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Soil Microclimate and Chemistry of Spruce–Fir Tree Islands in Northern Utah

Helga Van Miegroet,* Molly T. Hysell, and Amber Denton Johnson

ABSTRACT

The objective was to investigate differences in soil properties in high-elevation tree islands composed of subalpine fir [*Abies lasiocarpa* (Hook.) Nutt.] and Engelmann spruce [*Picea engelmannii* Parry ex Engelm.] relative to semiarid meadows in Northern Utah. We compared snow depths, surface soil temperature and moisture, and soil chemical properties (0–30 cm) between tree islands and the surrounding meadow. Snow accumulated evenly around the tree islands. Snow depth differences developed during snowmelt when shaded areas to the north of the islands retained snow longer. Less snow accumulated inside and at the edge of the tree islands. In summer, canopy shading inside the islands slowed soil moisture loss and decreased the magnitude and fluctuation of soil temperatures relative to the exposed meadow. Tree islands affected O horizon mass and chemistry: 6 to 10 kg m⁻² of O material, with higher macronutrient concentrations and lower C/N ratio, had accumulated under tree canopies; 3 kg m⁻² in the island interior; and <1 kg m⁻² in the meadow. Surface soils inside the tree islands had significantly higher C and N soil concentrations and higher C/N ratio. The pH of meadow soils was constant with depth (6.22–5.95). Below the trees, the pH in the upper soil was 0.1 to 0.3 units higher than in the meadow and decreased 0.8 to 0.9 pH units with depth. The presence of tree islands significantly modified the soil microclimate and nutrient distribution relative to the surrounding meadows.

PLANT GROWTH and production in arid and semiarid zones of the western United States is primarily limited by water availability and the ability of plants to optimally utilize this limited resource. Nutrient availability and nutrient cycling processes in such environments are also strongly linked to soil moisture conditions. Desert shrubs develop “islands of fertility”, that is, zones of increased nutrient availability and improved soil moisture conditions below the plant and immediately surrounding each individual (Charley and West, 1975; Barth and Klemmedson, 1978; Garner and Steinberger, 1989; Hysell and Grier, 1996). In such ecosystems, improvements in soil fertility can result directly from the presence of the shrub and its influence on nutrient cycling and redistribution of nutrients (Charley and West, 1975; Barth and Klemmedson, 1978; Garner and Steinberger, 1989; Rostagno et al., 1991; Hysell and Grier, 1996) or water within the soil profile (Richards and Caldwell, 1987; Caldwell et al., 1991). Indirect plant effects occur through shading, causing a decline in evaporative water loss, or by creating a favorable environment for microbes and other organisms due to greater litter accumulation, which in turn stimulates decomposition and ultimately results in greater nutrient availability (West, 1991).

In the subalpine zone of the Intermountain West, dispersed tree clumps and islands are frequently observed at the boundary between spruce–fir forests and subalpine meadows (e.g., Arno and Hammerly, 1984; Jean, 1990; Long, 1994). The distribution of spruce–fir ecosystems in this region is driven by a low tolerance for high temperature and moisture deficiency (Alexander, 1987). In northern Utah, most precipitation falls during winter. Following snowmelt in May and June, precipitation inputs are limited during summer, and water retained in the soil becomes the main source of plant-available moisture. Thus, the accumulation and melt of snow plays an important role in water availability, in the timing and duration of the growing season (Walker et al., 1993), and in the establishment and growth of spruce and fir (Peet, 1988). Long (1994), for example, noted that the differential snowmelt between northern and southern aspects may slightly lengthen the spring planting season for Engelmann spruce, presumably due to more favorable moisture conditions. Several authors have also shown the importance of seasonal soil moisture in creating pulsed nutrient availability in arid and semiarid systems (Schimel and Parton, 1986; Fisher et al., 1987; Burke, 1989).

This raises the question whether the presence of spruce–fir tree islands, relative to the surrounding montane meadows, induces changes in physical, chemical, and biological soil properties that influence regeneration and growth. Compared with desert ecosystems, considerably less research has been done on the biogeochemistry of tree islands in the semiarid region of the Intermountain west. The main studies of spruce–fir tree islands have been conducted at the alpine tundra ecotone in the Colorado Rockies (Marr, 1977; Benedict, 1984; Holtmeier and Broll, 1992) where tree islands typically take on a *krummholz* (i.e., low shrub) growth form and a triangular shape (Marr, 1977; Shea and Grant, 1986) in response to an environment that is strongly dominated by high-velocity winds. West of the Continental Divide, the wind regime is vastly different, wind stress is attenuated (e.g., Walker et al., 1993), and spruce and fir trees take on a more upright spire shape. Little is known about how trees get initially established in the open, but small-scale variations in edaphic conditions (e.g., soil texture, presence or depth of an organic layer) may play a role by the influence they exert on local soil moisture conditions (Pritchett and Fisher, 1987). The cache of small mammals is thought to be a potential seed source (T.W. Daniel, 1995, personal communication). Once a tree is established, its shelter may provide a favorable environment for seedlings of other species to become established (Arno and Hammerly, 1984). Both spruce and fir also have the ability to

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Abbreviations: ANOVA, analysis of variance.

Table 1. Summary of selected characteristics of the five tree islands used in this study.

Tree island	Tree island dimensions				Tree characteristics				
	Long axis		Short axis		Estim. total area†	Estim. area treeless center§	Trees density¶	Dominant mean height	Dominant height range
	Orientation	Length	Orientation	Length					
		m		m	m ²	treeless center§	trees ha ⁻¹	m	
BH	30° (NNE-SSW)	21.5	310° (NW-SE)	16.1	272	15	810	19.1	16.5–22.5
BS	65° (NE-SW)	23.1	310° (NW-SE)	17	308	13	1040	23.2	18–26.4
BY	350° (NNW-SSE)	28.5	70° (E-W)	18.5	414	22	820	20.3	17.4–22.5
BN	20° (N-S)	38.1	290° (W-E)	27.5	823	78	1080	22.3	18–29.7
DA	320° (NW-SE)	40.5	90° (E-W)	33.4	630‡	155	730	23	15.3–27.6
	20° (N-S)	42.1		(@N side)					

† Calculated area based on assumed shape of the island: ellipse for BH, BS, BY and BN; triangle for DA.

‡ Probably underestimated.

§ Calculated area based on ellipse shape.

¶ For trees with diameter at breast height >10 cm.

reproduce vegetatively (Marr, 1977), and an alternative pathway for tree island expansion is through layering, with a circle of clonal offspring surrounding a parent tree (Shea and Grant, 1986; Jean, 1990). As the tree island ages and the original parent tree in the center dies, a “timber atoll” develops (Griggs, 1938).

We hypothesized that tree islands in northern Utah behave more like desert ecosystems in the creation of islands of fertility in response to the site water limitations and less like the high-elevation spruce–fir tree islands in the Colorado Rockies, where wind is the major environmental stressor. The objective of this study was to compare soil microclimate, chemical properties of the mineral soil, and O horizon accumulation between tree islands and their surrounding meadows in a semi-arid environment of northern Utah.

MATERIALS AND METHODS

Study Site

The study was conducted at Utah State University’s T.W. Daniel Experimental Forest in the Wasatch Mountains of Northern Utah, at an elevation of 2600 m, 30 km NE of Logan. The moisture regime is semiarid with an average annual precipitation of 950 mm, 80% of which accumulates as snow. Snowmelt typically occurs between mid May and mid June. Monthly rainfall is low between May and October, with lowest precipitation (<2 cm) typically occurring in July. Average low temperature is around –10°C in January; highest mean monthly temperature (14.5°C) occurs in July (Schimpf et al., 1980; Skujins and Klubek, 1982).

The vegetation in the study area consists predominantly of spruce–fir forests <275 yr old. The periphery of the montane forb meadows consists of 20 to 40 m bands of quaking aspen [*Populus tremuloides* Michx], followed by a subalpine fir-dominated forest, into a climax forest of Engelmann spruce. Young spruce and fir, if present in the meadows, typically occur on the north margins of the conifer forests and in the tree islands. Tree islands of mature spruce and fir occur only in a small part of the meadow area, and tend to be more concentrated near the spruce–fir forest ecotone. Summer grazing of the area by cattle (*Bos taurus*) and sheep (*Ovis aries*) has occurred since the late 1800s (Schimpf et al., 1980) but was greatly reduced coincident with fire suppression since 1910 (Wadleigh and Jenkins, 1996). Following an increase in fire frequency during the 1856 to 1909 settlement period, fire frequencies have significantly declined during the last century, and there is no evidence of fire in the area since 1910. This has favored

the establishment of spruce and fir (Wadleigh and Jenkins, 1996).

Soils are classified as Mollisols, with little profile development since the last glaciation, and contain large amounts of coarse (>2 mm) material (Skujins and Klubek, 1982). They are derived from the Knight formation of the Wasatch group, a Tertiary conglomerate of quartzite, sandstone, and shale (Schimpf et al., 1980).

Study Approach

In the course of the study, a total of five tree islands were selected in two nearby meadows with <10% slope: DA in Doc’s Meadow (northeast aspect) and BS and BY in Big Meadow (east to northeast aspect) at the onset of the study; BH and BN in Big Meadow added 1 yr later, when a litter decomposition study was initiated. Selection was primarily based on access from the road and absence of distinct anthropogenic disturbances. Based on a cursory visual inspection of the research area, the tree islands were representative in terms of size, height, structure, and species composition. The Big Meadow islands were elongated in the north-south direction, with the maximum length ranging from 21 to 38 m and maximum widths (east-west axis) ranging from 16 to 27 m. The DA island, in the smaller adjacent Doc’s Meadow, had a triangular shape (with a wide base on the north side) and a semi-open structure (Table 1). All islands consisted of a treeless center, with evidence of an initial parent tree, surrounded by a concentric band of tree clusters or single trees (Fig. 1). Many fir showed regeneration through layering. All islands had variable mixtures of subalpine fir and Engelmann spruce and contained no fewer than 22 trees with a diameter at breast height >10 cm. Tree density on a per-hectare basis ranged from 730 to 1040 tree ha⁻¹. The average height of the dominant trees was very similar among the tree islands (between 19 and 23 m). Because of disturbances due to soil sampling and expansion of study objectives, not all measurements were made at all tree islands. However, each measurement type was performed in at least three tree islands.

To address whether tree islands influenced physical and chemical soil properties we compared soil climate including snow accumulation, soil moisture, and soil temperature; selected soil chemical properties such as pH, total and extractable N, organic C, and C/N; and O horizon accumulation and chemistry at various locations inside and outside the tree island. Within each tree island, one fir cluster (i.e., dominant tree with clonal offspring) was selected at the north and south side of the tree island because aspect was expected to have an effect on soil climate and organic matter dynamics (Fig. 1). Most measurements were taken in a systematic pattern

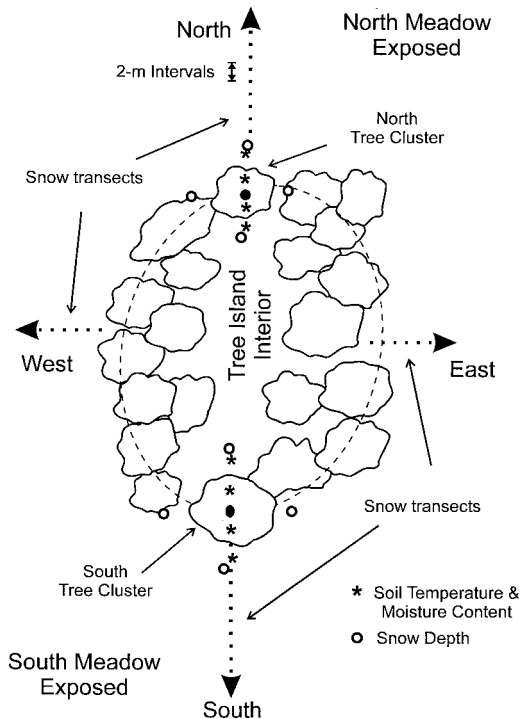


Fig. 1. Schematic representation of a tree island, location of north and south cluster (shaded), and soil microclimate measurements.

inside or outside these two clusters per island, but were further stratified during data analysis according to location in or around the tree island (e.g., exposed locations in the meadow at the south or north side of the island, under canopy cover at the south or north side of the island, or within the exposed tree island interior; Fig. 1 and 2).

Measurements

Snow Accumulation

Snow depth was measured around the DA, BY, and BH islands approximately every month and a half from December 1994 through May 1995 to determine whether spruce–fir tree islands influenced snow accumulation and redistribution as observed in the alpine zone of the Rocky Mountains in Colorado (Holtmeier and Broll, 1992). Twenty-meter-long transects extended to the north, south, west, and east from each island edge, and snow depths were recorded at 2-m intervals. In addition, snow depths were measured in the four cardinal directions around each tree cluster at a distance from the canopy edge equal to half the cluster tree canopy radius for each direction (Fig. 1). In the analysis phase these points were classified according to location relative to the tree island into: exposed meadow (south of south cluster; north of north cluster), island interior (north of south cluster; south of north cluster), and a transition zone (east and west of each cluster).

Soil Temperature and Moisture

Soil temperature was measured periodically from December 1994 through September 1995 and from June through October 1996 using soil moisture–temperature cells (SoilTest Model MC-310, ELE International, Pelham, AL) installed at 5-cm depth in the mineral soil at three tree islands (DA, BY, and BH). At the north and south side of each tree cluster, measurement points were located halfway between stem and canopy edge and at the same distance from the edge in the

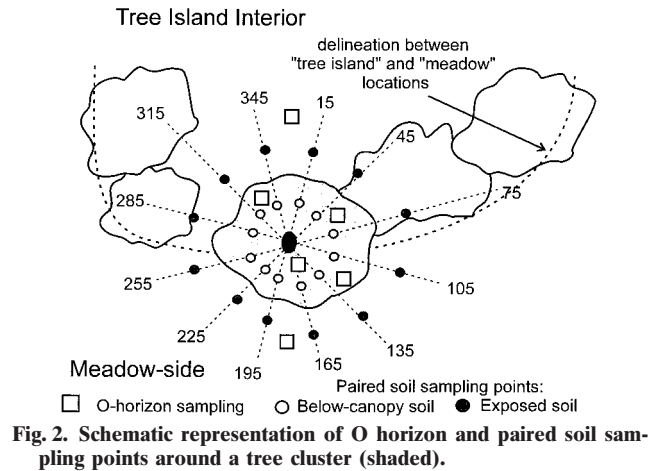


Fig. 2. Schematic representation of O horizon and paired soil sampling points around a tree cluster (shaded).

exposed soil, for a total of eight probes per tree island (2 tree clusters \times 2 directions \times 2 exposure levels). Soil moisture content was determined gravimetrically on 0- to 10-cm depth mineral soil samples taken near the probes at the same time temperatures were recorded (Gardner, 1986). For some locations, soil temperature records were not always complete due to animal damage to the probes. In late spring and early summer 1997 (from June 6 through July 10), periodic measurements of gravimetric soil moisture content and soil temperature (dial thermometer) to a soil depth of 5 cm were also made in the three tree islands in Big Meadow (BY, BH, and BN) in conjunction with a litter decomposition study, using the same measurement scheme (Fig. 1). In June 1997, snow depth was also recorded in the four cardinal directions within 2.5 m from the canopy edge around the north and south cluster in each of three islands (BY, BH, BN) to document the relative progression of snowmelt. In the statistical analysis and graphical representation of results, measurement points were categorized according to location relative to the tree island into: exposed soil to the north of the north tree cluster (north meadow exposed) or to the south of the south tree cluster (south meadow exposed), below-canopy locations within the north (north canopy) or the south tree cluster (south canopy), and exposed soils in the treeless island interior (island interior) (Fig. 1).

O Horizon Accumulation

Dry weight and nutrient content in the O horizon were determined for the island in Doc's Meadow (DA) and the three islands at Big Meadow used in the litter decomposition study (BY, BS, and BN), using a stratified random design. Four locations were identified in and around the south and north cluster: below-canopy sites toward the meadow side or tree island side of the tree cluster and exposed meadow or exposed tree island sites (within one-half the tree radius from the canopy edge) (Fig. 2). Organic material above the mineral soils was removed from a 15 by 15 cm area at two random points beneath the tree canopy and at one random point outside the canopy in both the direction of the meadow and the island interior for a total of 48 sampling points (6 points \times 2 tree clusters \times 4 islands) (Fig. 2). Samples were dried at 75°C, weighed, and ground with a Wiley mill (0.85-mm screen). They were then digested using a nitric acid–hydrogen peroxide method and analyzed for the major nutrients by inductively coupled plasma atomic emission spectrometry at the Utah State University Soil and Water Testing Laboratory (Jones et al., 1991). Samples were also analyzed for total N and C using a Leco C and N analyzer (CHN1000, Leco Corp., St. Joseph,

Table 2. Average snow depth between 4 and 20 m from tree island in the different directions.

Direction	Snow depth			
	December 1994	February 1995	April 1995	May 1995†
	cm			
North	105 ± 3‡	161 ± 9	190 ± 4	184
East	101 ± 3	159 ± 9	177 ± 4	155
West	97 ± 3	159 ± 9	176 ± 4	159
South	100 ± 3	160 ± 9	175 ± 4	153
<i>P</i> for direction effect	0.34	0.92	0.09	na§

† Snowdepth was measured in BY island only; no statistical analysis performed.

‡ Mean ± model-estimated standard error (mixed model).

§ na: not applicable.

MI.). In the statistical analysis of the data, locations were categorized according to exposure and location relative the tree island into four categories: exposed locations outside the tree islands (meadow exposed), exposed locations in the island interior (interior exposed), and locations below tree canopies oriented toward the meadow (meadow below-canopy) or the tree island interior (interior below-canopy) (Fig. 2).

Soil Chemical Properties

A systematic design in and around the north and south tree cluster of the DA, BY, and BH tree islands was used for the soil sampling in summer 1995 (BY and BH) and summer 1996 (DA). Twelve transects from the tree cluster center were set out at 30° increments between 0 and 360°. On each transect, paired soil cores were taken under the canopy midway between stem and canopy edge and in the exposed soil at a distance from the canopy edge equal to one-half the tree canopy radius, for a total of 48 sampling locations per island (2 tree clusters × 12 directions × 2 exposure levels) (Fig. 2). Soil cores were divided into 0- to 5-cm, 5- to 10-cm, 10- to 20-cm, and 20- to 30-cm depth sections. Fresh soils were extracted in the field with 2 *M* KCl, using methods described in Van Miegroet (1995). Bottles with soil-KCl mixtures and soils were stored in coolers, refrigerated upon arrival in the laboratory, and were processed as soon as possible thereafter. Within 24 h, all soil-KCl mixtures and blanks (KCl without soil) were shaken for ≈1 hr, then allowed to settle for 1 hr, after which the supernatant was filtered and the filtrate frozen until analysis for NH₄-N and NO₃-N on a Lachat autoanalyzer (Quik-CHEM, Zellweger Analytics, Milwaukee, WI). Soil subsamples were removed for gravimetric soil moisture determination (Gardner, 1986). Soils were then air-dried and soil pH determined on 1:1 soil-water slurry. Organic C was determined by the Walkley-Black procedure (Nelson and Sommers, 1982). Total N was determined on a subset of six out of 12 sample locations for each cluster (four depths; exposed or below-canopy soils) using a Leco C and N analyzer. Sampling locations were categorized as for O horizons into four categories (meadow exposed, meadow below-canopy, interior below-canopy, and interior exposed) (Fig. 2).

Statistical Analysis

All data were analyzed using an analysis of variance (ANOVA) of a two-way factorial in a blocked split design with tree islands as blocks using PROC MIXED in SAS Release 7.0 (SAS Institute, 1998). For the snow accumulation around the tree islands, the transects corresponding with the four directions were whole-plot units nested within each island and distances along the transect were subplots nested within each transect. Due to lack of random assignment of distances to transect positions, the distance × island interaction term was not pooled with residual variance. In the analysis of snow

accumulation patterns around tree clusters, tree clusters (north or south) were whole plots nested within the tree islands, and exposures (i.e., locations relative to the tree cluster: meadow exposed, transition, island interior) were subplots nested within each tree cluster. Although random assignment of exposure was not possible, the interaction between exposure and island factors was pooled with residual variance due to computational estimation problems. Snow accumulation data were analyzed separately by date.

For both soil temperature and moisture content, locations (north meadow exposed, north below canopy, island interior, south below canopy, and south meadow exposed) were whole plots nested within the tree islands, and subplots corresponded with repeated measures through time. Although date was not randomly assigned, the random effects factor representing the interaction between date and island was pooled with residual variance, as the former appeared negligible. Moisture content data were log-transformed prior to analysis to better meet the assumptions of the ANOVA. Data for 1995, 1996, and 1997 were analyzed separately. Temperatures from November 1994 to May 1995 (below-snowpack) were separated from the 1995 spring-summer data and analyzed by visual inspection only, as zero values for means and variances were incompatible with statistical testing. The 1997 analysis did not include temperatures from 9 June due to missing data.

For O horizon accumulation and nutrient concentration and for the chemistry of mineral soils, tree clusters (north or south) were whole plots nested within the tree islands, and relative locations (meadow exposed, meadow below-canopy, interior below-canopy, and interior exposed) were subplots nested within each tree cluster. As the error term for the interaction between location and island factors appeared negligible, it was pooled with residual variance. Where necessary, raw data were transformed prior to analysis, using square-root (O horizon mass, Ca concentration of O horizon), log (K concentration of O horizon, KCl-extractable NH₄-N and NO₃-N in soils, organic C in soils), arcsine-square-root (N concentration of O horizon), or reciprocal transformations (total N in mineral soils). For those data sets that had one or more values for extractable NH₄-N or NO₃-N equal to zero (i.e., below detection limits), a small increment equal to one-half the smallest nonzero observation was added to each value before transformation and taken into account during the back calculation of means and standard error. Soil chemical data were analyzed separately by depth. Following ANOVAs, post hoc comparisons between means were made using Tukey multiple comparisons.

RESULTS

Snow Accumulation

In the winter of 1994-1995, snow accumulated between December and April, while snow depth declined

Table 3. Average snow depth at the different locations around the tree clusters.

Location	Snow depth			
	December 1994	February 1995	April 1995	May 1995
Exposed meadow	97 ± 5a†‡	163 ± 12a	179 ± 13a	173 ± 17a
Transition zone	87 ± 5a	136 ± 12a	149 ± 13ab	122 ± 17ab
Island interior	63 ± 5b	95 ± 12b	120 ± 13b	72 ± 17b
<i>P</i> for location effect	0.004	0.002	0.020	0.035

† Mean ± model-estimated standard error (mixed model).

‡ Different letters following means indicate significant differences among locations for a given sampling data (Tukey-Kramer test, $P = 0.05$).

due to snowmelt between April and May (Table 2). Distance from the tree island edge had no strong effect on snowdepth, except for somewhat lower snow depths at and within a few meters from the island edge (10 to 40 cm and 5 to 15 cm less snow, respectively, compared with the more distant transect points, depending on date and island). Table 2 represents average snow accumulation between 4 and 20 m from the tree island edge in the four main directions. There were no significant differences among directions during winter, indicating that the presence of tree islands within the open meadow did not cause differential snow accumulation or snow redistribution around the tree islands. With the onset of snowmelt, there was a significant, albeit not strong ($P = 0.09$), direction effect in April, with a slightly thicker snowpack to the north of the tree island. A similar pattern was also observed in May 1995 for the BY island. In some locations, we observed local snow compaction from snowmobiles at the outer end of the transects (18 m and 20 m), but these occasional disturbances did not significantly influence the outcome of our data analyses nor the conclusions drawn from them.

By contrast, snow accumulation around the individual tree clusters was not uniform and the effect of location was statistically significant and the pattern consistent with time (Table 3). The island interior had the lowest snow accumulation. The snowpack in the exposed meadow was often more than 50% thicker than in the island interior, while the transition zones had intermediate snow depths that were not always statistically different from the two other locations (Table 3). We visually observed that differences with location were less pronounced in the DA tree island (February snow depths were 131, 110, and 109 cm in meadow, transition zone, and island interior, respectively), which may be due to its more open structure (Table 1). Between April and May, snow depth decreased by $\approx 40\%$ in the island interiors, compared with $<10\%$ in the exterior locations, and around 20% in the transition zone. During this period, differences in snow retention between south and north clusters emerged, and the magnitude of the differences among locations tended to be higher in the north clusters. This was also supported by the June 1997 data, which showed that the south clusters had small and thin patches of snow (14–50 cm depth at 2.5 m from the canopy edge) only at the west side on 9 June. By contrast, the north clusters were surrounded by crescent-shaped snowpatches with snow depths up to 60 cm in the north and west directions. In 1997, all tree islands were snowfree by the third week of June.

Soil Temperature and Moisture Content

As long as soils were covered with a snowpack, soil temperatures in the top 5 cm remained fairly stable around 0°C, irrespective of location or tree cover (November 1994–May 1995; Fig. 3a). Following snowmelt, all soils warmed up ($P < 0.0001$ for date effect in all years), but the seasonal pattern was not parallel among locations, as indicated by a statistically significant interaction between location and date in two of the three measurement years ($P = 0.013$ in 1995; $P = 0.257$ in 1996; $P = 0.034$ in 1997). The presence of tree islands generally had an attenuating effect on absolute soil temperatures and their seasonal fluctuations (Fig. 3a–3c). Summer temperatures in below-canopy soils ranged for the most part between 5 and 15°C, with peak temperatures generally around August, and relatively small differences among probe locations. Exposed meadow soils, especially those to the south of the tree islands, tended to be significantly warmer than island-interior and below-canopy locations throughout the summer and were also characterized by greater temporal variations. Summer soil temperatures in the exposed meadow soils ranged for the most part between 5 and 30°C, although in summer 1995, soil temperatures near 40°C were registered in the end of July in exposed meadow soils to the south of the tree islands. Aspect influenced soil temperatures in that the more shaded, northern meadow sites had significantly lower soil temperatures than those with southern exposure, which were significantly different from within-island locations only in 1997. There were no statistically significant differences between soil temperatures under the tree canopies and those in the relatively more exposed island interior.

With the disappearance of the snowpack in June, all surface soils progressively dried in summer ($P < 0.0001$ for date effect in ANOVA; Tukey-Kramer test on 1997 data) and most soils lost $\approx 50\%$ of their initial soil water content within 3 wk after being exposed (Fig. 4c). As with temperature, the presence of tree islands attenuated this process, and the relative ranking of locations in terms of soil moisture content was inverse of the pattern for soil temperature. Soils below tree canopies and in the island interior retained moisture longer during the late spring and early summer compared with the exposed meadow soils (Fig. 4a–4c). Soil moisture contents declined more rapidly and were consistently lower in the exposed meadow sites, especially to the south of the tree islands. However, by the second half of August, differences in soil moisture content among locations became less pronounced.

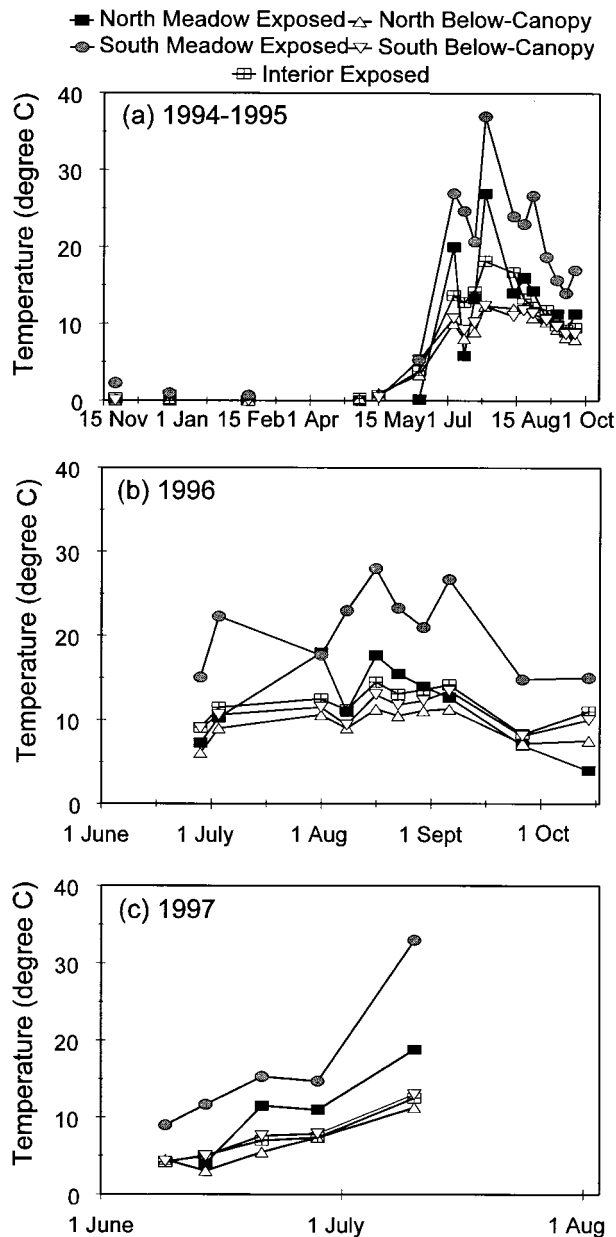


Fig. 3. Soil temperature at the 5-cm depth at various locations inside and outside the tree islands (a) 1995 (Sites DA, BY, and BH), (b) 1996 (Sites DA, BY, and BH), (c) 1997 (Sites BY, BH, and BN).

O Horizon Accumulation

The exposed meadow soils had only a thin O horizon (<1 kg m⁻²), while the largest amount of organic matter was consistently found beneath the canopies of cluster trees (6–10 kg m⁻²) and intermediate amounts in the exposed island interiors (3 kg m⁻²) (Table 4). The organic matter inside and outside the tree islands was also chemically different (Table 4). Macronutrient concentrations (except K) were consistently lower and the C/N ratio significantly higher in the exposed meadow sites than inside the tree islands. Below-canopy samples had the same composition, while the O horizon from the exposed tree island interior was chemically more similar to below-canopy material than to the samples in the exposed meadow locations (except for Mg) (Table

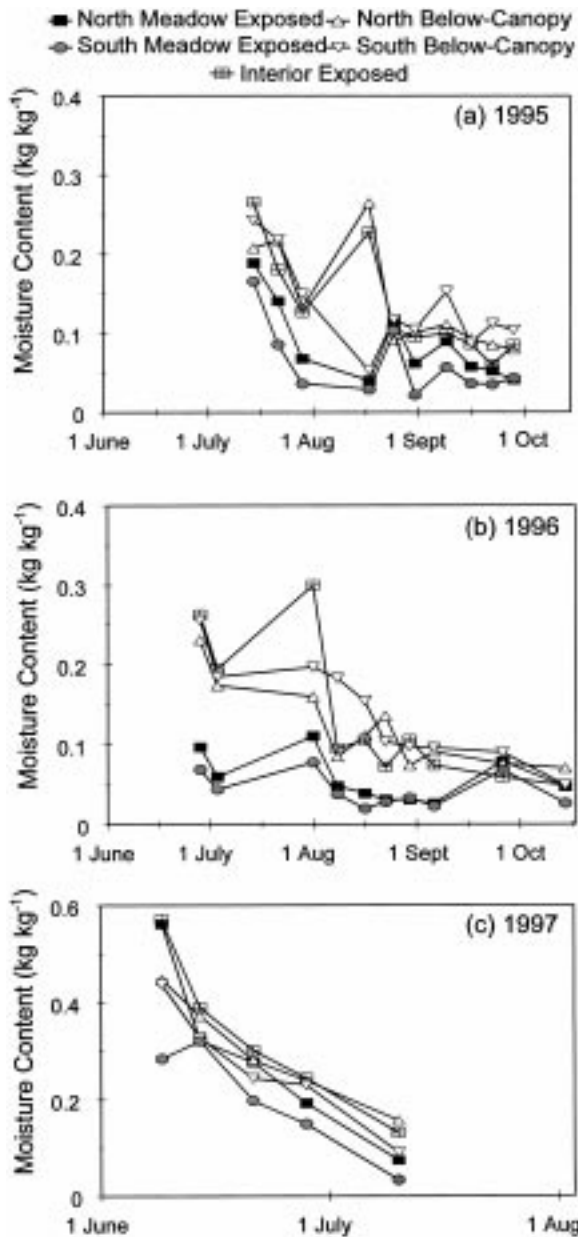


Fig. 4. Average gravimetric soil moisture content (0–10 cm) at various locations inside and outside the tree islands (a) 1995 (Sites DA, BY, and BH), (b) 1996 (Sites DA, BY, and BH), (c) 1997 (Sites BY, BH, and BN).

4). This combination of higher biomass and higher nutrient concentrations in the O horizon within the tree islands resulted in significantly higher nutrient accumulation than in the exposed meadow sites.

Soil Chemistry and Nutrient Distribution

The chemistry of the soils within tree islands was different from the surrounding exposed meadow soils in the upper soil layer (Table 5). Most noticeable differences were the higher organic C concentrations within the tree islands, which were statistically significant in the upper 5 cm of the soil only: ≈40 vs. 26 g kg⁻¹ in the exposed meadow soils (*P* = 0.006). The trend of relative C enrichment within tree islands gradually diminished

Table 4. Dry weight and chemical composition of the O-horizon samples in the meadow and tree island locations.

O-horizon characteristic	Location				<i>P</i> for location effect
	Meadow exposed	Meadow below-canopy	Interior below-canopy	Interior exposed	
Biomass, kg m ⁻²	0.33 ± 0.38c†‡	6.2 ± 1.4ab	9.7 ± 1.8a	2.9 ± 1.0c	<0.0001
N, mg g ⁻¹	6.5 ± 0.6b	10.9 ± 0.8a	11.3 ± 0.8a	10.7 ± 0.8a	<0.0001
C/N	46.3 ± 2.4a	31.9 ± 2.4b	30.7 ± 2.4b	33.0 ± 2.4b	0.0006
P, mg g ⁻¹	0.78 ± 0.06b	0.90 ± 0.06ab	0.95 ± 0.06a	0.96 ± 0.06a	0.012
S, mg g ⁻¹	0.59 ± 0.08c	1.06 ± 0.08ab	1.24 ± 0.08a	0.99 ± 0.08b	<0.0001
Ca, mg g ⁻¹	7.5 ± 0.7c	14.9 ± 1.8ab	17.1 ± 1.9a	11.8 ± 1.6b	<0.0001
Mg, mg g ⁻¹	1.1 ± 0.1c	1.5 ± 0.1ab	1.6 ± 0.1a	1.2 ± 0.1bc	0.0007
K, mg g ⁻¹	2.5 ± 0.3a	1.4 ± 0.2b	1.4 ± 0.2b	1.5 ± 0.2b	0.0005
Na, µg g ⁻¹	35 ± 5b	59 ± 5a	65 ± 5a	48 ± 5ab	0.003

† Mean ± model-estimated standard error (mixed model); due to asymmetry of mean ± standard error in backtransformation of statistical results, the larger of calculated standard errors is reported as a conservative measure of variability.

‡ Different letters following means indicate significant differences among locations for a given O-horizon characteristic (Tukey-Kramer test, *P* = 0.05).

with soil depth and was not statistically significant (Table 5). Total N concentrations were also ≈50% higher in the upper soils within the tree islands than in the exposed meadow (*P* = 0.05). Exposed soils in the island interior had an intermediate N concentration between exposed meadow soils and soils under tree canopies. As with organic C, there were no statistically significant differences below the 5-cm soil depth. Horizontal and vertical patterns in total N and organic C concentration appeared similar, suggesting that N was mostly in organic form. The only statistically significant differences in C/N ratio between meadow and tree island soils were observed in the upper 5 cm: C/N was around 18 in the meadow vs. 21 inside the tree islands (*P* = 0.04). Below the surface layer, C/N ratios and their variability tended to increase and no statistical differences between meadow and island soils could be detected.

The extractable NH₄-N and NO₃-N concentrations were highly variable among sampling points and generally decreased with soil depth. The only observed difference in extractable inorganic N among locations was the higher extractable NH₄-N in the interior below-canopy soil (5–10 cm) than in the exposed meadow soil.

Between 0- and 5-cm soil depth, below-canopy soils had a higher pH (0.3 pH unit) than the exposed meadow soil (Table 5). At greater depth, differences between exposed soils and soils below the tree canopy diminished and were no longer statistically significant. However, between 20- and 30-cm soil depth, the data suggest an opposite trend, with lower soil pHs under the tree canopies (5.6–5.7) than under the exposed meadow and tree island interior soils (≈6). The pH of exposed meadow soils showed relatively small variation with soil depth (0.2 pH unit). Soils below tree canopies exhibited the greatest variability in pH with depth (0.8–0.9 pH unit), reflecting an increase in soil pH relative to the meadow soil close to the soil surface, and suggesting a relative decline in soil pH relative to the meadow soil between the 20- and 30-cm depths. The exposed soil in the island interior, which may at some point in its development have been under the direct influence of tree canopies, showed some depth gradient in soil pH (6.4 vs. 6.0), but the pattern relative to the exposed meadow soil was not as consistent as for the soils currently under tree cover, and pHs were not statistically different from the exposed meadow soils (Table 5).

DISCUSSION

Contrary to the observations for krummholz tree islands in the alpine zones of the Rocky Mountains in Colorado (Holtmeier and Broll, 1992), snow redistribution via wind and the impact of tree islands thereupon, is not an important phenomenon in montane meadows of northern Utah. During most of the winter, snow tends to accumulate evenly around tree islands, and differences in snow depth around tree islands emerge only during spring snowmelt when the more shaded northern sides of the tree islands retain their snowpack longer. Inside and at the edge of the tree islands, differences in snow dynamics could be linked directly to the presence of trees. The outer edge of the tree islands and the treeless island interior generally accumulated less snow than the open meadow locations, probably due to snowfall interception and sublimation losses on the conifer branches and snowmelt from the emission of longwave radiation by the vegetation (e.g., Schmidt and Gluns, 1991; Satterlund and Adams, 1992). The latter also caused the snowpack to melt faster in the island interior during spring thaw. The fact that this pattern was less pronounced in the DA tree island is consistent with its more open structure (Table 1) and with the general observation that the island interior behaved microclimatically more like an exposed meadow site.

The presence of a thick snowpack, rather than having a negative impact on growth by shortening the growing season as is the case in the Rockies (Walker et al., 1993), may actually exert a positive influence on site conditions in this semiarid region (i) by creating favorable soil temperatures during the dormant season that allow organic matter decomposition to proceed, albeit at low rates (Bleak, 1970; Denton Johnson and Van Miegroet, 1997, unpublished data), and (ii) by improving the soil moisture status during the early part of the summer. Snow accumulation and snow depth play an important role in the depth of soil freezing (Pierce et al., 1958). As was also observed by Bleak (1970) in the Manti-LaSal National Forest in Utah, a persistent snowpack protects soils against freezing and tends to maintain soil temperatures around 0°C. Geiger (1966 as cited in Andersen and MacMahon, 1981) suggested that a snowpack 20 to 30 cm thick effectively insulates the soil from low ambient air temperatures, and Anderson and

Table 5. Average organic C concentration, pH (1:1 H₂O), total N concentration, and KCl-extractable NH₄-N and NO₃-N of mineral soils in meadow and tree island locations.

Soil depth cm	Location				P for location effect
	Meadow exposed	Meadow below canopy	Interior below-canopy	Interior exposed	
	Soil organic C, g kg ⁻¹				
0–5	25.6 ± 5.5b†‡	39.6 ± 8.5a	47.4 ± 10.6a	38.9 ± 8.6a	0.006
5–10	17.8 ± 3.1	22.8 ± 3.9	24.2 ± 4.4	22.8 ± 4.1	0.185
10–20	13.6 ± 2.5	14.5 ± 2.5	19.0 ± 3.5	15.6 ± 3.5	0.110
20–30	10.8 ± 3.8	12.9 ± 4.6	13.6 ± 5.0	15.8 ± 5.6	0.140
	Total soil N, g kg ⁻¹				
0–5	1.8 ± 0.3b	2.6 ± 0.7a	2.8 ± 0.9a	2.4 ± 0.7ab	0.055
5–10	1.2 ± 0.2	1.4 ± 0.3	1.4 ± 0.3	1.4 ± 0.3	0.547
10–20	0.9 ± 0.2	0.8 ± 0.1	1.1 ± 0.3	1.0 ± 0.2	0.284
20–30	0.8 ± 0.3	0.7 ± 0.2	1.1 ± 0.7	1.2 ± 0.8	0.208
	KCl-Extractable NH ₄ -N, µg g ⁻¹				
0–5	3.3 ± 1.7	4.2 ± 2.1	8.4 ± 4.6	5.1 ± 2.8	0.168
5–10	1.4 ± 0.6b	1.6 ± 0.7ab	4.1 ± 2.0a	2.6 ± 1.3ab	0.071
10–20	0.8 ± 0.3	1.0 ± 0.4	1.8 ± 0.7	1.1 ± 0.4	0.213
20–30	0.6 ± 0.4	0.6 ± 0.4	0.9 ± 0.8	0.8 ± 0.5	0.921
	KCl-Extractable NO ₃ -N, µg g ⁻¹				
0–5	2.9 ± 4.1	1.1 ± 1.7	3.8 ± 5.7	1.5 ± 2.3	0.232
5–10	0.66 ± 1.35	0.34 ± 0.71	0.99 ± 2.20	0.52 ± 1.18	0.736
10–20	0.21 ± 0.40	0.13 ± 0.25	0.09 ± 0.20	0.20 ± 0.43	0.885
20–30	0.06 ± 0.13	0.13 ± 0.25	0.28 ± 0.59	0.12 ± 0.23	0.398
	Soil pH				
0–5	6.22 ± 0.10b	6.55 ± 0.10a	6.51 ± 0.11a	6.39 ± 0.11ab	0.037
5–10	6.19 ± 0.16	6.25 ± 0.16	6.38 ± 0.17	6.21 ± 0.17	0.336
10–20	6.20 ± 0.18	6.14 ± 0.18	6.21 ± 0.18	6.01 ± 0.18	0.395
20–30	5.95 ± 0.14	5.64 ± 0.14	5.71 ± 0.18	6.01 ± 0.14	0.193

† Mean ± model-estimated standard error (mixed model); due to asymmetry of mean ± standard error in backtransformation of statistical results, the larger of the calculated standard errors is reported as a conservative measure of variability.

‡ Different letters following means indicate significant differences among locations for a given soil sampling depth (Tukey-Kramer test, $P = 0.10$).

MacMahon (1981) observed soil freezing to depths >25 cm at our study site in the 1976–1977 winter when low snowfall resulted in the late development of a snowpack.

In this climatic region, where most precipitation falls as snow, the majority of available water during the growing season is derived from snowmelt. The surface soils, irrespective of location, tend to dry out by midsummer to <10% gravimetric moisture content. However, the rate at which this endpoint is reached differs significantly between meadow and tree island soils, which may in turn cause differences in the time period during which favorable soil moisture conditions persist. Relatively unshaded meadow soils (e.g., exposed meadow soils to the south of the tree islands) dry most rapidly because they lose their protective and water-supplying snow cover earlier in spring and are subject to more direct solar radiation and accelerated evaporative losses early in the season. An indirect tree island effect through shading tends to slow this processes somewhat in the meadow soils close to the northern edge of the tree islands. On the other hand, surface soils within the tree islands retain their moisture longer as a result of tree shading, despite the thinner snowpack and thus inherently lower early-season soil water recharge sources. Both Engelmann spruce and subalpine fir are relatively intolerant to high temperature and low moisture availability. Successful regeneration of these species is strongly tied to the moist soil conditions following snowmelt and protection through shading from direct insolation and elevated air temperatures (Alexander, 1987). Soils inside and to

some extent to the immediate north of tree islands appear to exhibit these necessary characteristics that favor the establishment and growth of both spruce and fir. Thus, once established, tree islands may modify soil microclimate and moisture conditions sufficiently to ensure maintenance and expansion of the tree islands. Greater shading at the north side of tree islands, and the concomitant change in soil microclimate, may be responsible for the elongation of these islands along a south–north axis (Table 1).

The tree island effect is also expressed in terms of amount and quality of organic matter accumulated in the O horizon and upper mineral soil. As is the case for snow, wind is not an important driver of litter redistribution, and the accumulation of organic matter and nutrients in the O horizon is more directly influenced by the density and the type of litter source (trees vs. forbs) immediately above the soil. The macronutrient pool in the organic layer is significantly lower in the meadow surrounding the tree islands, which we assume to be caused by lower annual aboveground litter production and lower nutrient concentrations of that litter. Differences in vegetation C input between meadow and tree island locations is also translated into greater organic C and N contents especially in the upper mineral soil, a trend also observed in other arid shrub-grass community comparisons (Doescher et al., 1984), under arid tree cover (Sharma and Gupta, 1989), under semi-arid pinyon (*Pinus edulis* Engelm.)–juniper [*Juniperus osteosperma* (Torr.) Little] (Klopatek, 1987), and in Cal-

ifornia oak (*Quercus agrifolia* Née) woodlands (Dahlgren et al., 1997). Soil organic C concentrations measured in this study are somewhat higher and N concentrations are in the same range as soil concentrations reported for sagebrush (*Artemisia* spp.) communities in Utah (Charley and West, 1975), some big sagebrush communities in eastern Oregon (Doescher et al., 1984), and for desert shrub communities in Argentina (Rostagno et al., 1991). Carbon concentrations are 50% lower under spruce–fir than under pinyon–juniper canopies in Arizona (Klopatek, 1987) and about one-third lower than those found under blue oak (*Quercus douglasii* Hook. & Arn.) in the Sierra Nevada foothills of California (Dahlgren et al., 1997). The vertical and horizontal gradients in soil C and N are similar to the ones induced by desert shrubs (Charley and West, 1975; Barth and Klemmedson, 1978). We also noted increased pocket gopher (*Thomomys talpoides*) activity inside and in the immediate vicinity of the tree islands. These rodents tend to inhabit meadows with interspersed tree islands rather than the surrounding closed spruce–fir forests, and their burrowing rates are strongly affected by soil microclimate (Andersen and MacMahon, 1981). Soil mixing and the accumulation of organic debris in tunnels and nests by these gophers may also have contributed to a greater vertical enrichment in tree island soils with organic matter compared with the surrounding meadow soils, as well as to the large spatial variability in soil organic matter content in these soils, as has been observed worldwide for a variety of burrowing animals (Graff and Makeschin, 1979; Hole, 1981).

The pH effect of tree islands is somewhat different from findings for desert shrubs, where changes in soil pH tend to be a function of vegetation type: in some cases little or no plant effects on soil acidity were detected (Charley and West, 1975), or shrubs tended to increase [palo verde (*Cercidium floridum* Benth.)], or decrease the soil pH [mesquite [*Prosopis juliflora* (Swatz) DC]] compared with the adjacent bare soils (Barth and Klemmedson, 1978). The latter has been attributed to acidic stemflow, throughfall, and litter leachates, even though no clear evidence to that effect is available (Barth and Klemmedson, 1978). Soils under mature pinyon–junipers were found either to be significantly more acid or not different from those in the exposed interspaces (Klopatek, 1987). The pH depth profile observed in the tree islands (i.e., higher pH near the surface, decline deeper in the soil) relative to the nearby meadow soils (where soil pH remained fairly stable with depth) may be the reflection of root uptake of cations (especially Ca) deeper in the profile followed by cation enrichment near the surface through litter deposition and incorporation and decomposition, as observed under California oak woodlands by Dahlgren et al. (1997). Although we currently do not have the exchangeable cation data to support this hypothesis, this interpretation is consistent with the higher Ca concentration and content of O horizon material within the tree islands. Fresh litter samples collected in nearby spruce–fir islands and at the forest edge showed high Ca concentrations (2.1%; Van Miegroet and Denton

Johnson, 1997, unpublished data), suggesting that the Ca enrichment in the O horizon is a biological rather than physical (e.g., dust input) phenomenon. Furthermore, Stark (1973) showed that surface soils under litter in a dry Jeffrey pine (*Pinus jeffreyi* Grev. & Balf.) forest in western Nevada had significantly higher Ca contents than in the open meadow, and that litter removal significantly reduced Ca (and Mg) content in the upper mineral soil within a period of <2 yr. Our interpretation is also consistent with the results from earlier studies by Alban (1982) who demonstrated the cation pumping capability of white spruce [*Picea glauca* (Moench) Voss] in Minnesota expressed by greater cation sequestration in biomass and elevated cation contents in the forest floor. Also, the fact that pH trends are most pronounced at locations currently under canopy cover (meadow below-canopy and interior below-canopy) and less under sites that were previously or more indirectly under the influence of island trees (interior exposed), further suggests a gradient in processes that is directly related to the presence of these trees and the C fluxes associated with them.

CONCLUSIONS

Many of the physical and chemical impacts of tree islands in high-elevation meadow soils in semiarid regions are intimately linked to the accumulation and distribution of snow and organic matter in and around the tree islands. The dynamics of both may play a significant role in maintaining conditions that favor regeneration and growth of trees in an otherwise austere environment. The presence of a thick and prolonged snowpack during winter at these high-elevation sites may be important to the microbial activity during the dormant season as well as during the subsequent short snowmelt period. In areas where there is little precipitation during the summer months, water availability from snowmelt, and the expected nutrient pulse associated with it, may be critical to growth during the low-precipitation part of the growing season. Through shading, tree islands tend to improve and extend early-summer soil moisture conditions by slowing down snowmelt and evaporative water losses. This greater water availability in early summer, coupled with more even and moderate soil temperatures, and the elimination of extreme highs in summer, would be expected to favorably impact biological processes.

The presence of trees in meadow sites induces greater C sequestration in aboveground biomass and C cycling through needle litterfall, which improves both physical and chemical attributes of local site fertility, especially in the upper parts of the soil profile. First, the presence of such a thick O horizon within the tree islands probably further attenuates soil water losses and improves soil water and temperature conditions, especially in early summer. With the development of a distinct O horizon and organic C enrichment in the upper mineral soil comes a distinct change in nutrient distribution and availability inside the tree islands that further accentuates differences in fertility status compared with the

surrounding meadow soils. These differences in soil organic matter content may also influence water-holding capacity, especially in the upper part of the soil profile. Thus, while the initial establishment of spruce–fir tree islands may result from chance or stochastic events, the subsequent changes in microclimate and biogeochemical characteristics that emerge from their presence provide feedbacks that would favor the persistence of such tree islands.

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DIVISION S-10—WETLAND SOILS

Influence of Phosphorus Loading on Organic Nitrogen Mineralization of Everglades Soils

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ABSTRACT

There have been recent concerns about the anthropogenic phosphorus (P) loading to the naturally oligotrophic Everglades ecosystem. We investigated the effect of P loading on the biogeochemical cycling of nitrogen (N). We investigated the distribution of the potentially mineralizable N (PMN) rate as an indicator of the influence of P loading on selected microbial activities in soil and detritus layers. Soil characteristics measured included bulk density; total C, N, and P; microbial biomass C; and N and extractable NH_4^+ . PMN rates ranged from 10.4 to 325 $\text{mg N kg}^{-1} \text{d}^{-1}$. The highest values of microbial biomass C and N, total P, extractable NH_4^+ , and PMN were observed in the detrital layer, and rates decreased with increasing soil depth. An increase in the size of the microbial pool and heterotrophic activity (organic N mineralization) was found to be related to the P-loading rate and related to the distribution of total P content in the soil and detrital layers. Extractable NH_4^+ was a good indicator of PMN rates and total P was found to be significantly correlated to microbial biomass C and N. The stimulatory effect of P enrichment on microbial activity, overall size of the microbial biomass pool, and the PMN rate has led to an increased availability of inorganic N, which could potentially affect macrophyte growth and water quality of the northern Everglades system.

ORGANIC N MINERALIZATION (ammonification) in wetland soils is an important process regulating water column inorganic N concentrations and providing a steady N supply to aquatic vegetation. Ammonification, or the net release of ammonium N ($\text{NH}_4\text{-N}$) is a continuous decomposition process by which high molecular weight organic N compounds are sequentially hydrolyzed into simpler compounds by extracellular enzyme activity (Sinsabaugh et al., 1991), followed by the breakdown of dissolved amino acid compounds and release of $\text{NH}_4\text{-N}$ (Fuhrman and Bell, 1985; Gardner et al., 1989). The rate limiting step can occur anywhere along the decomposition continuum, but the process is

generally limited by the rate of hydrolysis of the larger organic compounds (Stanford and Smith, 1972).

Ammonification is dependent on a number of factors including the C:N ratio of the soil organic matter (SOM) and detrital tissue (Amador and Jones, 1997), temperature (Reddy, 1982; Addiscott, 1983), O_2 status (Gale and Gilmour, 1988; Humphrey and Pluth, 1996), size and activity of the microbial pool (Perucci, 1990; Wardle, 1992; Amador and Jones, 1993), and limiting nutrients (Munevar and Wollum, 1977; Damman, 1988; Nair, 1996). Net N mineralization has been observed in flooded peat soils with C:N ratios of > 24:1 (Williams and Sparling, 1988), 45:1 (Humphrey and Pluth, 1996), and 80 to 100:1 (Damman, 1988). Therefore, there is little evidence that a specific C:N ratio in peat soil can be applied to predict field anaerobic organic N mineralization rates (Williams, 1984).

The microbial pool sequesters N in organic forms (proteins, amino acids) which are released upon cell death. Inorganic N, released from the organic N pool via ammonification, accumulates in wetland soils as NH_4^+ rather than NO_3^- , because of the anaerobic status of the flooded soil system (Reddy and Patrick, 1984) and diffusion limitations (Reddy et al., 1980). The high soil moisture content of peat soil restricts the supply of O_2 , leading to decreased organic matter decomposition rates (Humphrey and Pluth, 1996; Amador and Jones, 1997).

The availability of inorganic N in peat soils is mediated to a great extent by heterotrophic microbial activity. The soil microbial biomass has been significantly correlated with N mineralization rates in studies of wetland soils (Williams and Sparling, 1988; McLatchey and Reddy, 1998). The size and activity of the microbial pool can be regulated by the availability of nutrients. It is well established that the size of the soil microbial biomass is dependent upon the C content of soils and

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Abbreviations: CFE, chloroform-fumigation extraction; PMN, potentially mineralizable nitrogen; SINM, substrate induced nitrogen mineralization, SFWMD, south Florida water management district; SOC, soil organic carbon; WCA-2A, Water Conservation Area-2A.