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Organic Matter Decomposition following Harvesting and Site Preparation of a Forested Wetland

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ABSTRACT

Organic matter accumulation is an important process that affects ecosystem function in many northern wetlands. The cotton strip assay (CSA) was used to measure the effect of harvesting and two different site preparation treatments, bedding and trenching, on organic matter decomposition in a forested wetland. A Latin square experimental design was used to determine the effect of harvesting, site preparation, and relative position within the wetland on organic matter decomposition at soil depths of 5, 10, and 20 cm. Repeated measures analysis of variance was used to test for treatment effects on organic matter decomposition, soil temperature, and soil oxidation depth. Cellulose decomposition increased at each soil depth as site disturbance increased, with bedding > trenching > whole-tree harvest > reference. The cellulose decomposition response was correlated with changes in soil temperature; the temperature coefficient Q_{10} equaled 6.0, which is greater than previously reported values. Position within the wetland relative to an adjoining river affected the decomposition and soil oxidation depth. Because the rate of decomposition is strongly controlled by temperature, higher rates of organic matter decay are expected to continue on harvested and regenerated sites until canopy closure reduces soil temperature.

ORGANIC MATTER DECOMPOSITION in boreal wetlands is controlled primarily by soil temperature, moisture, fertility, and organic matter quality (Heal et al., 1981; Oades, 1988). Nutrients mineralized from that organic matter comprise the primary nutrient supply for plant uptake in most ecosystems (Damman, 1978; Richardson, 1978; Van Cleve et al., 1983; Van Cleve and Yarie, 1986). In undisturbed wetlands, nutrient mineralization is balanced by microbial immobilization and plant uptake, resulting in little leaching loss (Hemond, 1980; Verry and Timmons, 1982). Disturbance of wetland vegetation and soil increases the rate of organic matter decomposition, usually by altering the soil moisture or temperature regime, or by increasing substrate availability to soil microorganisms (Armentano and Menges, 1986; Trettin et al., 1995). Understanding how varying degrees of disturbance affect organic matter decomposition is fundamental to constructing C balances of wetland ecosystems, modeling decomposition processes (Meentemeyer, 1978; Armentano and Menges, 1986; Ineson et al., 1988; Eijsackers and Zehnder, 1990), and evaluating the potential for C and nutrient leaching. Artificial drainage has been used as a basis for determining the effect of disturbance on organic matter decomposition in forested and nonforested wetlands (Armentano and Menges, 1986). However, more common, less intensive disturbances of forested wetlands, such as timber harvesting and regeneration practices that involve site preparation, may have larger cumulative effects than drainage due to the higher frequency and broader aerial extent of those silvicultural practices.

Silvicultural practices in wetlands can affect organic matter decomposition rate and C pool size by changing soil temperature, moisture, and substrate availability, and by physical displacement of the forest floor. However, few studies have considered the effects of silvicultural practices on decomposition in forested wetlands. In the southeastern USA, Mader (1990) measured increased organic matter decomposition following clear-cutting in bottomland hardwoods. Similarly, Haines et al. (1975) reported that bedding, a site preparation practice that is used to create an elevated planting bed, increased soil organic matter decomposition. Several studies in Europe and Canada have considered the impacts of silviculture in association with forest soil drainage systems. Organic matter decomposition increased as a result of drainage and harvesting (Lahde, 1969; Lieffers, 1988), which usually resulted in a net loss of soil C from the wetland (Trettin et al., 1995). We are aware of no studies on organic matter decomposition response to silvicultural practices in northern wetlands that do not involve drainage.

Litter bags are usually used in studies to investigate soil organic matter decomposition. However, due to the important effect of substrate quality on litter decomposition (Coulson and Butterfield, 1978; Swift et al., 1979, p. 118–163), use of a standard substrate is more appropriate for comparing decomposition among different sites (Heal et al., 1981). The CSA provides an effective index of organic matter decomposition by employing a uniform substrate whose degradation is related to environmental factors and soil conditions (French, 1988; Hill et al., 1988). This method cannot be used to quantify the decay of native cellulose because of structural differences in organic matter from native vegetation compared with the cotton substrate (French, 1988). However, results from the CSA and other cellulitic substrates have been positively related to decomposition of native organic matter (Fox and Van Cleve, 1983; Hopkins et al., 1990). The CSA method provides a relative measure of site condition effects on cellulose decomposition (Latter and Harrison, 1988), and it has been used effectively to characterize decomposition potential among different forest soil conditions (Mader, 1990) and sites (Heal et al., 1981; Hill et al., 1985; Maltby, 1988; Bridgham et al., 1991a).

Our objective was to test the hypothesis that silvicultural practices in a sub-boreal wetland increases organic matter decomposition, and that the increase in decomposition corresponds to the relative degree of soil distur-

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bance imposed by the silvicultural practice. One harvesting and two site preparation practices were selected for study: whole-tree harvesting, trenching, and bedding. Trenching, like bedding, is a regeneration practice; but instead of a broad elevated planting bed, it involves the creation of a narrow elevated berm adjacent to a shallow (15–30 cm) trench. These silvicultural practices provided a range in disturbance regimes that are representative of forest management in northern wetlands. We used the CSA because it functions as an effective integrator of environmental and soil conditions, is effective in contrasting treatments within a particular site, and is convenient to use (Harrison et al., 1988). We also report measurements of soil temperature, and soil oxidation and water table depth to evaluate the sensitivity of the CSA to changes in these abiotic factors. A Latin square experimental design was used in order to test the effects of both treatment factors and position within the wetland relative to a river on organic matter decomposition.

METHODS

Site Descriptions

A 30-ha study site was located in Alger and Delta counties within the Upper Peninsula of Michigan, at approximately 46°9′30″ and 86°41′30″E. The site is located in a sandy outwash plain that has a drift thickness ranging from 30 to 75 m; the outwash overlies Ordovician limestone. A hydric soil, classified in the Kinross series (sandy, mixed, frigid Typic Haplaquod), is representative of the site; the soil is characterized by a histic epipedon overlying an acid, fine sand solum, with a weakly developed spodic horizon. The epipedon is composed of fibric and hemic horizons of *Sphagnum* with an average thickness of 13 cm. The study site is forested with an overstory of black spruce [*Picea mariana* (Mill.) B.S.P.], tamarack [*Larix laricina* (Du Roi) K. Koch], and jack pine (*Pinus banksiana* Lamb.). Dominant species in the shrub layer include: blueberry [*Vaccinium angustifolium* (Ait.) Gray and *V. myrtiilloides* Michx.], leather leaf [*Chadaedaphne calyculata* (L.) Moench.], and Labrador tea (*Ledum groenlandicum*). *Sphagnum* sp. is the dominant ground layer plant. The climate is cool and continental, with a mean annual temperature of 5°C and mean annual total precipitation of 840 mm, with approximately 40% of the total precipitation as snow.

Experimental and Treatment Design

The experimental design consisted of three 3 × 3 Latin squares. Within each square, the three disturbance treatments were assigned randomly to the plots, resulting in a total of nine replicates per treatment across the three squares. The squares were located parallel to the West Branch of the Sturgeon River (Fig. 1). The row factor of the Latin square represented a gradient along a vector perpendicular to the river and it was common to each square. The column factor represented a gradient along a vector parallel to the river; this gradient was considered unique within each square due to possible site differences along the length of the riparian zone. Nine reference plots were located parallel to the Latin squares in the uncut forest. Each plot was 1024 m^2, with an 8-m-wide buffer strip within the plot; three subplots were located at equal intervals along a diagonal within each square plot. The subplots were used as the primary sample unit.

Fifteen hectares of the wetland adjacent to the West Branch of the Sturgeon River were clearcut in July 1988, using a mechanized whole-tree harvesting system. The site preparation treatments were installed on the study plots 1 mo after the harvest. Each of the two mechanical site preparation treatments were sprayed with 4.7 L ha^{-1} of glyphosate [*N*-(phosphonomethyl) glycine] at the time of treatment installation. The trench treatment prepares a bare soil planting site using a disk implement that creates a shallow trench and an adjoining berm. The furrow–berm was repeated every 3 m, effectively tilling approximately 45% of the soil surface. The bedding treatment is a form of soil mounding that is commonly used in northern wetlands (Sutton, 1993). The beds were created by disking a 3-m-wide strip into an elevated, 1-m-wide planting bed, which resulted in 100% tillage of the soil surface area.

Cotton Strip Assay

The CSA was conducted according to procedures described by Latter and Howson (1977) and Harrison et al. (1988) using Shirley Soil Burial Cloth (Sagar, 1988) obtained from the Shirley Institute in Manchester, England. The Cloth was cut into strips 12 cm wide and 30 cm long. One strip was inserted so that approximately 2 cm of cloth remained above the soil surface on each subplot within each of the nine treatment replicates (27 samples per treatment). The strips were placed where the surface was uniform on the control and harvest-only treatments, between the trenches on the trench treatment, and in the center of the planting bed on the bed treatment. Two consecutive 5-wk incubations were conducted during 27 June to 30 July (Period I), and 30 July to 8 Sept. 1989 (Period II). Results from a pilot study conducted during August to September 1988 indicated that a 5-wk incubation period was necessary to achieve approximately 50% loss in tensile strength, which is optimal for the CSA (Hill et al., 1985). At the end of the incubation period, the cloth was carefully excavated, gently rinsed in water to remove adhering soil particles, air dried, and stored in an air-tight container with desiccant until analyzed. At the beginning of each incubation period, 10 strips (field controls) were also inserted into the soil and then immediately removed. Four-centimeter-wide subsamples were cut from each incubated cotton strip with the sample midpoint corresponding to the 5-, 10-, and 20-cm soil depth. Tensile strength (TS) was measured on a Monsanto 10 Tensometer configured with rubber-padded jaws 5 cm wide and 2.5 cm long, a gauge setting of 5 cm, and a speed of 5 cm min^{-1}. The cotton strips were tested at 100% moisture content, which was accomplished by soaking the cloth strips in water prior to testing.

The cotton tensile strength loss (CTSL) was computed as:

$$\mathrm{CTSL\,(kg)} = y_o - y \qquad [1]$$

where y_o is the tensile strength of the field control and y is the final tensile strength of the incubated sample. The annualized rate of cotton decay (CRR) was calculated according to the function derived by Hill et al. (1985):

$$\mathrm{CRR} = (\mathrm{CTSL}/y)^{1/3}\,(365/t) \qquad [2]$$

where t is the incubation period length in days. This function linearizes the curvilinear response that is characteristic of tensile strength loss and facilitates comparison among sites with different incubation periods (Hill et al., 1985).

Soil Oxidation Depth

Oxidation of silver and steel rods has been an effective method for assessing anaerobic conditions in wetland soils (Lahde, 1969; Bridgham et al., 1991b). We used steel rods

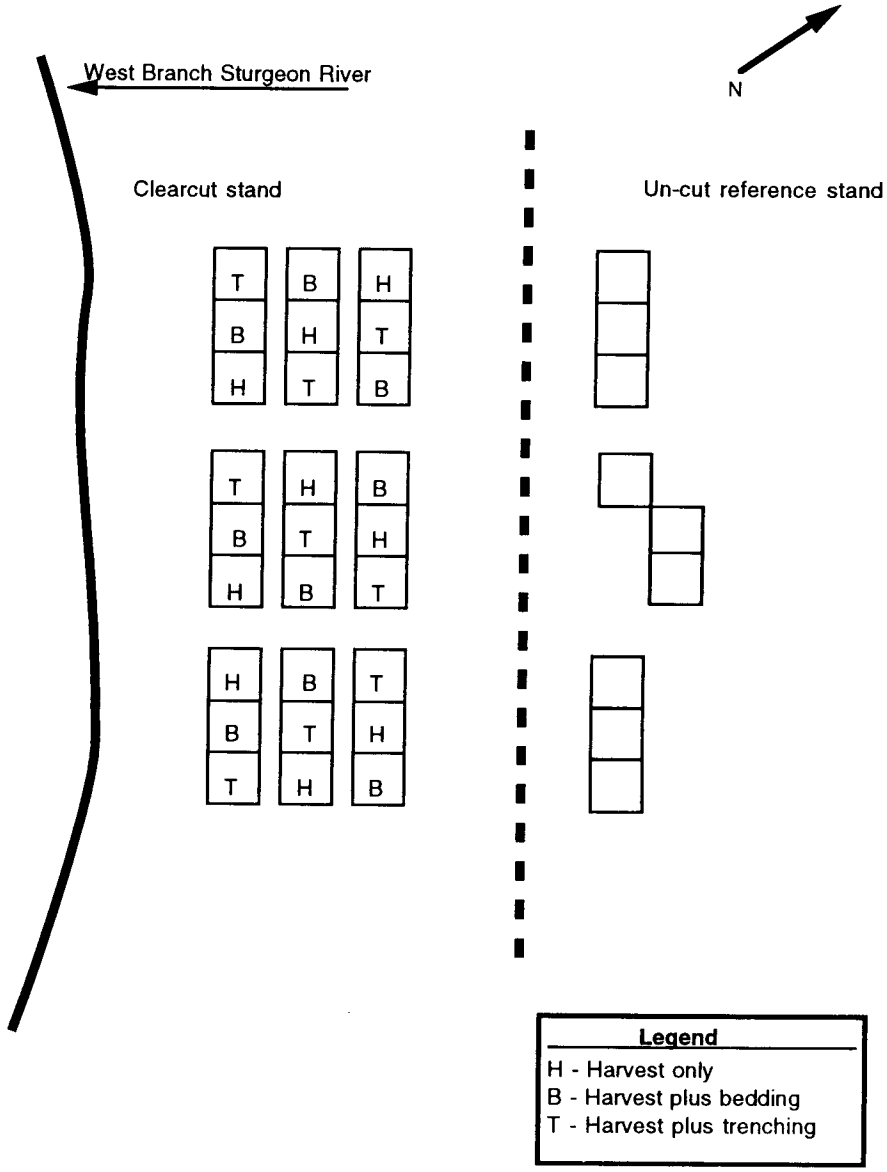


Fig. 1. Schematic showing the layout of the Latin square relative to the river, the harvest boundary, and the location of the reference plots.

(1.5-cm diam.) inserted on each subplot to approximately 75 cm below the soil surface to measure the depth of aerobic soil conditions (Carnell and Anderson, 1986). The rods were placed between the trenches on the trench treatment, and in the center of the planting bed on the bed treatment. The soil oxidation depth was determined by measuring the length on the rod from the soil surface to the anaerobic boundary, which was indicated by a matte gray color. Measurements were taken on four dates (27 June, 20 July, 23 Aug., and 27 Sept. 1989).

Soil Temperature

Soil temperature was measured at 7.5, 15, and 25 cm below the soil surface using a portable thermocouple. Measurements were taken on two subplots within each plot by preparing an access hole with a steel rod to within 2 cm of the desired measurement depth. The probe was then inserted to the measurement depth. Soil temperature was measured on 26 June, 21 July, 23 Aug., and 8 Sept. 1989, during the CSA incubations.

Statistical Analyses

Repeated measures analysis of variance was used to test the independent factors affecting the response variables. The independent factors included the gradient vectors represented by rows (R) and columns within squares [C(Sq)], and disturbance treatments (T). Repeated measures factors were: sampling depths (D), and time periods (P). The fixed effects, linear model using whole-plot means was:

$$y = m + \mathrm{R} + \mathrm{C(Sq)} + \mathrm{T} + u + \mathrm{D} + \mathrm{T} \times \mathrm{D} + \mathrm{R} \times \mathrm{D} + \mathrm{C(sq)} \times \mathrm{D} + \mathrm{P} + \mathrm{P} \times \mathrm{T} + \mathrm{P} \times \mathrm{D} + \mathrm{P} \times \mathrm{D} \times \mathrm{T} + \mathrm{P} \times \mathrm{R} + \mathrm{P} \times \mathrm{C(Sq)} + e \quad [3]$$

where y is the dependent variable, m is the true population mean, u is the between-plot error term, and e is the within-plot error term. The model, including interaction terms for the gradients, treatments, and period, was run on each dependent variable data set, which are discussed below. When the gradient factors [R & C(Sq)] were not significant, the model was reduced to Eq. [4] and rerun to include the reference site.

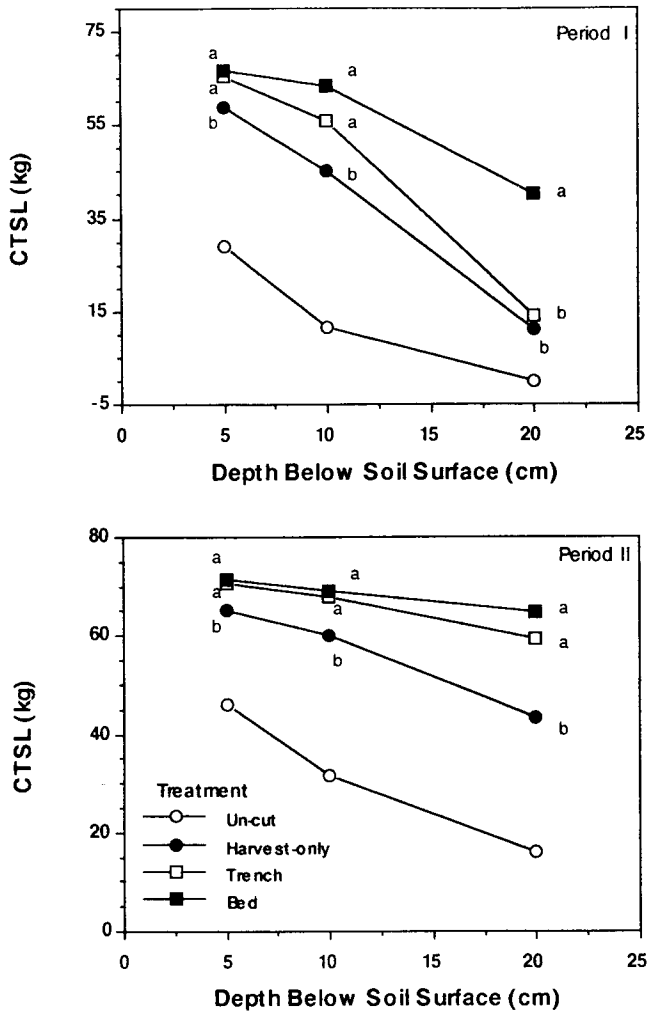


Fig. 2. Average cotton tensile strength loss (CTSL) after timber harvesting and site preparation, and an uncut stand after two 5-wk incubation periods: Period I is for June to July, and Period II is July to September 1989. Samples were measured at 5-, 10-, and 20-cm soil depth. Data means (n = 9) with same lowercase letter are not statistically different (P = 0.05).

$$y = m + \mathrm{T} + \mathrm{D} + u + \mathrm{T} \times \mathrm{D} + \mathrm{P} + \mathrm{P} \times \mathrm{T} + \mathrm{P} \times \mathrm{D} + \mathrm{P} \times \mathrm{T} \times \mathrm{D} + e \quad [4]$$

Orthogonal contrasts were used to test for differences between treatment means, and polynomial contrasts were computed for those measures that showed a significant effect of depth or period to assess differences in the nature of the relationship between the measure and depth or period among treatments and gradients. All analyses were conducted using the General Linear Models module of SAS (SAS Institute, 1988). Tests of significance were conducted at P = 0.05.

RESULTS AND DISCUSSION

Effects of Harvesting and Site Preparation

Organic Matter Decomposition

Organic matter decomposition (measured as cellulose by the CTSL) was significantly different among the silvicultural treatments during the two incubation periods (Fig. 2). The ranking of CTSL response corresponded to the relative degree of soil disturbance imposed by the silvicultural treatments. Bedding exhibited significantly greater CTSL than the other disturbance treatments at each assay depth in Period I. During incubation Period II, which corresponded with mid to late summer, there was no measurable difference in cellulose decomposition between bedding and trenching; however, both of those treatments were significantly greater than the harvest-only treatment. Both the harvesting and site preparation treatments exhibited greater cellulose decay than the uncut plots (Fig. 2). However, direct statistical comparison of the CTSL response on the offset, uncut plots and the harvesting and site preparation treatments was precluded because analyses of the gradient vector perpendicular to the river showed a significant, nonlinear effect.

Table 1. Effect of soil depth and incubation period cotton tensile strength loss (CTSL) among silvicultural treatments, summarized from linear contrasts in a repeated measures ANOVA.

Treatment comparison	Soil depth	Period	Soil depth × period
	$P > F$		
Harvest-only vs. bed	0.0002	0.0934	0.4977
Harvest-only vs. trench	0.3380	0.4221	0.0275
Bed vs. trench	0.0010	0.0199	0.0070

Analysis of CTSL among treatments with respect to soil depth and incubation period demonstrated that these factors were important in determining cellulose decomposition response (Table 1). The significant depth–linear contrast between the harvest-only and bed treatments means that these two treatments differ in the trend (i.e., steepness) of the response profile across depths (averaged across periods). Similarly, the linear contrasts of depth, period, and their interaction were significant between the bed and trench treatments, indicating different response trends. The different response patterns among the two site preparation treatments is probably a result of altered abiotic conditions imposed by the tillage regime. During the early growing season (Period I) there was no difference among the trench and bed treatments at the 5- and 10-cm soil depth. However, at the 20-cm soil depth, during the same time, decomposition in the beds was 260% greater (Fig. 2). In contrast, during Period II CTSL was essentially the same at each soil depth and higher than earlier in the growing season. The effect of soil depth and season on CTSL demonstrated that these are important factors to consider when interpreting cellulose decomposition response. For example, if this study were conducted only during the late growing season (Period II), one could conclude there was no difference in decomposition response among the two site preparation treatments. Similarly, analysis of cellulose decomposition at different soil depths and times demonstrates how the effect of abiotic and biotic factors are manifest among treatments, which would not be possible if these factors were not considered.

The use of CRR (Eq. [2]) facilitates comparison of cellulose decay among different sites. Other CSA studies have consistently found that disturbance, whether imposed by silvicultural practices or agricultural conversion, result in increased rates of cellulose decomposition

Table 2. Rate of cellulose decomposition (CRR) at three soil depths in undisturbed and managed forested wetlands in the northern and southern USA.

Site characteristics and period of cotton strip assay (CSA)	Treatment or site type	Rate of cellulose decomposition 5 cm	10 cm	20 cm	Reference†
Poconsin peatlands, North Carolina; CSA: March-May	tall pocosin	5	3	1	1
	short pocosin	4	3	2	1
	pine forest	10	9	10	1
	agriculture	27	27	21	1
Bottomland hardwoods, mineral soil, Alabama; CSA: July	uncut forest	49	35	29	2
	clear-cut with vegetation control	62	55	45	2
Sub-boreal, coniferous, histic mineral soil swamp, Michigan; CSA: July-August	uncut forest	11	9	6	3
	clear-cut only	17	15	11	3
	clear-cut plus bedding	23	19	17	3

† References: 1, Bridgham et al. (1991a); 2, Mader (1990); 3, this study.

(Table 2). The most common site factors attributed to the increase in cellulose decay are altered temperature and moisture regimes. Studying the effects of agricultural and silvicultural land management practices on cellulose decay, Bridgham et al. (1991a) reported significant increases compared with undisturbed forest soils in North Carolina. The high cellulose decomposition rates measured in the agricultural site were attributed to decreased soil anoxia as a result of drainage and increased soil temperature. Lahde (1969) also reported increased cellulose decomposition in drained peatlands. Mader (1990) reported cellulose decay to be sensitive to changes in temperature and water table fluctuations following clear-cutting of a bottomland hardwood forest in the Mobile River delta. These effects of soil temperature and moisture are discussed below.

The rate of cellulose decay measured in U.S. Forested wetlands (see Table 2) encompasses the range reported

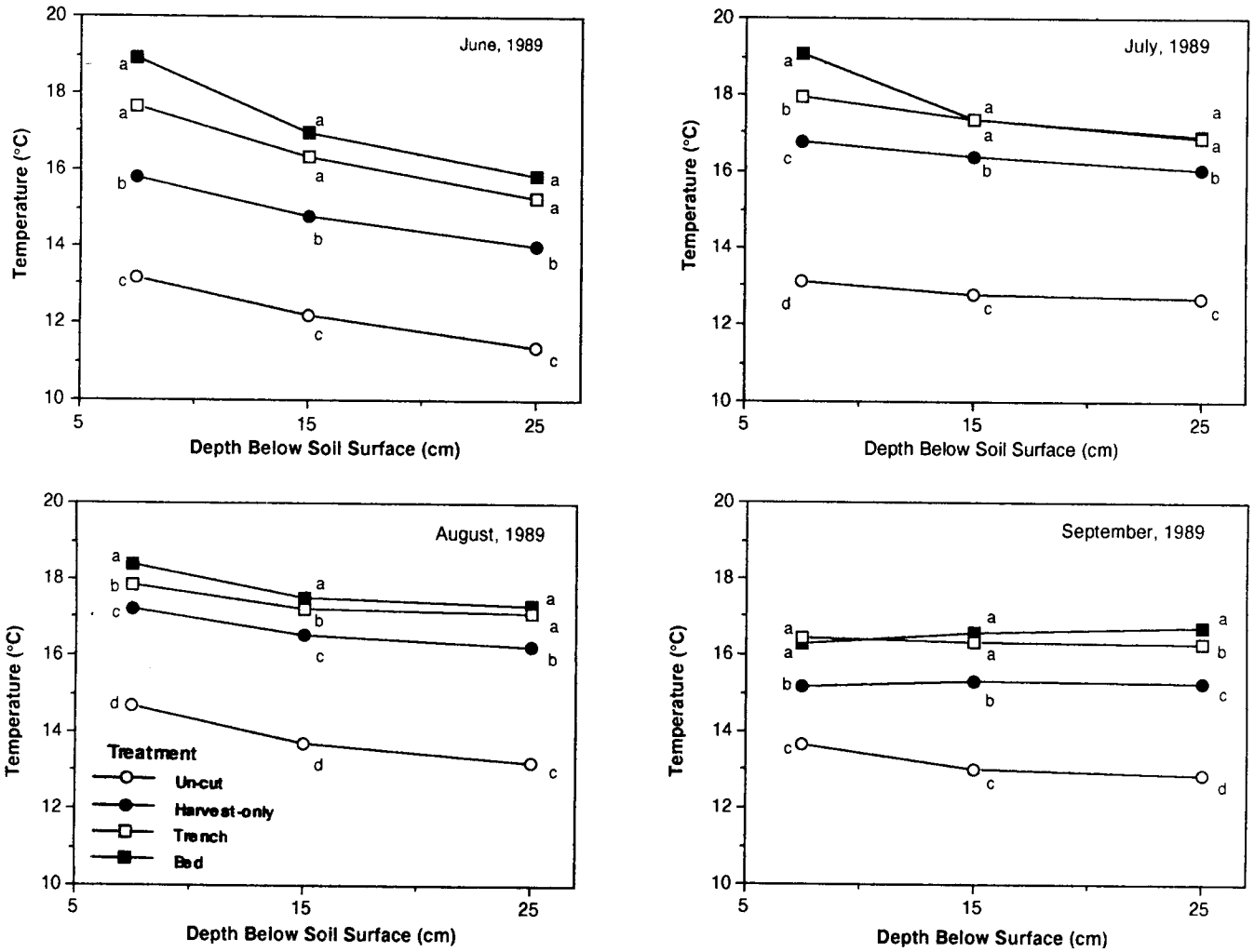


Fig. 3. Mean soil temperature by soil depth for the uncut, harvest-only, trench, and bed treatments on four dates in 1989. Data means (n = 9) with same lowercase letter are not statistically different (P = 0.05).

for a worldwide data set (Ineson et al., 1988). The rate of cellulose decay in the uncut treatment in this study was within the range (CRR <10) for other northern soils (Ineson et al., 1988). Correspondingly, the increase in CRR due to harvesting and site preparation was greater than the norm for undisturbed soils with comparable mean annual soil temperatures. Interestingly, CRR was greater in this study than rates measured by Bridgham et al. (1991a) during the early growing season in North Carolina pocosins. Consideration of seasonal effects is important when comparing CRR data. Although CRR are usually expressed on an annual basis, unless the CRR value is a mean based on incubations conducted throughout the year, it is biased to the season during which the data were calculated, not the entire year. The high CRR rates measured by Mader (1990) are an example; those results are based on the mean of two, 9-d incubations in July. If the CSA were conducted throughout the year, the mean annual CRR would probably have been lower.

The CSA is an index of decomposition (Latte and Walton, 1988), and is not a surrogate for assessing decomposition of native organic materials (Howard, 1988). Although there may not be a direct relationship between CSA and organic matter decomposition, recent studies have shown correspondence between cellulose and litter decomposition. French (1988), studying decomposition using both the CSA and litter bag techniques in a moor soil, reported that decay rates were in order of substrate quality, with cotton being intermediate between the grass leaves and heather stems. Other studies (Lieffers, 1988; Farrish and Grigal, 1988) have compared cellulose and *Sphagnum* sp. decomposition rates in peatlands and found that the two substrates exhibit similar patterns of decomposition, but that the rate of mass loss was less for *Sphagnum* sp. than the cellulose substrate.

Soil Temperature

The silvicultural treatments in this study caused a significant increase in soil temperature that corresponded to the degree of soil disturbance and vegetation removal. Soil temperature measurements at 7.5-, 15-, and 25-cm depths were significantly different on each of the four measurement dates. Mean soil temperature for each date decreased with soil depth in order of bedding > trenching > harvest-only > uncut (Fig. 3). Analyses of soil depth across treatments and measurement dates demonstrated that soil temperature was significantly different among the three soil depths and four dates. There was a significant depth × period interaction caused by soil cooling in the fall. There was no interaction of the silvicultural treatments with either the depth or period factors in the ANOVA. The effect of the silvicultural treatments on temperature was particularly evident during the first incubation period when the bed and trenching treatments exhibited significantly higher temperatures than the harvest-only and uncut treatments.

Temperature is the dominant factor affecting cellulose (Donnelly et al., 1990) and soil organic matter decomposition (Dickinson, 1974; Tate, 1987; Oades, 1988). Fox and Van Cleve (1983) have shown that the effect of soil temperature on organic matter decomposition is consistent among northern forest types. Increased soil temperature is a common response following clear-cutting of both peatland and bottomland hardwood wetlands (Aust and Lea, 1991; Trettin et al., 1995). Correspondingly, bedding is considered to increase soil temperature, resulting in increased organic matter decomposition (Sutton, 1993).

Using the temperature response imposed by the silvicultural treatments, it was possible to evaluate the effects of temperature on cellulose decomposition. Hill et al. (1988) used the observed temperature Q_{10} response for cellulose decomposition to express the CRR as:

$$\mathrm{CRR} = k\,Q_{10}^{t/10} \qquad [5]$$

where k = constant and t = temperature. Following, Q_{10} may be calculated as:

$$Q_{10} = \exp(10b) \qquad [6]$$

where b is the slope of the regression of ln(CRR) on temperature.

Comparison of the coefficients from the regression of CRR on soil temperature for the individual incubation periods showed they were not significantly different. The pooled linear regression model showed a significant relationship between soil temperature and CRR (Fig. 4). Using Eq. [6], the Q_{10} for cellulose decomposition was 6.0.

These analyses of cellulose decomposition response with soil temperature are based on measurements during aerobic soil conditions. During Period I, samples from the 20-cm soil depth on the trench, harvest-only, and uncut treatments were below the water table. The CRR response to temperature was much lower for these samples (Fig. 4), which we attribute to slower cellulose decomposition under anaerobic conditions (Lahde,

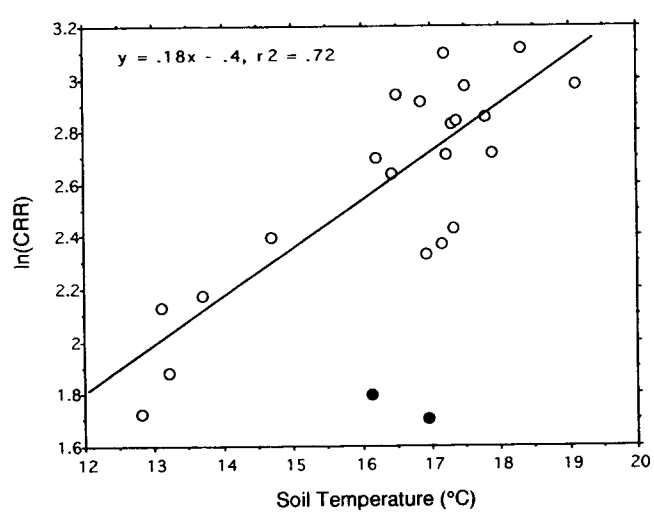


Fig. 4. Relationship of the rate of cellulose decomposition (CRR) to soil temperature, expressed by the linear regression of ln(CRR) with soil temperature. The data set includes uncut, harvest, and site preparation treatments for two incubation periods. Solid filled data points represent anaerobic conditions, and they were excluded from the analyses.

1969). Unfortunately this field data set was insufficient to test the interaction of water table depth and temperature on cellulose decomposition. Bridgham et al. (1991a) also reported lower cellulose decay rates on wetland soils that had not been drained, thereby inferring a moisture control on decomposition. In contrast, Mader (1990) reported higher CRR when the water table fluctuated within the incubation zone than under unsaturated conditions.

Analyses of CSA data, collected primarily in the northern hemisphere, have demonstrated that temperature is the single most important factor affecting cellulose decomposition (Ineson et al., 1988). The temperature coefficient for that global data set was $Q_{10} = 2.5$, similar to surface soils ($Q_{10} = 2.4$) and subsoils ($Q_{10} = 1.8$ at 12–16 cm) in upland forest in the U.K. (Hill et al., 1985). Results from our study indicate a significantly greater temperature response ($Q_{10} = 6.0$) following perturbation of the wetland.

In addition to temperature, available soil N has been recognized to affect cellulose decomposition (Lahde, 1969), because N used by the microorganisms that degrade the cotton fabric is necessarily derived from the soil (Hill et al., 1985; French, 1988; Ineson et al., 1988). Accordingly, the potential exists for the CRR response to be affected by soil N availability. Since silvicultural practices commonly increase N mineralization (Carlyle, 1986), one possible explanation of the higher Q_{10} in our study is that it reflects increased N availability. Unfortunately, there have not been any field experiments to evaluate cellulose decomposition when both soil temperature and N levels have been altered.

Soil Aeration and Water Table Depth

Soil moisture and aeration also influence cellulose decomposition (Williams and Crawford, 1983; Donnelly et al., 1990). In wetland soils, water table depth affects soil aeration (Lahde, 1969; Braekke and Finer, 1990), metabolic activity (Lahde, 1969; Williams and Crawford, 1983), and the rate of cellulose decomposition (Isotalo, 1951). Accordingly, the CTSL response should also be sensitive to changes in moisture and aeration as a result of the harvesting and site preparation treatments. In this study, water table and aerated soil depth were nearly equivalent except when the water table was near the surface (<15 cm) or deeper than 50 cm (Fig. 5). The shallower oxidized soil depth may reflect a lag in reaeration following a decline in the water table (Lahde, 1969). Accordingly, the CTSL response for the trench, harvest-only, and uncut treatments at 20 cm (during Period I) is largely influenced by saturated soil conditions. In contrast, during Period I the incubation zone in the bed treatment was above the water table the entire time, thereby providing an aerobic decomposition environment. During incubation Period II the water table was below the cotton strip for all the treatments, thereby minimizing or negating the effect of saturation on the measured cellulose decomposition. Bridgham et al. (1991a) also reported that soil moisture was a controlling factor on CTSL in wetlands in North Carolina, particularly when sites had been drained.

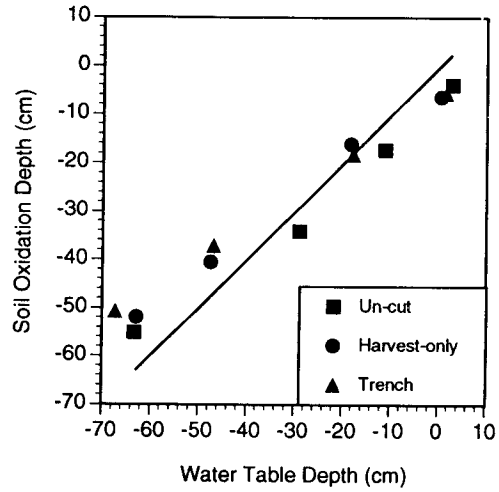


Fig. 5. Soil oxidation depth, as measured using steel rods, vs. water table depth on the uncut, harvest-only, and trench treatments during the 1989 growing season. The 45° diagonal line indicates a 1:1 correspondence.

Oxidation of metal rods has been an effective method for assessing the depth to anaerobic conditions in wetland soils (Lahde, 1969; Bridgham et al., 1991b). Based on the steel rod oxidation depth, the anaerobic soil zone exhibited a complex response pattern that was affected by the silvicultural treatments, position within the wetland, and measurement period. The bed treatment had the greatest oxidized soil depth at each measurement date (Fig. 6), and it was significantly different from the other treatments in July and August. The trench and harvest-only treatments were not significantly different at any of the measurement dates, although the probability of a greater F was 0.086 in July and 0.064 in August. These treatment responses reflect differences in soil tillage. The objective of bedding is to produce an elevated planting microsite that is above the normal soil surface elevation. Characteristically, bedding and other mounding methods produce microsites that have improved aeration (Sutton, 1993). In contrast, measurements of soil oxidation depth on the harvest-only and trench treatments were taken at the normal soil surface elevation, hence there was no mounding effect. It should be noted, however, that the trench treatment includes a berm of disked soil; it is likely that soil volume exhibited an aeration regime similar to the bed treatment.

Effects of Intra-Wetland Position on Decomposition

Hydrology controls soil moisture and aeration regimes in wetland soils. Because the hydrologic regime changes both spatially and temporally, it is important to recognize the potential effect that gradients associated with changes in hydrologic regime may have on within-site variation of response parameters. These gradients are particularly important with respect to ecosystem dynamics (Johnston,

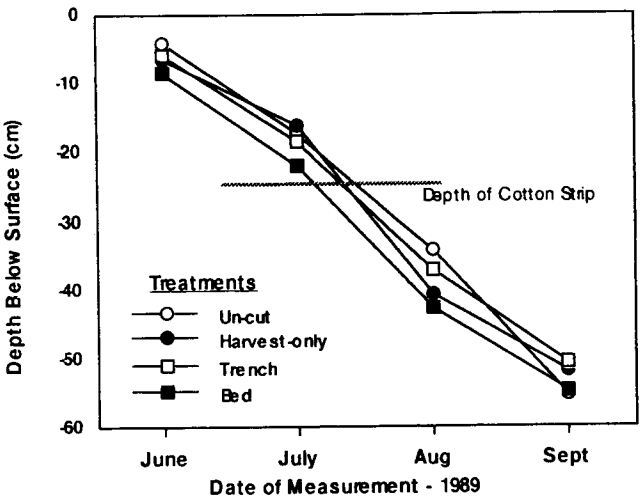
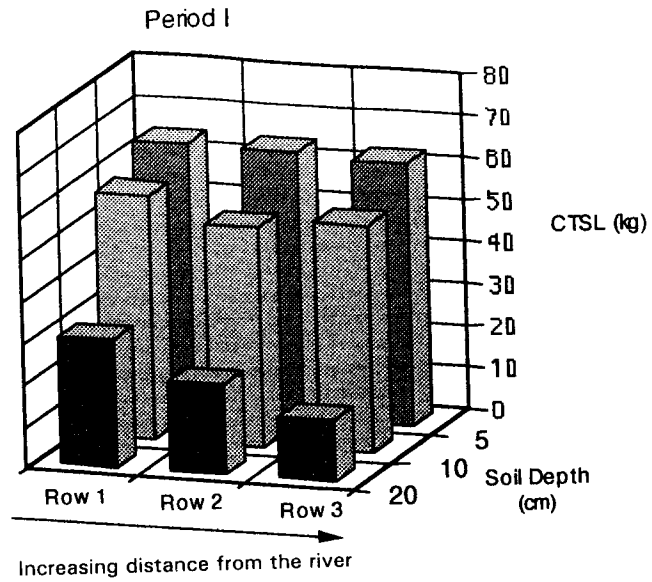


Fig. 6. Mean soil oxidation depth, measured by iron rod oxidation. Data points represent means (n = 9). Dashed line denotes maximum depth of cotton strip.



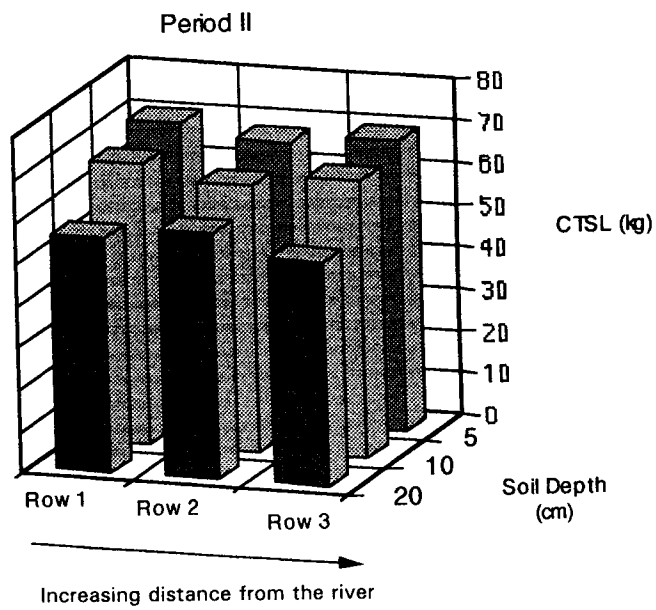


Fig. 7. Average cellulose decomposition (CTSL) by rows within the Latin square for incubation Periods I and II. The row factor represents a gradient vector perpendicular to the river.

1993), and they should be considered when studying wetland processes, otherwise there is the potential that the experimental treatment response may be confounded. Gradients associated with variations in hydrologic regime, water quality, substrate, past management, or disturbance regimes are common to wetlands. Often gradients are obvious, as exemplified by distinct vegetation community types within a single wetland landform. In these situations, site variations may be accommodated through the use of common blocking or stratified experimental designs. In other wetlands, the presence of gradients may not be evident; such was the case in our experimental site. Use of the Latin square design enabled us to assess spatial variations associated with gradients perpendicular and parallel to the river adjoining the wetland. Both cellulose decomposition and the soil oxidation depth exhibited spatially dependent variation.

Cellulose decomposition (i.e., CTSL) measured at the 5- and 10-cm soil depths along a vector perpendicular to the river was not statistically different (Fig. 7). However, there was a significant interaction between soil depth at 20 cm and position along the vector perpendicular to the river, which did not allow us to make direct comparisons among the CTSL response on the silvicultural treatments with the uncut forest, as a simple function of distance from the river, for example. However, given (i) that the magnitude of the difference in CTSL among the silvicultural treatments and the uncut forest was large relative to variation associated with the gradient, and (ii) that soil temperature increased as a result of harvesting and site preparation, it is quite likely that the measured difference at that depth is largely attributable to the experimental treatments.

Soil oxidation depth was also spatially dependent (Fig. 8), with sampling positions along vectors both perpendicular and parallel to the river having a significant effect. Soil oxidation depth generally decreased as distance from the river increased. There was a significant interaction between position along that gradient and time of sampling, which is evident in the varied response during the 1989 growing season (Fig. 8). The vector parallel to the river that represents a relative upstream–downstream position was also significant, and it exhibited an interaction with time (Fig. 8). Generally, upstream segments tended to have a greater oxidation depth than downstream segments. In this type of northern wetland, the period following snowmelt is the predominant hydrologic event. Following snowmelt, the entire site is typically inundated. Upstream segments, because of the natural gradient along the stream reach, and areas adjacent to the river, because of a natural levee, tend to drain first. Accordingly, these areas would inherently have an increased soil oxidation depth relative to interior and downstream wetland segments.

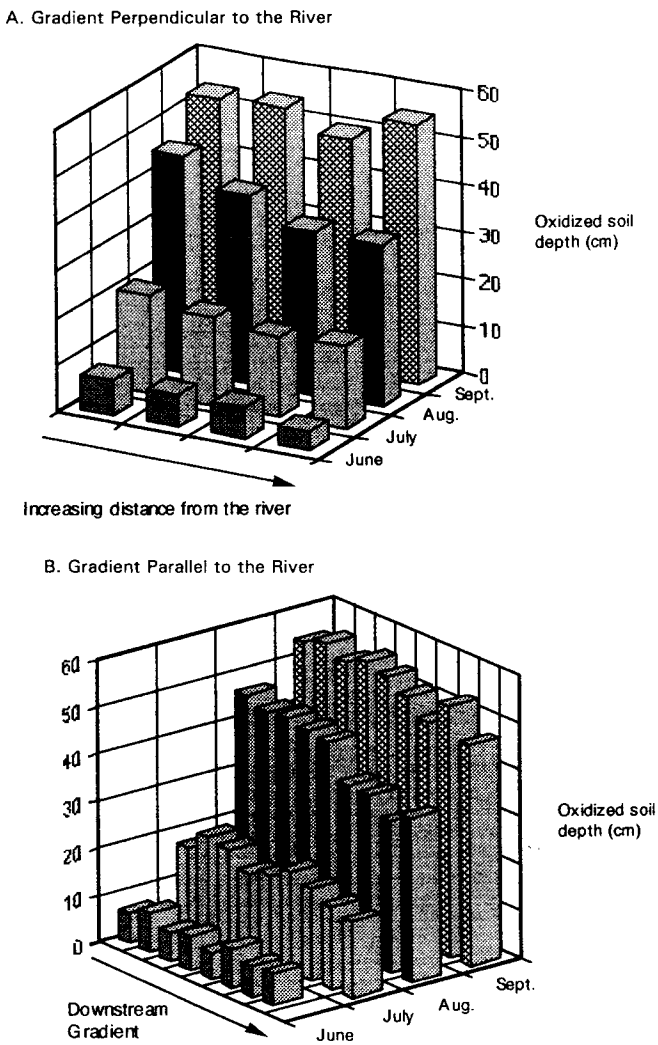


Fig. 8. Average soil oxidation depth by the row and column factors of the Latin square. The row factor represents a gradient vector perpendicular to the river, and the column factor represents a gradient vector parallel to the river.

SUMMARY

The primary effect of harvesting and site preparation was to increase soil temperature, thereby increasing the rate of organic matter decomposition. Bedding caused the greatest increase in organic matter decomposition because of the effect of a tilled planting bed on temperature and aeration early in the growing season. Late in the growing season, there was no difference in organic matter decomposition among the two site preparation treatments, however both were greater than the harvest-only treatment. The differential response among the harvesting and site preparation treatments is primarily a result of the inverse relationship between vegetative cover and soil temperature. The CSA, while not a surrogate for the analyses of native organic matter, was a useful bioassay to establish the effects of silvicultural treatments on organic matter decomposition.

Within the wetland, variation in cellulose decomposition was sensitive to position relative to the adjoining river. Similarly, soil oxidation depth exhibited distinct gradients, both parallel and perpendicular to the adjoining river. These results highlight the need to accommodate variation that may be associated with environmental gradients, particularly wetland hydrology.

Increased organic matter decomposition following forest soil drainage is a recognized consequence of that silvicultural practice (Trettin et al., 1995). Results from this study have demonstrated that the abiotic mechanisms for altering C dynamics exist following disturbance by harvesting and site preparation in the absence of drainage. The effect of the silvicultural practice on organic matter decomposition is largely a function of the degree of soil tillage and vegetation removal. Changes in the quantity of soil organic matter or in the rates of C cycling may have important effects on nutrient cycling, soil moisture regimes, and vegetative composition and productivity. These responses are particularly important for Histosols (i.e., peatlands) and histic-mineral soils, which accumulate C, and have an important role in the global C budget. How alterations in soil C dynamics are manifest in the long-term functionality of forested wetlands should be the focus of further study.

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