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Nitrogen-fertilization impacts on carbon sequestration and flux in managed coastal Douglas-fir stands of the Pacific Northwest

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Abstract

We examined whether N-fertilization and soil origin of Douglas-fir [Psuedotsuga menziesii (Mirb.) Franco] stands in western Washington state could affect C sequestration in both the tree biomass and in soils, as well as the flux of dissolved organic carbon (DOC) through the soil profile. This study utilized four forest sites that were initially established between 1972 and 1980 as part of Regional Forest Nutrition Research Project (RFNRP). Two of the soils were derived from coarse-textured glacial outwash and two from finer-textured volcanic-source material, primarily tephra, both common soil types for forestry in the region. Between 1972 and 1996 fertilized sites received either three or four additions of 224 kg N ha⁻¹ as urea (672–896 kg N ha⁻¹ total). Due to enhanced tree growth, the N-fertilized sites (161 Mg C ha⁻¹) had an average of 20% more C in the tree biomass compared to unfertilized sites (135 Mg C ha⁻¹). Overall, N-fertilized soils (260 Mg C ha⁻¹) had 48% more soil C compared to unfertilized soils (175 Mg C ha⁻¹). The finer-textured volcanic-origin soils (348 Mg C ha⁻¹) had 299% more C than glacial outwash soils (87.2 Mg C ha⁻¹), independent of N-fertilization. Soil-solution DOC collected by lysimeters also appeared to be higher in Nfertilized, upper soil horizons compared to unfertilized controls but it was unclear what fraction of the difference was lost from decomposition or contributed to deep-profile soil C by leaching and adsorption. When soil, understory vegetation and live-tree C compartments are pooled and compared by treatment, N-fertilized plots had an average of 110 Mg C ha⁻¹ more than unfertilized controls. These results indicate these sites generally responded to N-fertilization with increased C sequestration, but differences in stand and soil response to N-fertilization might be partially explained by soil origin and texture. © 2005 Elsevier B.V. All rights reserved.

Keywords: Carbon sequestration; Lysimeters; Dissolved organic and inorganic carbon; Pseudotsuga menziesii; Urea fertilization; Soil texture; Volcanic and glacial soils

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1. Introduction

Due to the potential for increased forest products yield as well as higher financial returns, N-fertilization

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impacts on Pacific Northwest forests continue to be a subject of interest in the region, including additional C sequestration from applied N (Johnson, 1992; Canary, 1994; Harrison et al., 2003). Carbon uptake through increased growth of trees is well documented, but the effects of N-fertilization on soils are much less understood (Johnson, 1992; Birdsey et al., 1993; Huntington, 1995; Lal, 2004), particularly at time intervals greater than a few years (Carter et al., 2002). Variations in input of litterfall over time, changes in fine and coarse-root growth, death, decay and production and decomposition of exudates are particularly poorly understood (Prescott et al., 1999; Neff and Asner, 2001; Kalbitz et al., 2000; Qualls, 2000). Most studies of N-fertilization impacts on C sequestration in soil have also sampled relatively shallow soil profiles (Canary, 1994; Harrison et al., 2003), sometimes ignoring what happens in the deeper, more massive subsoil horizons common in the region. Carbon in subsoil horizons can change substantially over time periods of decades under certain conditions (Cole et al., 1991), though this is commonly discounted as a major impact of N-fertilization. Earlier work on Nfertilization effects on soil C indicated that C sequestration in aboveground tree biomass increased with fertilization in sandy skeletal to rocky soils (Canary et al., 2001; Nohrstedt et al., 1989), but results on finer-textured soils were more variable. Urea fertilizer increased the short-term movement of SOC by a factor of 2-3 in an eastern deciduous forest (Kelly, 1981) with most of this flux occurring during the 3 months following urea application. There is no data available on long-term impacts of N-fertilization, though there is evidence that it can affect mineralization and movement of organic N (Prietzel et al., 2004).

This study considered previous N-fertilization effects on stand and soil C in two important soilorigin types for intensive forestry in Pacific Northwest Douglas-fir: (1) two soils derived from coarse-textured glacial outwash, and (2) two soils derived primarily from volcanic-origin. Ecosystem C pools to 1.0 m depth were quantified, and soil-solution C flux at four soil depths were estimated to determine if movement of soluble C into the soil profile might partially explain any changes in C in the soil profile over time due to fertilization.

2. Materials and methods

2.1. Site description

Starting in 1969, the Regional Forest Nutritional Research Project (RFNRP) established several hundred studies in the Pacific Northwest to evaluate the response of coastal Douglas-fir to N-fertilization (Stegemoeller and Chappell, 1990a; Stegemoeller et al., 1990b; Briggs, 1999). Research installations normally included N-fertilization, and always included an unfertilized control. Plot measurement areas were typically 0.0404 ha. Stand response was measured over time by periodic measurement of tree diameters and heights. The studies were not initiated with the idea of measuring C sequestration, but the relatively long life of the RFNRP compared to typical research projects makes these sites ideal for determining the long-term impact of N-fertilization on forests and soil. For this study, four installations were selected (Table 1) that had been previously fertilized beginning at least 20 years previously. Data on the stand and site are presented in Table 1. Total N application rates ranged between 672 and 896 kg N ha⁻¹, with either three or four individual applications of 224 kg N ha⁻¹ as urea.

The soils represent a regional grouping of parent material types from a very coarse skeletal glacial outwash to deep, silt loam derived from volcanic-origin (Soil Survey Staff, 2004). Soil profile descriptions are given in Table 2. Site 1, a Barneston series soil, was coarse outwash with 88% of the soil >2 mm. Site 2, a Poulsbo series soil, was deep sandy outwash, with only 23% of the soil in the silt or clay fraction, and finer only in comparison to the soil at Site 1. Site 3, a Winston series soil, was coarse loamy ash above glacial or fluvial (mudflow) material with 57% silt and 8% clay, and Site 4, a Typic Hapludand, was a deep (>1 m) ashy loam, tephra mix, with 64% of the total soil matrix in the silt fraction (Table 2).

2.2. Aboveground tree carbon

As part of RFNRP protocols, stem diameters at 1.3 m and heights of all live trees (DBH) on each plot were measured between the time of the initiation of fertilization and over a 20-year period. Aboveground tree biomass (including branches, bark and foliage)

Table 1
Site characteristics and installation establishment data

Parameters	Control/treated							
	Site 1, RFNRP #159, Cedar river	Site 2, RFNRP #196, Port gamble	Site 3, RFNRP #247, Radio hill	Site 4, RFNRP #235, Mud Mountain				
Trees ha ⁻¹	780	750	750	750				
Quadratic mean dbh (cm ²) ^a	22.6/27.7	12.9/20.7	31.9/32.7	30.2/30.8				
Total height (m) ^b	26.2/29.1	22.0/19.5	28.7/26.4	27.6/27.1				
Basal area $(m^2 ha^{-1})$	38.7/49.0	33.1/49.1	51.3/51.8	51.0/53.3				
Elevation (m)	320	140	646	555				
Mean precipitation (mm year $^{-1}$)	1250	900	1350	1350				
SI50 (m, unfertilized)	26	36	37	43				
Soil series	Barneston	Poulsbo	Winston	Unnamed				
Installation establishment year	1972	1975	1980	1980				
Years since planting	48 (not planted)	35	31	26				
Fertilization (kg N ha^{-1})	0/1120	0/1120	0/896	0/896				
Fertilization dates	1972-1980-1984-1988	1975-1983-1987-1991	1980-1988-1996	1980-1988-1996				
Fertilization regime (kg N ha ⁻¹)	224-224-224-224	224-224-224-224	224-224-224	224-224-224				
Years since last fertilization	13	10	5	5				
Location	47°22′38″N,	47°49′58.01″N,	47°11′N,	47°8′48.75″N,				
	121°55′W	122°36′11.44″W	121°51′W	121°43′4.22″W				

^a Calculated by summing squares of DBH, then taking square root.

^b Average total height of tallest 99 trees ha⁻¹.

was estimated using allometric equations developed by Gholz et al. (1979). A plot of diameter versus total height showed that these equations were likely the best predictive equations available (Harrison et al., 2005). The study plots contained entirely Douglas-fir.

The estimates of biomass in bark, bolewood, branches (live and dead), foliage and roots generated from the equations of Gholz et al. (1979) were then multiplied by the average C concentrations of six samples of Douglas-fir tissue collected from another study to generate estimates of C in aboveground biomass during the time after N-fertilization (Table 3). The C concentrations of these samples ranged from 0.481 to 0.546 g C g⁻¹, with an average of 0.509 g C g⁻¹. These results compared well to the data for overall average C concentrations (0.512 g C g⁻¹) of Douglas-fir trees in the Pacific Coast and Rocky Mountain regions (Birdsey, 1992; Kimmins et al., 1985).

2.3. Soil sampling

Due to the large amount of rocks in the subsoil of Sites 1 and 2, the pit excavation method was the only method practical for both representative soil sampling and accurate determination of bulk density (Harrison et al., 2003). For Sites 3 and 4, core methods were used for estimating bulk density and soil profiles were sampled along the face of the pit with a hand trowel (Blake and Hartge, 1986). One pit was dug at each plot (4 installations \times 2 pits per installation = 8 pits). Pits were dug near the plot centers and at least 1 m from the nearest tree bole or log in an area where the surface was most representative of the entire plot area. Soil layers were delineated and sampled based on color, textural and structural breaks (Table 2). Soil material and gravels <25 mm and rocks >25 mm were weighed as two separate components in the field. A 1.0 kg subsample of the <25 mm component was taken from each soil horizon layer and used to determine field moisture, particle size distribution, and C and N content (Whitney and Zabowski, 2004). Three 0.25 m^2 soil "O" horizon samples were taken at each plot behind the soil pit in undisturbed material. Live understory material that originated within the "O" horizon sample grid was clipped at ground level and collected, bagged, and analyzed as organic material. Understory was an extremely small component of total site biomass and is only added to the final determination of ecosystem C. Dead coarse organic

Table 2	2				
Profile	descriptions	of soils	at	study	sites

Horizon	Control depth (cm)	$Mg C ha^{-1}$	$Mg N ha^{-1}$	Fertilized depth (cm)	$Mg C ha^{-1}$	$Mg N ha^{-1}$	Description
Site 1. Sat	ndy-skeletal, miz	ked, mesic Typic	vitrixerands, s	lope 1-3% (Soil	Survey Staff, 2	004) [42, 46, 8,	3, 1] ^a
0	7.5–0	10.9	0.32	5.3–0	10.7	0.49	Fresh, decomposed moss, needles, twigs, logs, etc.
А	0-12.3	31.3	0.85	0-10.5	28.0	1.16	Gravelly, silt loam
Bs	12.3-62.3	34.0	0.98	10.5 - 58.0	29.0	1.30	Gravelly, silt loam
BC	62.25-100	8.5	0.47	58.0-100	7.8	0.51	Extremely cobbly coarse sand
Total		84.6	2.62		75.3	3.47	
Site 2. Co	arse-loamy, isoti	c mesi mesic V	itrandic Dystrox	erept, slope 0–5	% (Soil Survey	Staff, 2004) [0,	23, 54, 15, 8]
0	2.0-0	18.4	0.76	2.0-0	10.0	0.39	Fresh, decomposed moss, needles, twigs, logs, etc.
Е	0-3.0	15.2	0.42	0-4.0	24.5	0.85	Gravelly, sandy loam
Bs	3.0-21.0	11.7	0.58	4.0-33.0	28.8	1.46	Gravelly, sandy loam
Bsm	21.0-100	28.9	3.52	33.0–100	49.1	3.45	Gravelly weakly cemented sandy loam
Total		74.2	5.29		114.7	6.17	
Site 3. Coa	arse-loamy over s	sandy-skeletal, n	nixed, superactiv	e, mesic Andic I	Dystroxerepts, slo	ope 0–1% (Soil S	urvey Staff, 2004) [8, 19, 8, 57, 8]
0	5.5-0	41.1	1.43	4.25–0	35.0	1.51	Fresh, decomposed moss, needles, twigs, logs, etc.
А	0-8.8	34.9	1.03	0-22.3	148.4	4.72	Ashy loam
AB	8.0-14.0	12.4	0.453	22.3-34.3	65.4	1.99	Ashy loam
Bs	14.0-61.8	38.7	2.43	34.3-76.3	133.0	5.15	Ashy loam
2C	61.8–100	31.6	2.28	76.25–100	23.5	1.50	Gravelly sand
Total		158.7	7.63		405.3	14.86	
Site 4. Me	edial over loamy	, amorphic over	isotic, frigid Ty	pic Hapludands,	slope 0-5% (So	oil Survey Staff,	2004) [0, 28, 4, 64, 4]
0	6.8–0	32.0	1.35	8.0-0	24.1	1.02	Partially decomposed twigs and needles
А	0-21.3	105.4	4.47	0-21.5	114.9	4.61	Silt loam
AB	21.3-33.3	42.7	1.84	21.5-59.0	224.8	8.06	Silt loam
Bw	33.3-100	203.9	8.70	59.0-80.0	64.9	3.11	Silt loam
BC				80.0-100	14.3	1.04	Silt loam
Total		384.0	16.4		443	17.8	

^a Values in the square brackets denote the particle size distribution at 15 cm reading from left to right >25, 25–2 mm, sand, silt and clay.

material >2.5 cm in diameter was weighed, later determined to be a small component of biomass, but was not analyzed further.

2.4. Soil analysis

Organic samples were dried at 70 $^{\circ}$ C until constant weight. A separate study showed the moisture content of organic and mineral soil horizons at 70 $^{\circ}$ C to be the same as at 100 $^{\circ}$ C. The soil O horizon material was ground in a Wiley mill

using a 1 mm screen. Soil mineral horizon samples were screened to 2 mm and ground to a fine powder using a mortar and pestle. Samples were analyzed for total C on an automated CHN analyzer (Perkin-Elmer 2400, Norwalk, CT). A subsample of air-dried soil was oven-dried at 70 °C to correct for moisture content of the air-dried sample.

Per-hectare amounts of C and N were calculated using soil horizon thickness, C and N concentrations, and bulk density. Values for all layers within each horizon were then summed to a 1.0 m depth (Table 2).

Table 3 Increase in above ground biomass (Mg C ha^{-1} year⁻¹) in trees vs. time and treatment^a

Years since fertilization	Site 1: glacial outwash			Site 2: glacial outwash		Site 3: volcanic-source			Site 4: volcanic-source			
	Control	N- fertilized	Change from N	Control	N- fertilized	Change from N	Control	N- fertilized	Change from N	Control	N- fertilized	Change from N
0	9.9	9.8	0.0	24.8	26.0	0.0	18.7	20.2	0.0	5.4	4.7	0.0
2	20.6	23.2	2.7	31.6	37.5	4.7	32.4	37.5	3.5	15.2	14.8	0.4
4	32.7	38.3	5.7	39.8	50.1	9.1	47.6	55.8	6.7	30.5	30.4	0.6
6	45.7	52.7	7.0	49.1	62.7	12.4	64.0	71.5	6.0	46.1	46.9	1.5
8	59.3	66.9	7.7	58.6	75.1	15.4	82.9	91.1	6.7	68.0	69.1	1.9
10	-	-	-	68.5	92.0	22.3	101.6	111.0	7.9	90.8	94.5	4.5
12	72.4	104.7	32.4	78.6	100.2	20.4	119.7	127.9	6.7	110.8	115.1	5.1
14	82.7	122.3	39.7	85.0	112.4	26.2	132.9	140.9	6.4	127.0	133.6	7.3
16	86.1	135.9	49.9	93.1	125.7	31.3	147.3	155.2	6.4	142.8	151.7	9.7
20	-	-	-	112.7	154.8	40.9	173.1	177.5	2.9	167.8	176.8	9.7

 $\label{eq:action} {}^a\ Calculated\ as\ (N-fertilized_{year}-control_{year})-(N-fertilized_{start}-control_{start}).$

2.5. Installation of lysimeters

For the collection of soil solutions, four lysimeters were installed by excavating into the face of the pit dug at each plot. For each pit, one zero-tension lysimeter (Krejsl et al., 1994) was placed immediately below the soil O horizon. Three tube tension lysimeters, 5.13 cm diameter with 2.5 μ m maximum pore size (Soilmoisture, 1994) were placed in holes augered at a 35–45° angle to depths of 15, 50 and 100 cm in mineral soil (Titus and Mahendrappa, 1996). Lysimeters were staggered so a zone of clear soil to the surface was located above each lysimeter.

To establish good soil pore contact with the porous ceramic cups and to avoid clogging, a <2 mm fraction of soil from the same horizon the lysimeter was placed in was obtained by field sieving at each site, and this finer material was placed and tamped around each porous cup. Bentonite was placed around the tube in a zone above to lysimeter cup to prevent surface water from running down the tubes and maximize collection from the target horizon (Krejsl et al., 1994). The pits were then backfilled with material collected and set aside to replicate each horizon as closely as possible. Each lysimeter had undisturbed soil material above it from the lysimeter cup to the soil surface.

2.6. Dissolved organic carbon (DOC) determination

Prior to collection, lysimeters were charged to 6 kPa and flushed two times. DOC samples were

collected at 4–6-week intervals. Collections were transported from field to lab in a cooler containing both ice and liquid water (0 °C) and samples were frozen upon arrival at the lab (Kaplan, 1992, 1994). For organic carbon determination, approximately 10 mL of solution was analyzed by Pt-catalyzed persulfate oxidation with an OI model 700 automated infrared carbon analyzer (OI Corporation, College Station, TX).

2.7. Hydrologic flux

Hydrologic flux was estimated by comparing measured precipitation with estimates for potential evapotranspiration as determined by the Thornthwaite method (Dunne and Leopold, 1978). All precipitation and temperature data required were taken from weather data from stations near the study sites (National Climatic Data Center, 2003; Washington Annual Precipitation, 1998). For Site 1 the Landsburg Station was used, for Site 2 the Chimacum Station and for Sites 3 and 4 the Mud Mountain Dam Station. For months in which precipitation values were higher than potential evapotranspiration, the net soil-water flux favored leaching beyond the rooting zone. When potential evapotranspiration exceed precipitation, no leaching was assumed to have occurred.

A majority of rainfall occurred during the period October–March when temperature and evapotranspirative demands are relatively low. Thus, once the soil profile became saturated, it remained at or above field capacity throughout the duration of the rainy

Soil depth (cm)	Glacial ou	itwash			Volcanic-source			
	Site 1		Site 2		Site 3		Site 4	
	Control	N-fertilized	Control	N-fertilized	Control	N-fertilized	Control	N-fertilized
"O" horizon	1.01	1.37	0.37	0.47	1.06	0.87	0.77	0.84
15	0.71	0.54	0.36	0.22	0.59	1.14	0.36	0.21
50	0.20	0.17	0.20	0.25	0.10	0.10	0.10	0.11
100	0.15	0.15	0.04	0.06	0.04	0.04	0.03	0.02

Table 4 Dissolved organic carbon (Mg C ha⁻¹ year⁻¹) collected during August 2001–July 2002

season. Due to the lack of movement of a wetting front, it was not necessary to factor net soil-water storage into the monthly water budget as described by Iseman et al. (1999). Given the nature of both the slope and the precipitation, as well as high infiltration rates of these soils, it was also determined that consideration of surface runoff was not a necessary addition to the water budget calculation (Ring, 1995). At no time was standing water, runoff, or evidence of surface runoff observed at the sites, even during the wettest times of the year, or during and after the most intense rainfall events.

The Thornthwaite method has been shown to underestimate potential evapotranspiration at equatorial latitudes (Dunne and Leopold, 1978), which would lead to overestimates of net soil-water leaching fluxes. It is assumed, however, that at temperate latitudes characterized by less intense solar radiation inputs, and specifically in maritime climates with less intraannual variability in temperature and precipitation regimes, the magnitude of the differences would be much lower. To estimate DOC fluxes, the mean DOC concentration for each month was multiplied by the water volume flux estimated by the Thorhthwaite method. Each monthly estimate of DOC flux was summed to give a yearly estimate of total DOC flux through each lysimeter-collection depth (Table 4).

2.8. Statistical analyses

For comparisons of C in the trees, a randomized complete block design with n = 1 for each block was used (Hurlbert, 1984). To test for differences between soil contents in control versus fertilized plots, a paired Student's *t*-test was used (Steel et al., 1997; Systat, 1990). In each of these cases, n = 4 as there were four sites, each with an N-fertilized and control plot. A final

Table 5 Per-hectare C contents (Mg C ha⁻¹) of forest ecosystems

	Treatment	Difference ^a	
	Control	N-fertilized	
Site 1 ^b	179	208	30
Site 2 ^b	228	270	42
Site 3 ^b	332	583	244
Site 4 ^b	552	620	67
Alderwood ^c	395	482	87
Everett ^c	339	385	46
Teneriffe ^c	320	377	57
Mean	335	418	83 ^d

^a Difference = N-fertilized - control.

^b Data from this study.

^c Data from Canary et al. (2001).

^d Difference significant at 0.014, paired *t*-test.

analysis where total ecosystem C estimates from this study was pooled with another study (Canary et al., 2001; n = 7) was analyzed with a paired Student's *t*-test. To test for differences between independent means (glacial outwash compared with volcanic-origin), an independent samples Student's *t*-test was used (Systat, 1990). In this case, n = 4 as there were four total plots located in the glacial outwash soil type and four in the volcanic-origin soil that was compared (Table 5).

3. Results and discussion

3.1. Aboveground tree carbon

A dynamic analysis of C increase in trees was developed using previous stem measurements (Table 3) and the biomass estimation equations of Gholz et al. (1979). As is typical of studies of natural stands, initial stand stocking was not exactly identical. The average difference was 0.5 Mg C ha^{-1} , or about 3.2% of the average biomass for the control plots.

Following fertilization, the periodic increment increased in all four stands due to the N treatment, resulting in 49.9, 31.3, 6.4 and 9.7 Mg ha⁻¹ additional C in the four sites, respectively, for an average of 24.3 Mg ha⁻¹ additional C from the 16-year growth period common to all four sites. Differences continued to increase during each growth period except for Site 3. Differences between fertilized and unfertilized mean C pools was statistically significant (p = 0.039).

The aboveground living tree component in the two fertilized plots of glacial outwash soils had a mean of 40.6 Mg ha^{-1} more C than their respective controls. In contrast, trees in fertilized plots of volcanic-origin soils showed a smaller response in aboveground C, differing by a mean of 8.0 Mg C ha^{-1} more at 16 years. In this case, fertilization of plots with lower site indices resulted in more C sequestered in standing trees. Though C sequestration in particular has not been studied a great deal in relation to site, it is often observed that stands with lower site indices respond more to N-fertilization (Ballard, 1984; Miller et al., 1989; Hopmans and Chappell, 1994).

3.2. Soil N and C

Total soil N was 32% higher in fertilized plots (average of 10.6 Mg N ha⁻¹) compared to controls (average of 8.0 Mg ha^{-1} ; differences not significant). Higher N content in the fertilized plots indicated that some impacts on site N from the urea applications were present 5-13 years after fertilization ceased (Prietzel et al., 2004). These average differences in soil N of 2.59 Mg N ha^{-1} are larger than the actual applications of N made previously (0.67- $0.90 \text{ Mg N} \text{ ha}^{-1}$ total), but the limitations of the study design do not allow a clear determination of the fate of applied N. The differences in Site 1 (0.85 Mg N ha^{-1}) and Site 2 (0.88 Mg N ha⁻¹) are very close to the original N applications made at those sites. The differences measured for Site 3 (7.2 Mg N ha^{-1}) and Site 4 $(1.4 \text{ Mg N ha}^{-1})$ are much larger than that N originally applied. These differences are relatively small compared to the site total N, and it is uncommon to be able to quantitatively account for N from forest fertilization after a long time period (Prietzel et al., 2004).

The finer-textured volcanic-origin soils (348 Mg C ha^{-1}) had 299% more C than glacial outwash soils (87.2 Mg C ha⁻¹; p = 0.013), indicating that the soil origin had impacts on soil C independent of the application of N fertilizer. Differences in soil C from different mineralogy are commonly observed. Overall, total soil C to 1.0 m depth was 48% higher in the fertilized plots (average of 260 Mg C ha⁻¹) compared with controls (average of 175 Mg ha^{-1} ; differences not statistically significant). These results correspond to the observations of others that have seen increases in soil C from fertilization in quaking aspen (Populus tremuloides Michx.) stands in Alaska (Van Cleve and Moore, 1978), Swedish pine forest (Nohrstedt et al., 1989), and Douglas-fir forests of the Pacific Northwest (Canary et al., 2001). Baker et al. (1986) compared the growth of Pinus radiata D. Don on sand dunes in New Zealand when a mixed fertilizer (including N, P, K, S, Ca and Mg) was added, and found that the fertilized area had higher soil C. Others have found no major increase in soil C due to the presence of N-fixing species (Paschke et al., 1989) or after N-fertilization (Harding and Jokela, 1995).

3.3. Dissolved organic carbon (DOC)

The impacts of urea addition on short-term (immediate to a few years) soil-solution chemistry is better researched than longer-term effects of more than a decade (Crane, 1972). Unfortunately, this retrospective study did not include the entire period following fertilization, but the focus was on effects of a longer-term (>10 years) following fertilization. Soil-solution DOC was collected and analyzed from January 2001 to July 2002. Though the sampling period was not sufficient to determine annual cycles of DOC concentrations, DOC concentrations did appear to follow seasonal patterns related to the amount of water flux through soil (Fig. 1). However, the late winter of 2001 was unusually dry, and that may have affected results of this study. This observation of DOC positively related to hydrologic flux has been observed in other studies (Neff and Asner, 2001; Jardine et al., 1989). As expected, DOC concentrations also rapidly decreased with soil depth (Jardine et al., 1989; Kaiser et al., 1996; Lilien et al., 2004), ranging from an average of about 70 mg C L^{-1} underneath the soil "O" horizon to less than 10 mg C L^{-1} at 100 cm depth.



Fig. 1. Dissolved organic carbon concentrations are shown by season and soil depth. Bars are standard errors. Data points are slightly offset to increase ability to view error bars separately.

When the soil-solution DOC concentrations are converted into C flux by multiplying the period of collection by the estimated water flux through the soil profile using the Thornthwaite method, seasonal patterns of water flux can be clearly seen, as well as the impact of the very dry late winter season of 2001. For instance, Fig. 2 shows the calculated monthly precipitation, potential evapotranspiration and water fluxes for the period January 2001–July 2002. The combination of relatively low DOC levels observed during the dry winter and the low flux of water through the soil profile combine to give low estimated fluxes both through the winter of 2001 until the Fall rains start in 2002. Much higher fluxes of DOC are estimated starting about October of 2002, and they extend into the Spring and early summer of 2002 (Fig. 3).

There are relatively small differences noted due to the N-fertilization treatment, which generally results in DOC levels higher than the unfertilized control sites, but the results are highly variable. A 1-year sampling period was summed to include the relatively dry summer of 2001, the wetter winter of 2001–2002, and until the dry season started during summer 2002 (Table 4). In all cases the highest DOC average fluxes are found in the N-fertilized sites, with DOC levels showing almost no difference at the 100 cm depth. No mean differences in DOC due to N-fertilization are



Fig. 2. Site 4 (Mud Mountain) summary graph of Thornwaite equation (Dunne and Leopold, 1978) output used to determine net water and carbon flux for each plot. Total DOC (Mg L^{-1}) is plotted for the control to show the increase in absolute DOC concentration in winter 2000–2001 compared to summer 2001 and winter 2001–2002.



Fig. 3. Total DOC flux as determined by Thornwaite equation for four study sites with control compared with treatment at four depths.



Fig. 3. (Continued).

statistically significant. The data is too variable and limited in duration to explain differences in soil C contents, but there is some indication of increased DOC leaching into subsoil horizons due to the N-fertilization treatments.

3.4. Total C sequestration

The scope of this study is limited due to the small sample size and variation associated with installation location. These limitations were imposed on us by the original study design of the RFNRP, starting in 1969. Such limitations are common for retrospective studies of field installations not originally designed to answer the questions now being asked, but the results of this study would take over 30 years and significant additional funding to replicate with a better statistical design.

Fortunately, there has been one additional similar study of C sequestration in RFNRP sites that duplicated part of the work in this study on C sequestration on three different sites (Canary et al., 2001). That study did not find any statistically significant differences in soil or total C sequestration due to high variability and low sample size (n = 3) either. In order to increase sample size, the Canary et al. (2001) data for total C content was paired with this study and analyzed for total C.

When the results of the Canary et al. (2001) study are incorporated into the results of this study, an average increase of 82.8 Mg C ha⁻¹ from N-fertilization for the seven sites is calculated, somewhat lower than the 110 Mg C ha⁻¹ of the four sites in this study. When a paired Student's t-test is applied, the difference is statistically significant (p = 0.014). If the average results from these seven sites is averaged over the approximately 10 million hectares of intensively managed Douglas-fir forest in this region, N-fertilization at the levels of this study would result in an additional 828 million Mg C for the region. Certainly not all of those stands are of the same age or type, so this assessment should not be widely applied. Assessing the absolute impact of such fertilization over longer-time scales would require additional study, but it is important to note that currently N-fertilization is undertaken as a profitable enterprise by forest products companies in the region, not as an altruistic effort for C sequestration. This study suggests that N-fertilization of commercial forests in western Washington should be encouraged from a C sequestration standpoint, as it could increase C stored in these forest ecosystems substantially, but the soil type will have an impact on the absolute results, and additional study is required to determine which forests and soils types would benefit most from N-fertilization.

4. Conclusions

- 1. N-fertilization of seven Douglas-fir forests increased C storage by an average of 82.8 Mg C ha⁻¹.
- 2. A large portion of the total and soil C was located below the soil surface horizons.
- 3. The biggest relative change in C due to N-fertilization was in the forest biomass.
- 4. Results were variable, but there was evidence that N-fertilization increased DOC flux.

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