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Controls on Soil Carbon Sequestration and Dynamics: Lessons from Land-use Change

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Abstract: Soil carbon (C) dynamics and sequestration are controlled by interactions of chemical, physical and biological factors. These factors include biomass quantity and quality, physical environment and the biota. Management can alter these factors in ways that alter C dynamics. We have focused on a range of managed sites with documented land use change from agriculture or grassland to forest. Our results suggest that interactions of soil type, plant and environment impact soil C sequestration. Above and below ground C storage varied widely across sites. Results were related to plant type and calcium on sandy soils in our Northern sites. Predictors of sequestration were more difficult to detect over the temperature range of 12.4°C in the present study. Accrual of litter under pines in the moist Mississippi site limited C storage in a similar manner to our dry Nebraska site. Pre-planting heterogeneity of agricultural fields such as found in Illinois influences C contents. Manipulation of controls on C sequestration such as species planted or amelioration of soil quality before planting within managed sites could increase soil C to provide gains in terrestrial C storage. Cost effective management would also improve soil C pools positively affecting soil fertility and site productivity.

Key words: soil carbon, management, sequestration, global change.

Organic carbon (C) and nitrogen (N) accumulation in soils is a consequence of a series of biotic and abiotic controls on plant primary production and decomposition. Land-use changes significantly alter soil organic matter (SOM) dynamics through changes to controls such as through alterations to the physical environment (e.g. moisture, temperature, etc.), physical (aggregation) and chemical (clay) protection, and biota (Morris and Paul, 2003; Grandy and Robertson, 2007; D'Angelo et al., 2007). Land management strategies are often focused on plant productivity and increasingly there has been interest in maintaining or increasing plant community diversity. The strategies for achieving desired production or diversity outcomes often involve manipulations to soils, including fertilization, biocide and/or water applications, tillage or aeration, and alterations to vegetative communities. These strategies impact rooting depth and litter quality and quantity. Management practices will impact the quantity and quality of soil C and N found in a given site (Ogle et al., 2003; Jandl et al., 2007; Grandy and Robertson, 2007). But management practices have seldom been specifically applied to increase C and N sequestration or ameliorate the effects of global change. Soil C pools are being managed intentionally or unintentionally. The recent need for sustainability and mitigation of climate change has directed attention to the potential C gains from deliberate management of these important pools.

Soil C sequestration that will benefit global climate change scenarios will be a result of management strategies that increase organic matter inputs to soil (Janzen, 2006). Scenarios that decrease decomposition rates alone have the potential to adversely impact site fertility. This could lead to long-term decreases in site fertility, which will decrease aboveground production. Afforestation either by planting or plant invasion of marginal agricultural or grassland sites has been recommended under C sequestration scenarios to increase CO_2 uptake and increase organic matter inputs. It has the added benefit of improving soil fertility and providing a source for biofuel production. The results from current studies suggest that the specific impacts of afforestation on C pools vary across sites (Johnson, 1992; Post and Kwon, 2000; Paul et al., 2003; Morris et al., 2007). Given the current interest in managing terrestrial C pools a greater understanding of soil C dynamics following land use change and the consequences of specific management techniques are needed.

The overall objective of our ongoing studies has been to evaluate soil C dynamics in central and eastern deciduous forests planted on agricultural or grassland sites. We have the implicit goal of characterizing C dynamics following afforestation, so that we may better understand the controls on C accumulation across a wide range of soils, mean annual temperatures (MAT) and vegetation. To achieve this goal we sampled ten sites across a 12.4°C MAT gradient that underwent afforestation within the last 80 yr. Here we present data on three additional sites (IL, NC, and MS) and a more recently planted MI site and explore C dynamics in those sites compared with the previously characterized northern sites (Paul et al., 2003; Morris et al., 2007) and a central grassland site. Our work should improve the knowledge available on soil C stocks across a set of managed and unmanaged sites and allow the development of greater predictive capacities based on the dynamics identified with our work.

MATERIALS AND METHODS

Sites in Illinois (IL), North Carolina (NC), and Mississippi (MS) were identified for study. For each site,

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land managers were contacted for information regarding the site history of the area of interest. Each area consisted of land currently under cultivation and areas that were formerly cultivated land but had been returned to forest. In two of the sites (MS, NC) native forest sites were also identified for comparison. In MS a pasture was also identified on former agricultural land. Specific site characteristics including location, soil type, vegetation, and time since cultivation are available in Table 1. Data from the Kellogg Biological Station LTER (KBS), in Hickory Corners, MI, for the cultivated, poplar plantation, and deciduous afforested and pine afforested sites are also presented here for comparison.

At each site, composite soil samples were collected by horizon (MS, NC) or depth (KBS, IL). Samples generally consisted of three composites. Each soil sample was weighed when returned to the laboratory, analyzed for gravimetric water content and bulk density was determined using sampling volume and dry soil weight. Soils were then air dried and sieved to 2 mm. Soils for C and N analysis were ground to pass a 180-μm screen and analyzed by dry combustion in a Carlo Erba CN analyzer using calibration standards and instrument and soil controls (Robertson et al., 1999; Sollins et al., 1999). Phosphorus (P), calcium (Ca), potassium (K), magnesium (Mg) and pH were determined by the soil-testing laboratory at Michigan State University (Brown, 1998). Soils were extracted with 1.0 *M* COOCH$_3$NH$_4$. Extractable Ca, K, and Mg were determined using an atomic absorption spectrometer (Warncke and Brown, 1998). The amount of available P was determined using the Kurtz P-1 Test and Bray (Frank et al., 1998). Litter was also collected at each location using a 7 cm diameter collector. Litter was dried, weighed and for the NC and MS site, litter was analyzed for C and N content as described for soils.

TABLE 1. Site characteristics (soil texture, location, land-use types and age of afforested areas) for more southern sites (IL, NC, MS) and 10 year old poplar in MI in the North-South transect of sites used for evaluating C storage and dynamics.

Site	Soil texture	Geographic Location	Land-Use Types	Years afforested
East Peoria,	Ross silt	40° 45’ N	Agriculture	
Illinois	Loam	89° 25’ W	Aff. Deciduous	30
Kyle,	Rosman	35° 16’ N	Agriculture	
North	fine	83° 40’ W	Native	
Carolina	sandy		Aff. Deciduous	80
	loam			
Hubbard,	Memphis	32° 18’ N	Agriculture	
Mississippi	silt loam	90° 66’ W	Aff. Coniferous	20
			Native	
			Pasture	
Kellogg	Kalamazo	42° 24’ N	Agriculture	
Biological	Loam	85° 24’ W	Aff poplar	10
Station	Oshtemo		Aff Coniferous	40-60
Hickory	Silt loam		Native	
Corners,				
MI				

For each soil sample, C and N were calculated for each depth by adjusting each for bulk density and horizon depth. The total soil weight for each profile was determined for each sample at each site. Total profile soil contents were determined by summing horizon contents to the depth of a meter as adjusted so that within each site C and N contents for all land-use types were represented based on equivalent soil weights within all sites. All profile calculations therefore represent the same amount of soil at each site (Ellert and Gregorich, 1996; Six et al., 2002). The change in C content for each of the sites is reported as the total profile C in the afforested site minus the agricultural site on the same soil type. All response variables were checked for normality (proc univariate) and homogeneity of variance (hovtest=levene welch). When the data met the assumptions of ANOVA, they were then analyzed using analysis of variance (Proc MIXED; SAS, 1999). Where the main effects were significant, difference among land-use types were determined using least square means.

The change in ecosystem C content for all afforested sites was also determined. For the three sites reported on here as well as the ones in earlier studies (Table 2; Pregitzer and Palik, 1997; Paul et al., 2003; Morris et al., 2007; Unpub. data) the changes in soil, litter and biomass pools were determined. All soil C and litter C pools were determined as described above. Above and belowground biomass were determined from data obtained either in forest inventories or estimated using

TABLE 2. General characteristics (texture, land-use, age of afforested areas, and profile soil C {Mg/ha} to 1 M with exception[a]) of sites used to examined to determine C sequestration following afforestation of agricultural soils. Aff=afforested.

Site	Texture	Land-use	Years afforested	Soil CMg/ha[a]
[b]Kemptville,	Grenville	Agriculture		78.9^{a}
ONT	Sandy	Native		78.0^{a}
	Loam	Aff. Deciduous	23	76.5^{a}
		Aff. Conifer	29	94.1^{a}
[c]Russ Forest,	Kalamazoo	Agriculture		52.6^{a}
Cass County,	Loam	Native		75.7^{b}
MI		Aff. Deciduous	53	71.2^{b}
		Aff. Conifer	50	72.0^{b}
[d]Kellogg	Kalamazoo	Agriculture 1942		14^{a}
Forest, MI	Loam	Aff. Conifer 1988	46	11.3^{a}
[b]Maumee,	Ottokee	Agriculture		68.1^{b*}
OH	fine Sand	Native		88.2^{b}
		Aff. Deciduous	50	95.9 ^{b*}
		Aff. Conifer	50	27.4 ^{a}
[b]Delaware,	Morley silt	Agriculture		106.4^{a}
OH	Loam	Native		153.4^{b}
		Aff. Deciduous		113.8^{a}
[e]Halsey,	Valentine	Prairie		32.45^{b}
Nebraska	fine sand	Aff. Cedar	55	36.96^{c}
		Aff. Pine	72	25.13^{a}

[a] Kemptville to a depth of 40 cm and Kellogg Forest to 10 cm.
[b] Paul et al. 2003
[c] Morris et al. 2007
[d] Pregitzer and Palik,1997
[e] Unpub. data.

TABLE 3. Mean soil organic C content, total N content, C:N ratio, litter C and litter C:N ratio with standard error from soils from agricultural, afforested, native forest and pasture sites in Illinois, North Carolina and Mississippi (n= number of replicates). Means followed by the same letter are not significantly different within a site at $p \leq 0.05$. All profile values are based on equivalent soil weight within sites to a depth of 20 cm for IL, 50 cm for NC and 1 M for MS.

	N	Profile C Mg/ha	Profile N Mg/ha	Soil C:N Ratio	[a]Litter C Mg/ha	Litter C:N Ratio
Illinois						
Agriculture (field 1)	5	27.88^{a}(2.56)	2.7^{a}(0.18)	10.3^{a}(0.27)	3.49[b]	
Agriculture (field 2)	5	29.26^{a}(2.23)	2.9^{a}(0.20)	10.3^{a}(0.44)	2.89	
Afforested (stand 1)	3	56.87^{c}(1.49)	4.1^{b}(0.51)	14.2^{bc}(2.36)	2.89	
Afforested (stand 2)	3	47.6^{b}(3.18)	4.0^{b}(0.35)	11.8^{ab}(0.27)	3.69	
North Carolina						
Agriculture	3	44.29^{a}(1.83)	3.14^{a}(0.05)	14.11^{a}(0.40)	0.84^{a}(0.20)	28.20^{a}(2.84)
Afforested	6	75.31^{b}(5.24)	5.12^{b}(0.32)	14.69^{a}(0.19)	2.44^{b}(0.21)	59.42^{b}(3.22)
Native Forest	5	113.00^{c}(3.31)	7.31^{c}(0.61)	16.73^{b}(0.65)	3.43^{c}(0.27)	35.69^{a}(1.20)
Mississippi						
Agriculture	3	13.87^{a}(1.47)	2.49^{a}(0.15)	5.55^{a}(0.31)		
Afforested	6	22.55^{b}(0.60)	3.29^{b}(0.05)	6.85^{b}(0.19)	7.18^{a}(0.76)	33.13^{b}(1.29)
Native Forest	6	30.85^{c}(3.45)	3.45^{b}(0.19)	8.80^{c}(0.50)	10.13^{b}(0.93)	28.38^{a}(1.21)
Pasture	3	32.75^{c}(0.64)	4.00^{c}(0.08)	8.20^{c}(0.03)		

[a] litter from current stand.

[b] litter C for IL estimated based on measured litter weight the average C content (35%) of litter from our other studies.

literature values for similar sites. The total amount of C in the above and belowground tree materials was evaluated using biomass determinations and conversion factors of 52.1% C for conifers and 49.8% C for deciduous species from Birdsey (1992). The total amount of N in the biomass for deciduous species was calculated based on tissue N contents of 0.26% for aboveground tissues and 0.46% for roots. Biomass N for conifer species was estimated based on the tissue N content of 0.19% for tissues aboveground and the value of 0.36% for tissues belowground (Goodale et al., 2002).

RESULTS

Soil C and N contents and the C:N ratios were greater in the afforested sites sampled in IL, NC and MS when compared to the agricultural sites on the same soil type (Table 3). Soil C and N contents were greater in the native forest sites compared to the afforested sites in NC and MS. The soil C and N contents in the MS pasture soils were greater than the afforested and agricultural sites. The C:N ratios were lower in the afforested than the native forest sites across all sites sampled and the MS soils showed generally low C:N ratios in both forest and agriculture in spite of having litter C:N ratios similar to NC. Soils accrued appreciable amounts of C and N following afforestation at IL, NC, and MS, with the largest accrual in NC and the highest rate of accumulation in IL (Table 4).

Soil pH and nutrients differed across land use types (Table 5). At the IL site, one of the two agricultural sites had significantly lower pH, Ca, and Mg and higher P than the other three land-use types, which did not differ from each other in these nutrient contents. At the NC site, the native forest was considerably more acidic than the afforested site, which did not differ from the agricultural field. The Ca, K and P contents were greater in the agricultural field than either the native forest or the afforested site which did not differ. At the MS site, the pasture and agricultural tended to have higher K and Mg than the native forested and afforested sites.

At the KBS site, where forest represents the native pre-agricultural conditions, the soil C and total N were greater in the native and afforested pine forests than in the agriculture or 10 year old planted poplar stands to a depth of 25 cm. However, there were no significant differences in the organic C or total N to a depth of 100 cm across treatments (Table 6). This site has extreme variability with clay lenses at depth and thus there were no significant differences when the soils were sampled to 100 cm.

Afforestation led to ecosystem C gains for all sites sampled in central and eastern North America (Fig. 1). Soil organic C increased at 9 out of 13 sites sampled. Litter C and plant biomass increased at all sites with biomass contributing the bulk of C gains at all sites. Gains

TABLE 4. Change in soil organic C and total N content (Mg/ha) and rate of change following afforestation of agricultural land across sites in IL, NC, and MS.

	ΔC[a] Mg/ha	ΔN Mg/ha	ΔC/yr Mg/ha/yr	ΔN/yr Mg/ha/yr
Illinois 30 yr				
Afforested Deciduous	23.67	1.25	0.79	0.04
North Carolina 80 yr				
Afforested Deciduous	31.02	1.98	0.39	0.02
Mississippi 20 yr				
Afforested Pine	8.68	0.8	0.43	0.04

[a] IL was to a depth of 20 cm, NC was to a depth of 50 cm and MS to a depth of 1 m.

TABLE 5. Mean A horizon[a] pH, calcium, magnesium, potassium and phosphorus (mg/kg) with standard error from soils from agricultural, afforested, native forest and pasture sites in Illinois, North Carolina and Mississippi (n= number of replicates). Means followed by the same letter are not significantly different within a site at $p \leq 0.05$.

			Calcium	Potassium	Magnesium	Phosphorus
		pH	mg/kg			
Illinois						
Agriculture (field 1)	5	5.0^{a}(0.08)	511^{a}(85)	137^{a}(26)	126.3^{a}(13.9)	63.8^{b}(8.5)
Agriculture (field 2)	5	7.2^{b}(0.34)	1090^{b}(66)	91^{a}(5)	304.8^{b}(25.2)	12.1^{a}(2.4)
Afforested (stand 1)	3	7.2^{b}(0.48)	1153^{b}(226)	79^{a}(19)	309.1^{b}(38.8)	6.0^{a}(2.2)
Afforested (stand 2)	3	7.3^{b}(0.27)	1420^{b}(93)	98^{a}(12)	369.3^{b}(17.0)	2.7^{a}(0.4)
North Carolina						
Agriculture	3	5.2^{b}(0.03)	223^{b}(42)	116^{b}(12)	10.5^{a}(6.1)	101.6^{b}(3.8)
Reforested	5	5.2^{b}(0.04)	143^{ab}(26)	50^{a}(3)	8.1^{a}(4.0)	4.6^{a}(0.4)
Native Forest	2	4.6^{a}(0.15)	48^{a} (0)	63^{a}(17)	8.0^{a}(2.5)	5.0^{a}(2.5)
Mississippi						
Agriculture	2	4.7^{a}(0.00)	752^{a}(100)	163^{c}(32)	228.1^{bc}(2.5)	26.6^{b}(1.0)
Afforested	6	5.6^{a}(0.08)	549^{a}(36)	56^{a}(5)	158.1^{ab}(23.8)	10.0^{a}(1.5)
Native Forest	6	5.2^{a}(0.29)	522^{a}(192)	88^{ab}(13)	117.0^{a}(20.5)	8.2^{a}(0.8)
Pasture	3	5.6^{a}(0.11)	891^{a}(104)	113^{bc}(12)	299.5^{c}(6.9)	20.4^{b}(5.9)

[a] IL site represents the top 10 cm.

in ecosystem N were similar to C gains (data not shown). The southern sites reported in this study did not deviate from the patterns observed for the northern sites. Figure 1 shows that soil C changes in afforested sites were not related to tree biomass accrual or litter inputs, as there were variable soil C gains and even losses in some sites.

DISCUSSION

In this study, soil C accrual rates were greatest in IL. This site is on silt loam soils with high productivity. The rate of litter C accumulation with corn (annual corn residues of ~3 Mg/ha) was as high as the litter accumulated with time on the afforested sites on these soils. The IL site was afforested for the shortest period of time and was sampled more shallowly than the other sites, indicating that with time this site will show even greater overall accumulation. The rates of C accrual in NC and MS were similar even though MS was sampled much more deeply than the NC site. That afforested soil C had not yet reached the contents of the native forests on these sites suggests that these soils have not yet reached steady state or C saturation. The values 0.39 Mg/ha/y for MS and 0.43 Mg/ha/y for NC are similar to the averages from meta analyses of published literature (Guo and Gifford, 2002; K. I. Paul et al. 2002). The 0.79 Mg/ha/yr for IL is however outside the range of -0.141 to 0.617 reported by Post and Kwon (2000) or Paul et al. (2003). The changes in N contents (Table 4) were somewhat smaller than the those found by Paul et al. (2003) but are higher than inputs by rainfall, confirming the observation that N is accruing in afforested systems by unknown means possibly by ammonia absorption from the atmosphere.

Results from the poplar KBS site suggests that C accumulates more quickly in the upper depths. Sampling to deeper depths may obscure real C gains because of summative errors as a result of adding horizon C contents, each having an error term associated with it, and compounding issues of homogenizing large bulk samples for C content. Others have found that C does not accumulate in the plow layer following afforestation, but accumulates at lower depths (Hooker and Compton, 2003). This leads to a question of which sampling depth is the most useful in measuring C and N sequestration and whether specific depths should be reported versus natural horizons. As most of our sites were sampled as horizons, it is difficult to do cross-site comparisons, but more satisfying for understanding properties based on intrinsic horizon properties. Gains in soil C anywhere in the profile may actually forecast significant C accrual, as the site ages. Changes in soil C might be more easily interpreted if reported across a range of depths.

TABLE 6. Mean soil organic C content, total N content, and C:N ratio with standard error from soils from agricultural, planted poplar, afforested pine and late successional native deciduous sites at Kellogg Biological Station, Long-Term Ecological Research station in Kalamazoo MI (n= number of replicates). Means followed by the same letter are not significantly different within a site at $p \leq 0.05$. All profile values are based on equivalent soil weight within sites to the depth indicated.

	Profile C	Profile N	C:N Ratio
0-25 cm			
Agriculture	27.18^{a}(1.86)	2.98^{a}(0.17)	9.10^{a}(0.14)
Poplar	29.51^{ab}(2.98)	2.97^{a}(0.30)	9.92^{a}(0.23)
Aff-Con	38.51^{bc}(4.06)	2.98^{a}(0.19)	13.08^{b}(1.86)
Native	47.82^{c}(3.33)	3.75^{a}(0.32)	12.80^{b}(0.39)
0-100 cm			
Agriculture	61.18^{a}(7.75)	9.11^{a}(0.76)	6.61^{a}(0.25)
Poplar	56.41^{a}(6.66)	8.31^{a}(0.60)	6.69^{a}(0.32)
Aff-Con	60.26^{a}(4.72)	7.35^{a}(0.51)	8.28^{b}(0.87)
Native	73.93^{a}(2.52)	8.25^{a}(0.36)	8.97^{b}(0.12)

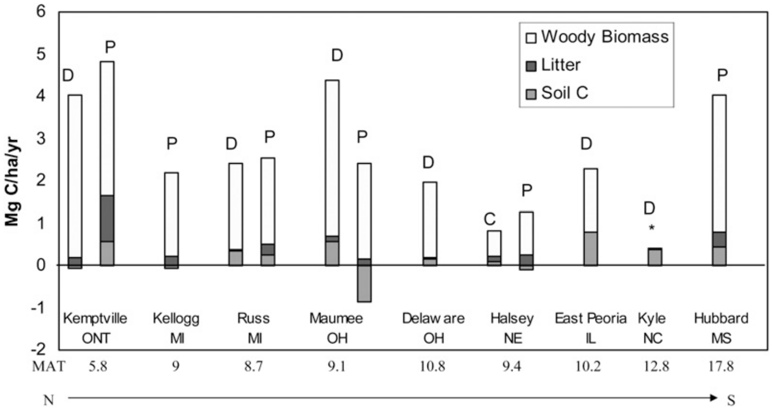

FIG. 1. Change in site C (Mg/ha/yr) for each compartment measured (soil, litter and woody biomass) following afforestation from North American sites listed from north to south along a gradient of increasing mean annual temperatures (MAT). Soils were sampled to 1 m with exception[a]. Litter was collected in each plot adjacent to soil sampling locations. Woody Biomass (above ground, understory, and roots) were determined by estimating tree biomass and using conversion factors of Birdsey (1992) to convert to total woody biomass C (D= deciduous, P=pine, C = cedar). [a]ONT was sampled to 60 cm, NC to 50 cm, IL to 20 cm, MI to 10 cm. *No woody biomass data was obtained.

Our goal was not to just detect patterns, but to understand dynamics that contribute to C accrual. On the more northern sites in our previous studies, the increase in C content was related to Ca on conifer sites, but not on deciduous sites (Paul et al., 2003; Morris et al. 2007). For the more southern sites reported in this study, the MS site had the only conifers and had low C and moderate Ca relative to other sites. The controls on more southern sites may not be similar to those detected on the other sites. This is not surprising as temporal dynamics of litterfall, dormancy, and nutrient turnover differ from north to south as the impacts of seasonal cold are not as apparent. It is also not unique in that local controls on soil C dynamics are likely dictated by differences in the actual soil type and predictions of changes in soil C dynamics must take into consideration the impact of local soil characteristics. For instance the Nebraska site had low soil C accrual. It is on a former grassland with half of the rainfall that occurs on the Eastern forested sites.

Land-use history has a great impact on C dynamics. While C gains were considerable on the MS pine stand the pasture had greater accrual suggesting vegetation and time since land use change are significant contributors to soil C change. The agricultural soils of the IL site are also of significance in terms of understanding soil C dynamics. There were two agricultural fields sampled on the same farm. The two fields had significantly different pH values and the second field had twice the Ca of the first field. When considered in the light of afforestation for biofuels or SOC sequestration, differences in soil nutrient content before planting have the potential to translate into great differences in the C content and stability of soil organic C. The difference in MS attributable to the pasture further highlights the need for investigating SOC and SON accrual under grasses such as those presently being examined for biofuel production.

Management for soil C sequestration together with management strategies to increase production of biofuel plantations would help global C balance without sacrificing agricultural lands with capacity for food production. Sites such as those we investigated are perfect for this use because most are currently managed as plantations; however, attention to soils is often not a priority. We suggest that in addition to accounting for above-ground C gains and losses in any forest plantation being used for C management, managers use standardized soil testing services for possible amelioration of low site fertility with nutrients, such as Ca, which may aid in rates of C accrual. Nitrogen appears to be taken care of by precipitation and possible ammonia absorption.

Our studies demonstrate that while northern soils have some similarities and predictable patterns based on nutrients the same factors are not operating on the more southern soils. Soils across the MAT gradient of sites sampled accrued C. Climate change should not alter the capacity for ecosystems to gain C. However when generalizing about C gains local effects (vegetation, nutrient status, texture, history) have great impacts on C content and C gains. This should be considered when modeling SOC dynamics for global climate scenarios.

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