses occurred when initial basal area of ponderosa pine was 18 m^2/ha or less (Youngberg 1975; Cochran *et al.* 1981; Powers *et al.* 1988). Initial basal area of stands in this study ranged from less than 10 to almost 30 m^2/ha. Initial basal area had little effect on basal area increment with any treatment which suggests that, although high basal areas may have limited response in some stands, some factor other than basal area may be more limiting to tree growth in this region even if high thinning rates are used prior to fertiliser treatment.

Current-year foliar nitrogen was at or below critical levels (1.1%, Powers *et al.* 1988) in all treatment plots prior to fertiliser application. Both ammonium nitrate and biosolids increased nitrogen concentrations above the critical level within the first year, and maintained higher concentrations through year 5. Although the response from urea was slower, it also increased current-year foliage nitrogen concentrations by year 2 but to a lesser extent than the other fertilisers. The delayed response to urea was unexpected, and no clear explanations are evident as highest levels of extractable nitrogen were found in the first year after application. It may be that high microbial immobilisation occurred in year 1, with a mineralisation release in spring of year 2 increasing uptake. This would not have been detected as soil sampling was done only in late summer.

Nitrogen concentration in the 1-year-old foliage was consistently higher than that of the current-year foliage before fertiliser application, and this continued throughout the study. Powers (1984) reported that lower concentrations of nitrogen in older foliage than in current foliage can indicate nitrogen stress. However, current-year foliage is also highly susceptible to annual changes in environmental conditions and subject to fluctuations throughout the growing season (Powers 1984). Although differences between current and 1-year-old foliage were not significant, it does not eliminate the possibility that nitrogen may be deficient in these stands, but does suggest that some other factor may be more limiting. A subsample of foliage was tested for phosphorus, sulphur, calcium, magnesium, potassium, boron, zinc, and copper, but no deficiencies of these nutrients were apparent. It is also possible that a growth response would occur at much higher nitrogen additions.

All fertilisers had only a short-term effect on extractable nitrogen, and no detectable effect on total soil nitrogen. However, the concentration of foliar nitrogen was maintained through year 5 with both chemical fertilisers. Biosolids continued to increase current-year foliage concentrations of nitrogen through year 5. Although a prolonged increase in available nitrogen with biosolids would be expected, it was not seen in the extractable soil nitrogen. This does not exclude the possibility of continued microbial mineralisation of the biosolids that was not captured by the chemical extraction, as there appears to be a continued enhancement of the available soil nitrogen pool over at least 5 years.

In summary, treatment with nitrogen fertilisers increased extractable soil nitrogen in some horizons in the first year, but these increases did not continue into subsequent years. Although foliar nitrogen concentrations increased, no increases were evident in basal area of ponderosa pine with any fertiliser treatment. The most probable cause for the lack of

response is a combination of a deficiency in some other nutrient and seasonal water limitations, as response in trees with high initial basal areas did not appear more limited than in those with low initial basal areas. Although tree vigour may be improved with fertiliser applications using typical levels of nitrogen additions such as these, enhancements in basal area are unlikely in forests of this age with similar locations and soils.

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