Calculation of organic matter and nutrients stored in soils under contrasting management regimes

B. H. Ellert[1] and J. R. Bettany[2]

[1]*Agriculture and Agri-Food Canada, Research Centre, P.O. Box 3000, Lethbridge, Alberta, Canada T1J 4B1;*
[2]*Department of Soil Science, University of Saskatchewan, Saskatoon, Saskatchewan, Canada S7N 5A8.*
Received 20 April 1994, accepted 3 May 1995.

Ellert, B. H. and Bettany, J. R. 1995. **Calculation of organic matter and nutrients stored in soils under contrasting management regimes.** Can. J. Soil Sci. **75**: 529–538 Assessments of management-induced changes in soil organic matter depend on the methods used to calculate the quantities of organic C and N stored in soils. Chemical analyses in the laboratory indicate the concentrations of elements in soils, but the thickness and bulk density of the soil layers in the field must be considered to estimate the quantities of elements per unit area. Conventional methods that calculate organic matter storage as the product of concentration, bulk density and thickness do not fully account for variations in soil mass. Comparisons between the quantities of organic C, N, P and S in Gray Luvisol soils under native aspen forest and various cropping systems were hampered by differences in the mass of soil under consideration. The influence of these differences was eliminated by calculating the masses of C, N, P and S in an "equivalent soil mass" (i.e. the mass of soil in a standard or reference surface layer). Reassessment of previously published data also indicated that estimates of organic matter storage depended on soil mass. Appraisals of organic matter depletion or accumulation usually were different for comparisons among element masses in an equivalent soil mass than for comparisons among element masses in genetic horizons or in fixed sampling depths. Unless soil erosion or deposition had altered the mass of topsoil per unit area, comparisons among unequal soil masses were unjustified and erroneous. For management-induced changes in soil organic matter and nutrient storage to be assessed reliably, the masses of soil being compared must be equivalent.

Key words: Soil carbon, soil nitrogen, soil phosphorus, soil sulfur, carbon cycle, carbon storage, bulk density effects, Gray Luvisol, soil erosion

Ellert, B. H. et Bettany, J. R. 1995. **Calcul de la matière organique et des nutriments emmagasinés dans les sols conduits selon des régimes différents.** Can. J. Soil Sci. **75**: 529–538. L'évaluation des modifications de la matière organique du sol liées au mode de conduite dépend des méthodes utilisées pour calculer les quantités de C et de N organiques emmasinées dans le sol. Les analyses chimiques en laboratoire fournissent les concentrations des éléments présents dans le sol, mais on doit tenir compte de l'épaisseur et de la densité apparente des divers horizons, lorsqu'on veut évaluer la quantité de ces éléments par unité de surface. Les méthodes classiques, qui calculent les quantités de matière organique emmagasinées d'après des concentrations ainsi que d'après la densité apparente et l'épaisseur du sol, ne prennent pas pleinement en compte les variations touchant la masse du sol. Les comparaisons entre les quantités de C, N, P et S organique dans des Luvisol gris sous tremblaie naturelle et sous divers systèmes culturaux étaient gênées par les différences de masse de sol utilisées.L'effet de ces différences était éliminé en calculant les masses de C, N, P et S dans une masse de sol équivalente, c'est-à-dire la masse du sol dans une couche de surface standard ou témoin. Une réévaluation des données publiées a permis également de montrer que les calculs de la matière organique emmagasinée dépendent de la masse du sol. Les calculs des pertes ou de l'accumulation de matière organique différaient dans l'ensemble selon que les comparaisons portaient sur la masse des éléments mesurés dans une masse de sol équivalente ou dans des horizons génétiques ou dans une profondeur d'échantillonnage fixe. Sauf là où l'érosion du sol ou les dépôts de sol avaient modifié la masse de la couche arable par unité de surface, les comparaisons entre masses de sol inégales ne se justifiaient pas et étaient faussées. Pour pouvoir évaluer de façon fiable les modifications des quantités de matière organique et des nutriments liées aux modes de conduite du sol, il est nécessaire que les masses de sol comparées soient équivalentes.

Mots clés: Carbone, azote, phosphore, soufre du sol, cycle du carbone, stockage du carbone, densité apparente, Luvisol gris, érosion du sol

The impact of management on soil organic matter has been researched extensively because organic matter is the primary reservoir of N, S and other essential nutrients, and it interacts with mineral components to determine aggregation and other soil properties. More recently, soil organic matter has been recognized as an important source and sink in the global carbon cycle. Since soils contain about three times as much C as the atmosphere, the balance between inputs and outputs of C to the soil has a critical influence on the concentration of atmospheric CO_2 and, possibly, global climate (Post et al. 1990).

Both biotic and geomorphic processes contribute to changes in organic C stored in soils under contrasting management regimes. Biotic processes dictate the balance between inputs of photosynthetically fixed C and outputs of CO_2 from decomposition of soil organic matter. Management-induced changes in soil organic matter usually are attributed to differences in the amount, placement and composition of organic residues returned to the soil, and to changes in the environment (i.e. temperature, moisture, accessibility of energy sources) of the soil organisms. The influence of geomorphic processes on soil organic matter

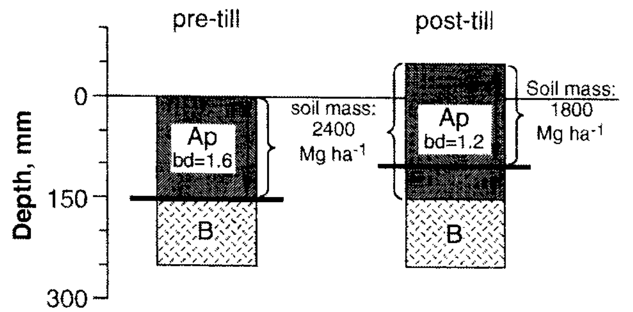

Figure 1. Tillage-induced changes in soil horizonation, bulk density and mass: tillage increases the thickness per unit area (i.e. volume) occupied by the same mass of soil and organic C, thus misinterpretations are inevitable for calculations based on the fixed 0- to 150 mm layer (indicated by the double arrow) and quite likely for calculations based on identification of the boundary between the Ap and B horizons.

has received less attention. Soil erosion may not explain large losses of C on a regional scale (Schlesinger 1986), but has a major impact on redistribution of organic C within ecosystems (Slater and Carleton 1938; De Jong and Kachanoski 1988).

The impacts of management on soil organic matter are well documented, but the impacts of methods used to calculate amounts of organic matter stored in soils are equally important and inadequately documented. Various methods have been used to calculate the organic matter, C, N, P, S or carbonate status of soils. Amounts of organic matter or C were expressed simply as concentrations (kg C/Mg soil) in most publications before 1970 (e.g. Alway and Trumbull 1910; Newton et al. 1945; Davidson et al. 1967). Although soil organic matter storage does increase with concentration, estimates in more recent publications account for the simple fact that storage of soil organic matter and nutrients per unit area or volume increase with concentration as well as soil bulk density and thickness.

Recognizing the dependence of organic matter storage on soil thickness and bulk density, most researchers now calculate soil organic matter and nutrient storage as the product of concentration, soil bulk density and soil thickness (e.g. Tiessen et al. 1982; Aguilar et al. 1988). This calculation method, although widely used, still is insufficient for assessing soil organic matter storage. As will be discussed, this method fails to account for the influence of soil mass on estimates of organic matter and nutrient storage.

Consider the amount of soil organic C in a soil before and after tillage without any gains or losses of soil or C (Fig. 1). The assumed concentration remains constant at 2% or 20 kg C Mg^{-1} soil. Before tillage the soil has a bulk density of 1.6 Mg m^{-3}, such that the 0 to 150 mm layer consists of 2400 Mg soil ha^{-1} and contains 48 Mg C ha^{-1}. Then consider the impact of a single tillage operation that decreases soil bulk density to 1.2 Mg m^{-3} without changing the soil C concentration or causing lateral redistribution of the soil (Fig. 1). The 0 to 150 mm layer, which now begins 50 mm above the original surface, consists of 1800 Mg soil ha^{-1} and contains 36 Mg C ha^{-1} or 25% less than present before tillage, despite the fact that organic matter has not been decomposed to CO_2 or eroded from the field. The masses of soil and organic C in the genetic Ap horizon remained unchanged, but accurate identification of horizon boundaries in the field is difficult at best. Consequently, the impacts of management (a single tillage operation in this hypothetical instance) on soil organic C storage will be misinterpreted.

The objectives of this study are to examine various methods for calculating soil nutrient storage, and to assess how the mass of soil under consideration may influence the interpretation of comparative data. We discuss the influence of soil thickness and mass on estimates of organic C, N, P and S stored in native and cultivated Gray Luvisols at a site in central Saskatchewan. In addition, we reassess previously published data on management–induced changes in soil organic matter at several sites in North America and elsewhere.

MATERIALS AND METHODS

Study site and soils

The study site was situated near Star City, Saskatchewan (52°48'N, 104°21'W), about 175 km northeast of Saskatoon. The soils were from the grassland–forest ecotone where cultivated farmland is interspersed with patches of trees. The soils are Orthic Gray Luvisols developed under forest vegetation on moderately calcareous, medium textured parent materials. The study site is nearly level (0.5–2.5% slope), and soils were sampled from level areas where erosion appeared to be minor.

Seven soil profiles were sampled at the study site, including: two under native **aspen forest** (**F1** and **F2**) which represent the soils prior to clearing for agriculture; one under a **recently cleared plot** (**RC**) that had been plowed to loosen roots and rocks, and to mix the LFH layer and Ae horizon; one profile under **long–term pasture** (**PA**) that remained uncultivated since clearing; one under an **alfalfa/oilseed rotation** (**AO**) with alfalfa harvested as forage for 7 to 10 yr periods; and two profiles under long–term **wheat/fallow rotations** (**WF1** and **WF2**). The profiles differed with respect to vegetation, years of cultivation and frequency of summer fallow (Table 1).

Modal soil profiles were sampled by genetic horizon from pits excavated in June 1985. A volumetric sampler was used to measure bulk density of the organic layers and surface horizons surrounding the sampling pits. Subsequent sampling indicated that the influence of management on soil bulk density did not extend below 200 mm, and that the mean bulk density of the subsurface horizons was approximately 1.5 Mg m^{-3}.

Analyses for C, N, S and P were performed on finely ground subsamples (< 150 µm). Methods used to determine total and inorganic C, N, S, P, and sulfate–S are outlined in Roberts et al. (1989). Organic C, N, S, P, and sulfate–S were calculated as differences between the concentrations of total and inorganic elements.

Calculations

Element concentrations (kg Mg^{-1}) were obtained directly from chemical analyses. Element masses in genetic horizons

Table 1. Management histories of the Gray Luvisol soils at the study site

Management	Profile abbreviation[z]	Dominant vegetation	Years cultivated	Fallow[y] frequency
Forest 1	F1	Aspen (*Populus tremuloides* Michx.)	0	0
Forest 2	F2	Aspen (*Populus tremuloides* Michx.)	0	0
Recently cleared	RC	Fallow[y] with sparse weeds	2	2 yr
Pasture	PA	Bluegrass (*Poa pratensis* L.)	≈85	0
Alfalfa/oilseed	AO	Alfalfa (*Medicago sativa* L.)	≈81	1 yr in 8
		Flax (*Linum usitatissimum* L.)		
		Canola (*Brassica napus* L.)		
Wheat/fallow 1	WF1	Wheat (*Triticum aestivum* L.)	≈81	1 yr in 2
Wheat/fallow 2	WF2	Wheat (*Triticum aestivum* L.)	≈81	1 yr in 2

[z]Horizon designations are appended to the profile abbreviations to identify specific soil layers, otherwise soils are from the surface horizons.
[y]Fallow refers to tillage which prevents plant growth throughout an entire growing season.

($Mg\ ha^{-1}$) were calculated from the thicknesses and bulk densities of the horizons:

$$M_{element} = conc \cdot \rho_b \cdot T \cdot 10\,000\ m^2\ ha^{-1} \cdot 0.001\ Mg\ kg^{-1} \quad (1)$$

where:

$M_{element}$ = element mass per unit area ($Mg\ ha^{-1}$)

conc = element concentration ($kg\ Mg^{-1}$)
ρ_b = field bulk density ($Mg\ m^{-3}$)
T = thickness of soil layer (m)

Area–based estimates of elements ($Mg\ ha^{-1}$) generally have been regarded as the most appropriate means to describe standing stocks of elements in soils and other ecosystem pools (Schlesinger 1986; Davidson and Ackerman 1993), but few authors consider the relative mass of the soils being compared:

$$M_{soil} = \rho_b \cdot T \cdot 10\,000\ m^2\ ha^{-1} \quad (2)$$

where:

M_{soil} = soil mass per unit area ($Mg\ ha^{-1}$)

Ideally, management–induced changes in organic matter can be assessed from comparisons among similar soils (i.e. identical original thickness, bulk density, texture) with contrasting management histories. Thus, management effects can be inferred simply from changes in element concentrations in the surface horizons, provided that changes in horizon thickness exactly compensate for changes in bulk density, such that soil masses are identical. In practice, however, management obliterates the genetic horizons, and alters the masses of the surface horizons (Fig. 2). At Star City the LFH layer, A horizon and top portion of the B horizon were mixed to form an Ap horizon.

To account for different soil masses, we calculated the amounts of C, N, P or S ($Mg\ ha^{-1}$) in an identical or "equivalent" mass of soil under contrasting management regimes. The mass of the heaviest soil layer which was most susceptible to the influence of management was designated as the "equivalent" mass. As will be discussed, the actual value selected as the equivalent mass was less important than the fact that the same standard or reference soil mass was used for comparisons of organic matter and nutrient storage at each particular study site. The additional soil thickness required to attain this equivalent mass in lighter soil layers was calculated as follows:

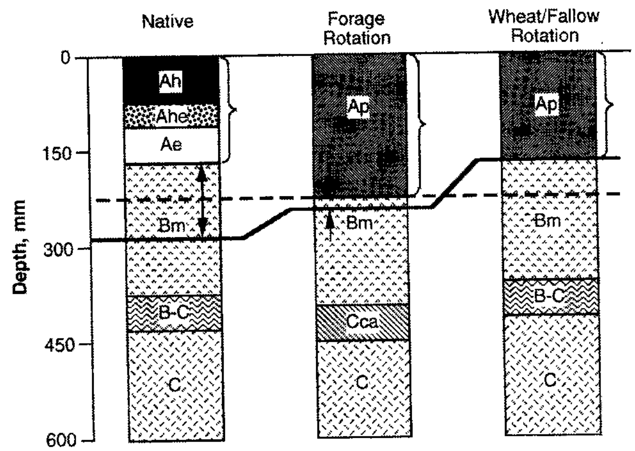

Figure 2. Schematic illustrations of methods to calculate the element status of soils under contrasting management regimes: brackets indicate layers for comparisons between genetic A horizons; the dashed line indicates layers compared for a fixed sampling depth; the solid line indicates layers compared for an equivalent mass of soil, and the arrows indicate the additional layer required to attain the equivalent soil mass.

$$T_{add} = \frac{(M_{soil,\ equiv} - M_{soil,\ surf}) \cdot 0.0001\ ha\ m^{-2}}{\rho_{b\ subsurface}} \quad (3)$$

where:

T_{add} = additional thickness of subsurface layer required to attain the equivalent soil mass (m)
$M_{soil,\ equiv}$ = equivalent soil mass = mass of heaviest horizon ($Mg\ ha^{-1}$)
$M_{soil,\ surf}$ = sum of soil mass in surface layer(s) or genetic horizon(s) ($Mg\ ha^{-1}$)
$\rho_{b\ subsurface}$ = bulk density of subsurface layer ($Mg\ m^{-3}$)

Masses of elements per unit area in an equivalent soil mass were calculated by summing the elements in surface layers or horizons, plus those in the additional thickness of subsurface layer required to attain the equivalent soil mass:

Table 2. Element status of surface soils from Star City expressed as concentrations, masses per hectare in the genetic horizons, masses per hectare to a fixed depth, and masses per hectare in an equivalent mass of surface soil

Management	Thickness (mm)	Soil mass (Mg ha^{-1})	Organic forms of nutrients C	N	P	S	Sulfate-S	Total P	Total S
			Concentrations (kg Mg^{-1})						
Forest 1 LFH			181.6	10.35	0.62	1.00	0.240	1.01	1.02
Forest 1 Ae			11.1	0.92	0.11	0.09	0.033	0.56	0.09
Forest 2 LFH			281.1	13.61	0.78	1.34	0.343	1.18	1.37
Forest 2 Ae			5.1	0.44	0.07	0.05	0.016	0.54	0.05
Recently cleared			31.0	1.76	0.14	0.20	0.055	0.60	0.21
Pasture			22.4	1.80	0.23	0.20	0.083	0.58	0.21
Alfalfa/oilseed			24.2	1.94	0.19	0.20	0.091	0.64	0.21
Wheat/fallow 1			22.2	1.84	0.22	0.19	0.079	0.62	0.20
Wheat/fallow 2			20.7	1.61	0.19	0.16	0.067	0.52	0.17
coeff. of variation			146%	124%	86%	120%	103%	34%	119%
			Element masses in genetic horizons (Mg ha^{-1})						
Forest 1 LFH+Ae	180	1199	45.9	2.91	0.23	0.28	0.08	0.76	0.29
Forest 2 LFH+Ae	320	3155	58.1	3.39	0.32	0.35	0.10	1.79	0.37
Recently cleared	150	1800	55.7	3.17	0.26	0.37	0.10	1.09	0.37
Pasture	180	2340	52.4	4.22	0.53	0.48	0.19	1.36	0.49
Alfalfa/oilseed	150	1800	43.5	3.50	0.34	0.37	0.16	1.15	0.37
Wheat/fallow 1	150	1920	42.7	3.53	0.43	0.36	0.15	1.20	0.38
Wheat/fallow 2	160	2208	45.7	3.56	0.42	0.36	0.15	1.15	0.38
coeff. of variation			13%	12%	29%	16%	31%	26%	16%
			Element masses to a fixed depth (Mg ha^{-1})						
Forest 1 + LFH[z]	280	2699	54.1	3.80	0.43	0.38	0.13	1.32	0.40
Forest 2 + LFH[z]	290	2726	55.9	3.20	0.30	0.33	0.09	1.56	0.34
Recently cleared	180	2250	57.3	3.42	0.28	0.39	0.11	1.28	0.41
Pasture	180	2340	52.4	4.22	0.53	0.48	0.19	1.36	0.49
Alfalfa/oilseed	180	2250	45.7	3.73	0.39	0.40	0.18	1.33	0.40
Wheat/fallow 1	180	2370	44.7	3.76	0.48	0.39	0.16	1.37	0.41
Wheat/fallow 2	180	2508	46.9	3.78	0.45	0.38	0.16	1.26	0.41
coeff. of variation			10%	9%	23%	11%	26%	7%	10%
			Element masses in equivalent soil mass (Mg ha^{-1})						
Forest 1	256	2340[y]	52.1	3.59	0.38	0.36	0.12	1.19	0.37
Forest 2	263	2340	53.9	3.03	0.27	0.31	0.09	1.35	0.32
Recently cleared	186	2340	57.6	3.47	0.29	0.40	0.11	1.32	0.42
Pasture	180	2340	52.4	4.22	0.53	0.48	0.19	1.36	0.49
Alfalfa/oilseed	186	2340	46.2	3.77	0.40	0.40	0.18	1.36	0.41
Wheat/fallow 1	178	2340	44.6	3.75	0.48	0.39	0.16	1.36	0.41
Wheat/fallow 2	169	2340	46.2	3.66	0.43	0.37	0.15	1.20	0.39
coeff. of variation			9%	10%	24%	13%	28%	6%	12%

[z] The forest profiles include 180 mm of mineral soil plus the LFH layer.

[y] The Ahe horizon of the Pasture profile was designated as the "equivalent soil mass" (2340 Mg ha^{-1}), and the thickness of Bt horizon required to attain 2340 Mg ha^{-1} in each of the other six profiles was used to calculate the quantity of element in the equivalent soil mass.

$$M_{\text{element, equiv}} = M_{\text{element, surf}} + M_{\text{element, Tadd}} \quad (4)$$

where:

$M_{\text{element, equiv}}$ = element mass per unit area in an equivalent soil mass (Mg ha^{-1})

$M_{\text{element, surf}}$ = sum of element mass in surface layer(s) Mg ha^{-1})

$M_{\text{element, Tadd}}$ = element mass in the additional subsurface layer (Mg ha^{-1})

Amounts of soil organic C, N, S and P at the Star City site were expressed as concentrations (kg Mg^{-1}), mass per unit area in genetic horizons (Mg ha^{-1}), mass per unit area to a fixed depth of 180 mm (the depth of the original A horizon), and mass per unit area in an equivalent soil mass. The additional thickness required to attain 180 mm was obtained by subtraction, and element mass in the fixed depth increment was calculated as the sum of those in the surface layer(s) plus the additional thickness. Published data were re-analyzed to assess the merits of quantifying nutrient status as element masses in an equivalent soil mass.

RESULTS AND DISCUSSION

Concentrations and masses per unit area of C, N, P and S in the surface soils varied widely among contrasting profiles (Table 2). The surface layers were most relevant to assess the impact of management on nutrient status, because surface soils were modified directly by cultivation. Concentrations in the LFH layers were much greater than those in the mineral

Table 3. Effect of method used to express nutrient status on comparisons between the native and cultivated soils investigated by Tiessen and co-workers (1982)

Management, years of cultivation	Thickness (mm)	Bulk density[z] (Mg m^{-3})	Soil mass (Mg ha^{-1})	Organic C Content	Organic C Decrease[y]	Total N Content	Total N Decrease
				Concentration (kg Mg^{-1})			
Blaine Lake Native				47.9		4.42	
Blaine Lake 4 yr				49.0	-1.1	4.39	0.03
Blaine Lake 60 yr				32.8	15.1	2.91	1.51
Blaine Lake 90 yr				20.0	27.9	2.18	2.24
Sutherland Native				37.7		3.04	
Sutherland 70 yr				23.7	14.0	2.50	0.54
Bradwell Native				32.2		3.28	
Bradwell 65 yr				17.4	14.8	1.76	1.52
				Genetic A Horizon (Mg ha^{-1})			
Blaine Lake Native	108	1.04	1123	53.8		4.96	
Blaine Lake 4 yr	133	1.04	1383	67.8	-14.0	6.07	-1.11
Blaine Lake 60 yr	145	1.22	1769	58.0	-4.2	5.15	-0.19
Blaine Lake 90 yr	90	1.30	1170	23.4	30.4	2.55	2.41
Sutherland Native	180	0.98	1764	66.5		5.36	
Sutherland 70 yr	180	1.28	2304	54.6	11.9	5.76	0.40
Bradwell Native	148	1.07	1584	51.0		5.19	
Bradwell 65 yr	138	1.45	2001	34.8	16.2	3.52	1.67
				Equivalent mass (Mg ha^{-1})			
Blaine Lake Native	157		1769[x]	63.8		6.03	
Blaine Lake 4 yr	161		1769	74.8	-11.0	6.76	-0.73
Blaine Lake 60 yr	145		1769	58.0	5.8	5.15	0.88
Blaine Lake 90 yr	133		1769	30.2	33.6	3.23	2.80
Sutherland Native	225		2304[w]	78.7		6.63	
Sutherland 70 yr	180		2304	54.6	24.1	5.76	0.87
Bradwell Native	200		2304	60.1		6.12	
Bradwell 65 yr	159		2304	38.1	22.0	3.86	2.26

[z]Bulk density of the A horizon.
[y]Refers to the decrease in cultivated soils relative to native counterparts (negative values indicate increases in cultivated relative to native soils).
[x]The A horizon which had been cultivated for 60 yr (greatest mass) was designated as the equivalent soil mass for comparisons among Blaine Lake soils.
[w]The cultivated A horizon of the Sutherland profile was designated as the equivalent soil mass for comparisons among Sutherland and Bradwell soils.

soils, and were smallest in the leached Ae horizons. Concentrations indicated element distribution within the profiles, but estimation of element mass per unit area required consideration of the physical dimensions of individual horizons in the profiles.

Element Masses (Mg ha^{-1}) in Genetic Horizons

Thicknesses of genetic horizons are dictated by profile morphology. Sampling by genetic horizon is justified when differences in profile morphology coincide with sharp changes in element concentration within the profile. At the Star City site, concentrations changed sharply with depth in profiles under native vegetation and in cultivated profiles with distinct Ap horizons. Element masses in the forest LFH and Ae horizons were summed because the two layers were combined in the other profiles (Table 2). Variability among element masses in surface soils of contrasting profiles was far less than variability among element concentrations, because low bulk densities compensated for high concentrations in the LFH layers.

Masses of soil in genetic horizons at the surface of the profiles varied according to the horizon thicknesses and bulk densities, and ranged from 1199 to 3155 Mg ha^{-1} (Table 2). Despite the small forest litter masses (150–190 Mg ha^{-1}), the LFH layers contained considerable masses of organic C, N, S and P. Differences among the masses of genetic horizons obscured the influence of cultivation on masses of elements per unit area. The dependence of the element masses on the soil mass was especially evident for total P

(total P = 0 + 0.00058 · soil mass, $R^2 = 0.996$, $P < 0.0001$), indicating that variability in total P was attributable to differences in soil mass rather than management.

Element Masses (Mg ha^{-1}) in a Fixed Sampling Depth

Element masses were calculated for the 0 to 180 mm thickness of mineral soils at the surface of the profiles (Table 2). The 0- to 180-mm thickness included the layers most influenced by management. Elements in the forest LFH layers were added to those in the surface 180 mm of mineral soil, because the litter had been mixed into the mineral soil at the surfaces of the other profiles. The soil masses contained in the fixed sampling depth were uniform (cv. = 8%, compared with 29% for masses of the genetic horizons), because the forest soil masses included 180 mm of mineral soil and the other surface soils had similar bulk densities (1.20–1.38 Mg m^{-3}). Since the soil masses were uniform, element masses in the fixed depth were less variable than those contained in the genetic horizons (Table 2).

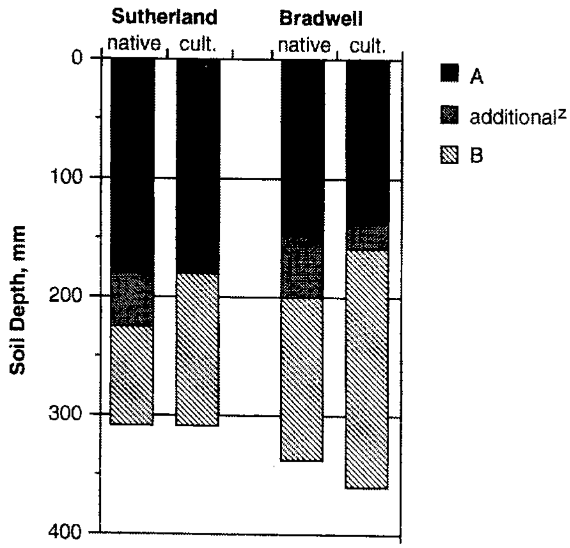

Figure 3. Thicknesses of genetic horizons and of layers required to attain the equivalent soil mass in native and cultivated profiles of the Sutherland and Bradwell soils studied by Tiessen et al. (1982). [z]additional = layer of B horizon required to attain the equivalent soil mass.

Element Masses (Mg ha^{-1}) in an Equivalent Soil Mass

The mass of the surface horizon of the PA profile (2340 Mg ha^{-1}) was designated the equivalent soil mass (Table 2). The surface layers (LFH + Ae) of the F2 profile had the greatest soil mass and thickness, but the mass and thickness of the surface layer of the PA profile were more representative of the other profiles. Selection of the equivalent soil mass, like selection of the fixed sampling depth, is somewhat arbitrary, but it must be identical for all profiles being compared and include the soil layer most susceptible to the influence of management. Differences in horizonation among study sites may justify the use of unique soil masses for each study, but evaluation of management impacts requires that soils at each site originally were comparable.

Element masses in the equivalent mass of surface soil were less variable than those in the genetic horizons, because variability caused by unequal soil masses was eliminated. The remaining variability among element masses originated from management impacts and unmeasured sources of error. The coefficients of variation for total P in the contrasting profiles were 34% for concentration, 26% for mass in genetic horizons, 7% for mass in the fixed depth, and 6% for mass in the equivalent soil mass (Table 2). The greater variability among the masses of organic C, N, P, S and sulfate in the equivalent soil mass indicated that management had a greater impact on elements in the organic fraction than on total P.

The mass of organic C in the soil thickness required to attain 2340 Mg soil ha^{-1} was less in the cultivated soils (46 ± 0.9 Mg C ha^{-1} in WF1, WF2, AO soils) than in soils that were not subjected to annual tillage (54 ± 2.5 Mg C ha^{-1} in F1, F2, RC, and PA soils) (Table 2). The loss of organic C from the equivalent soil mass after ≈ 80 yr of cultivation was 8 Mg ha^{-1} or about 15% of the C originally present. The mass of organic sulfate–S increased from an average of 0.10 Mg ha^{-1} in the F1, F2 and RC soils to 0.17 Mg ha^{-1} in the agricultural soils (PA, AO, WF1, WF2). Relationships between cultivation and masses of organic N, S and P in contrasting soils were unclear, but the PA soil accumulated the greatest nutrient masses (Table 2).

Nutrient storage was also calculated for the equivalent mass of subsoil (2340 Mg soil ha^{-1}) immediately below the equivalent mass of surface soil (data not shown). The amounts of C and N stored in the subsurface equivalent mass were about 20% of those stored in the surface equivalent soil mass, but differences associated with management were not apparent.

Reassessment of Previously Published Data

Reassessment of management–induced changes in soil organic matter indicated that comparisons among unequal soil masses influenced estimates of nutrient depletion. In the Chernozemic soils studied by Tiessen et al. (1982) cultivation increased bulk densities and soil masses of the genetic (Ap) horizons. Estimates of C and N depletion, therefore, were greater for comparisons between elements in an equivalent soil mass than those in genetic horizons (Table 3). The Ap horizon of the Blaine Lake soil which had been cultivated for 60 yr gained about 4 Mg C ha^{-1}, but 6 Mg C ha^{-1} was lost from the equivalent soil mass. Discrepancies between element depletion in genetic horizons and equivalent masses were especially obvious in the Sutherland and Bradwell soils. Since cultivation mixed some B horizon into the Ap, element masses in the portions of B horizon needed to attain equivalent soil mass were added to element masses in the A horizons of native profiles (Fig. 3).

Reassessment of data from several studies of management–induced decreases in soil organic C and N indicated that the decreases usually were greater when comparisons were between equivalent soil masses rather than genetic horizons or fixed sampling depths (Tables 4 and 5). Uncultivated soils tended to have lower bulk densities so that thicker soil layers were required to attain the equivalent soil mass in uncultivated compared to cultivated soils. Differences between element depletion in the equivalent mass and genetic horizons were large when the genetic horizons under consideration had different thicknesses (e.g. grassland soils in South Dakota and Missouri, Table 5). When soils under contrasting management had similar thicknesses and bulk densities, the decreases in C were similar regardless of the method used to calculate soil C (e.g. sandy loam in Ontario, Table 5).

Estimates of C and N stored in the surfaces of no–till and plowed soils also were influenced by the method used to calculate element status (Table 6). Doran (1987) reported that the surfaces of no–till soils contained more C and N than plowed soils. Reassessment of the data showed that the plowed soils (except for wheat on soil D in NB) had slightly lower bulk densities so that a greater thickness was required to attain the equivalent soil mass. Consequently the differences between C and N stored in no–till and plowed

Table 4. Influence of methods to express soil carbon and nitrogen on the interpretation of management-induced changes in soil organic matter

	C & N in sampled depth						C & N in an equivalent soil mass			
Management	Concentrations (kg C Mg^{-1})	Concentrations (kg N Mg^{-1})	Thickness (mm)	Soil Mass (Mg ha^{-1})	C Mass (Mg ha^{-1})	N Mass (Mg ha^{-1})	Thickness (mm)	Soil Mass (Mg ha^{-1})	C Mass (Mg ha^{-1})	N Mass (Mg ha^{-1})
Grassland soils (Rendzina), Texas (Laws and Evans, 1949)[z]										
Virgin IA	30.2	2.70	152	1583	47.8	4.27	190	2011	56.2	4.92
Cultivated IA	16.2	1.60	152	1466	23.8	2.35	201	2011	30.8	3.22
Decrease	**13.9**	**1.10**			**23.9**	**1.93**			**25.4**	**1.70**
Virgin IB	32.5	1.60	152	1684	54.7	2.69	181	2011	62.7	3.15
Cultivated IB	16.8	1.60	152	2011	33.8	3.22	152	2011	33.8	3.22
Decrease	**15.7**	**0.00**			**20.9**	**-0.52**			**28.8**	**-0.07**
Podzols and Gleysols, Quebec (Martel et Deschenes, 1976)										
Virgin Kamouraska Ah-Aeg	67.0	2.80	170	2380	159.5	6.66	188	2720	160.9	6.85
Cultivated Kamouraska Ap	37.0	2.30	170	2720	100.6	6.26	170	2720	100.6	6.26
Decrease	**30.0**	**0.50**			**58.8**	**0.41**			**60.2**	**0.59**
Virgin, Charlevoix L-H+Ae-Bfl[1y]			190	1608	99.0	4.90	283	2720	114.6	5.01
Cultivated Charlevoix Ap	37.0	2.20	150	1410	52.2	3.10	259	2720	74.4	4.23
Decrease					**46.9**	**1.79**			**40.2**	**0.78**
Virgin Greensboro Ah-Ae	103.0	7.80	70	420	43.3	3.28	262	2720	82.4	6.96
Cultivated Greensboro Ap	24.0	2.00	170	2040	49.0	4.08	222	2720	53.3	4.66
Decrease	**79.0**	**5.80**			**-5.7**	**-0.80**			**29.0**	**2.29**

[z]Bulk density was estimated from total porosity estimated by pressure pycnometer and an assumed particle density of 2.65 Mg m^{-3}; [Organic C] was calculated from [Organic Matter]/1.724.
[y]C and N concentrations are reported separately for the L-H and AeBfl layers in Martel and Deschenes (1976).

Table 5. Influence of methods to express soil carbon on the interpretation of management-induced changes in the storage of carbon in surface soils

	C in sampled depth			C in equivalent soil mass		
Management	Thickness (mm)	Soil mass (Mg ha^{-1})	C mass (Mg ha^{-1})	Thickness (mm)	Soil mass (Mg ha^{-1})	C mass (Mg ha^{-1})
Grassland soils (Borolls), South Dakota (Blank and Fosberg 1989)[z]						
Virgin	150	1995	69.8	202	2826	78.1
Cultivated	180	2826	73.5	180	2826	73.5
Decrease			**-3.7**			**4.7**
Tallgrass Prairie soils (Borolls), Missouri (Buyanovsky et al. 1987)[y]						
Prairie	250	3095	72.3	299	3790	80.8
Winter Wheat	280	3790	54.2	280	3790	54.2
Decrease			**18.2**			**26.7**
Tallgrass Prairie soils (Udolls), Oklahoma (Davidson et al. 1967)[y x]						
Perennial Forage	203	3022	28.3	216	3220	30.0
Continuous Cotton	203	3220	20.2	203	3220	20.2
Decrease			**8.1**			**9.8**
Grassland soils (Borolls), Nebraska (Doran 1987)						
Native Sod	150	1755	33.8	167	2070	36.7
SubTilled Wheat	150	2070	30.4	150	2070	30.4
Decrease			**3.4**			**6.3**
Brunisols and Gleysols, Ontario(Coote and Ramsey 1983)						
Untilled sandy loam	200	2630	64.5	229	3040	69.5
Tilled sandy loam	200	2790	71.0	217	3040	75.8
Decrease			**-6.5**			**-6.3**
Untilled loamy sand	200	2630	56.9	232	3040	62.6
Tilled loamy sand	200	2940	55.6	206	3040	56.5
Decrease			**1.3**			**6.1**
Untilled clay	200	1920	166.0	319	3040	259.8
Tilled clay	200	2240	145.7	268	3040	187.5
Decrease			**20.3**			**72.3**
Untilled clay loam	200	2680	56.1	230	3040	58.7
Tilled clay loam	200	3040	44.8	200	3040	44.8
Decrease			**11.3**			**13.8**
Alfisols, Nigeria (Aina 1979)[y]						
Iwo Grass Pasture	140	1806	39.1	165	2184	42.5
Iwo Cropped & Fertilized	140	2184	9.4	140	2184	9.4
Decrease			**29.7**			**33.1**
Oba Bush	140	1610	25.9	178	2184	29.1
Oba Cropped & Plowed	140	2072	7.6	147	21184	7.7
Decrease			**18.3**			**21.4**

[z]Horizon thickness are for the Williams site (site 1); other data are averages for all six sites.
[y] [Organic C] calculated from [Organic Matter]/1.724.
[x]51 to 127 mm layer assumed to represent 9 to 127 mm layer

Table 6. Influence of methods to express soil carbon and nitrogen on comparisons between the no-till and plowed soils investigated by Doran (1987)

	C & N in sampled depth				C & N in equivalent soil mass			
Management	Thickness (mm)	Soil mass (Mg ha^{-1})	C mass (Mg ha^{-1})	N mass (Mg ha^{-1})	Thickness (mm)	Soil mass (Mg ha^{-1})	C mass (Mg ha^{-1})	N mass (Mg ha^{-1})
Surface Layers								
No-till maize, KY	75	945	21.2	2.17	84	1073	22.6	2.35
Plowed maize, KY	75	893	12.1	1.49	88	1073	14.2	1.75
Decrease			**9.1**	**0.68**			**8.4**	**0.60**
No-till maize, IL	75	1065	13.8	1.28	76	1073	13.9	1.28
Plowed maize, IL	75	975	9.2	1.10	82	1073	10.1	1.20
Decrease			**4.6**	**0.17**			**3.7**	**0.08**
No-till maize, MN	75	975	29.4	2.60	83	1073	32.3	2.86
Plowed maize, MN	75	878	26.3	2.39	91	1073	32.6	2.96
Decrease			**3.2**	**2.20**			**-0.3**	**-0.10**
No-till maize, NB	75	1073	18.8	1.73	75	1073	18.8	1.73
Plowed maize, NB	75	915	13.0	1.19	87	1073	15.3	1.41
Decrease			**5.9**	**0.55**			**3.5**	**0.32**
No-till wheat A, NB	75	968	11.5	1.17	83	1073	12.5	1.29
Plowed wheat A, NB	75	938	9.1	0.90	85	1073	10.3	1.04
Decrease			**2.4**	**0.27**			**2.2**	**0.25**
No-till wheat D, NB	75	803	18.6	1.75	95	1073	22.0	2.10
Plowed wheat D, NB	75	915	13.2	1.40	87	1073	15.4	1.63
Decrease			**5.4**	**0.35**			**6.6**	**0.47**

soils were smaller when an equivalent soil mass was considered. Comparisons between no–till and plowed soils in England indicated no significant differences in soil C and N when differences in soil mass were considered (Powlson and Jenkinson 1981).

Validity of Comparisons among Elements in an Equivalent Soil Mass

Comparisons between native and cultivated profiles or among soils under dissimilar management regimes traditionally have been used to evaluate losses or gains of nutrients associated with cultivation and management (e.g. Lawes and Gilbert 1885; Alway and Trumbull 1910; Newton et al. 1945). The actual comparisons deviated considerably from ideal experiments in which treatments were uniformly imposed on identical soils. Spatial variability among adjacent soils introduced noise to the data, changes in bulk densities rarely compensated for changes in horizon thicknesses, and management altered the masses of the soils being compared (Fig. 2).

Variability among masses of genetic horizons and sola originate from landscape variability and sampling errors, from vertical redistribution by truncation of subsurface horizons or compaction of surface layers, and from lateral redistribution by soil erosion or deposition. Tillage often increases the masses of Ap horizons relative to uncultivated A horizons, because soil from subsurface horizons is mixed into the overlying Ap (Aguilar et al. 1988). To account for soil redistribution, some authors suggested that comparisons be made among organic C in entire sola (Voroney et al. 1981). Sola comparisons, however, obscure management effects that are most pronounced at the surface, and are unreliable indicators of soil redistribution. Recently Davidson and Ackerman (1993) recommended that assessments of soil C be based on genetic horizons rather than fixed depths, but their comparisons of C inventories in cultivated and uncultivated plots were influenced by differences in soil mass.

Comparisons among elements stored in an equivalent soil mass correct for changes in soil mass at sites that are influenced by vertical redistribution or landscape variability (Table 3). Sites with changes in soil mass that are caused by lateral redistribution require estimation of soil erosion and deposition before reliable comparisons of element masses can be made. Explicit assumptions about soil redistribution may justify comparisons among unequal soil masses, but indiscriminate comparisons among unequal soil masses have caused misinterpretations (Tables 4, 5 and 6). Simple comparisons among element masses in horizons or sola of contrasting soils provide only crude estimates of element depletion or accumulation and fail to distinguish between changes caused by geomorphic (erosion, deposition) and biotic (decomposition, photosynthesis) processes. Independent estimates of soil movement (e.g. ^{137}Cesium redistribution) are required to estimate nutrient losses in eroded landscapes (Gregorich and Anderson 1985).

Calculations of element masses in an equivalent soil mass are based on assumed element concentrations and bulk densities. The element concentrations and bulk densities of the entire subsurface horizons were assumed to represent those in the top portions of the horizon required to attain the equivalent soil mass. Concentrations in the portions of B horizon (immediately below the A horizons) likely exceeded the average concentrations for the entire B horizons, but such discrepancies would cause conservative increases in the element masses of light soils relative to heavy soils (i.e. soils near the equivalent mass). Detailed sampling at small depth increments will diminish errors caused by discrepancies between element concentrations in entire horizons and portions thereof.

Previous workers have used similar methods to compensate for the confounding influence of management on the masses of soil in genetic horizons or fixed depths. Nye and Greenland (1964) recognized that comparisons of soil organic matter "... should be based on the same soil mass, or the possible error involved in sampling to a fixed depth clearly recognized." Elaborate methods to account for changes in soil volume and for the mass of organic matter accumulated in the soil also have been considered (Henzell et al. 1967). The method we used to calculate element masses in an equivalent soil mass neglects small contributions of additional organic matter to soil mass, and is similar to the method used by workers at the Rothamsted Experimental Station (Jenkinson and Johnston 1976). These workers blended surface and subsurface soils to obtain samples that represented the same soil mass per hectare, and called their method "equivalent depth sampling" (Ayanaba et al. 1976; Powlson and Jenkinson 1981).

CONCLUSIONS

Assessments of management–induced changes in the quantities of C and other elements stored in soils were influenced by the method used to calculate element status. Comparisons among element concentrations were unreliable, because concentrations did not adequately reflect element masses per unit area or volume. Conventional estimates of element masses in genetic horizons or fixed sampling depths (calculated as the product of concentration, bulk density and thickness) usually resulted in comparisons among unequal soil masses. Such comparisons usually were unjustified, because soil sampling and identification of horizonation in the field were unreliable indicators of soil redistribution.

If soil redistribution was accurately indicated by field sampling procedures, the masses of cultivated soils should have been equal to or, if erosion had occurred, less than those of adjacent soils that had never been cultivated. Published data indicated the opposite: topsoil masses generally were greater for cultivated profiles than for profiles under native vegetation, because cultivation changed soil bulk density and thickness.

The masses of soil organic matter and nutrients stored per unit area or volume obviously were dependent on soil mass. Masses of soil in genetic horizons or fixed sampling depths were determined by haphazard variations in soil thickness and bulk density, whereas the equivalent soil mass corrected for unjustifiable differences in soil masses. In the absence of information on soil erosion or deposition to justify comparisons among unequal soil masses, comparisons among element masses in an equivalent soil mass were more valid. The effects of management on organic matter and nutrient storage were clarified by eliminating the differences attributable to unequal soil masses. The idea that nutrient masses must be normalized for differences in soil mass is not entirely new, but recent publications indicate a serious and persistent lack of awareness about the influence of soil mass on estimates of nutrient storage.

The impact of management on organic matter storage at the Star City site was obscured by differences in soil bulk density and thickness, and consequently, the masses of the genetic horizons. The impact of management was clarified by calculating the amount of organic matter stored in an equivalent soil mass, which indicated that ≈ 15% of soil organic C originally present under forest vegetation was lost after 80 yr of annual cropping. Total P was closely related to soil mass, and comparisons among masses of total P in the equivalent mass of contrasting soils indicated that the impact of management was minor.

Reassessment of published data indicated that bulk densities of native soils often were less than those of cultivated soils, and native A horizons often were lighter than the cultivated Ap horizons. Thus estimates of organic matter depletion in cultivated soils were greater for calculations based on an equivalent mass than for calculations based on genetic horizons or fixed sampling depths. Bulk densities and masses of no–till soils often were greater than those of conventionally tilled soils. Consequently, estimates of organic matter accumulation in no–till soils were smaller for calculations based on an equivalent mass than for calculations based on genetic horizons or fixed sampling depths.

ACKNOWLEDGMENTS

Eric Bremer and Henry Janzen provided constructive comments on the manuscript.

Aguilar, R., Kelly, E. F. and Heil, R. D. 1988. Effects of cultivation on soils in northern Great Plains rangeland. Soil Sci. Soc. Am. J. **52:** 1081–1085.

Aina, P.O. 1979. Soil changes resulting from long–term management practices in western Nigeria. Soil Sci. Soc. Am. J. **43:** 173–177.

Alway, F. J. and Trumbull, R. S. 1910. A contribution to our knowledge of the nitrogen problem under dry farming. J. Indust. Eng. Chem. **2:** 135–138.

Ayanaba, A., Tuckwell, S. B. and Jenkinson, D. S. 1976. The effects of clearing and cropping on the organic reserves and biomass of tropical forest soils. Soil Biol. Biochem. **8:** 519–525.

Blank, R. R. and Fosberg, M. A. 1989. Cultivated and adjacent virgin soils in northcentral South Dakota: I. Chemical and physical comparisons. Soil Sci. Soc. Am. J. **53:** 1484–1490.

Buyanovsky, G. A., Kucera, C. L. and Wagner, G. H. 1987. Comparative analysis of carbon dynamics in native and cultivated ecosystems. Ecology **68:** 2023–2031.

Coote, D. R. and Ramsey, J. F. 1983. Quantification of the effects of over 35 years of intensive cultivation on four field soils. Can. J. Soil Sci. **63:** 1–14.

Davidson, E. A. and Ackerman, I. L. 1993. Changes in soil carbon inventories following cultivation of previously untilled soils. Biogeochemistry **20:** 161–193.

Davidson, J. M., Gray, F. and Pinson, D. I. 1967. Changes in organic matter and bulk density with depth under two cropping systems. Agron. J. **59:** 375–378.

De Jong, E. and Kachanoski, R. G. 1988. The importance of erosion in the carbon balance of prairie soils. Can. J. Soil. Sci. **68:** 111–119.

Doran, J. W. 1987. Microbial biomass and mineralizable nitrogen distributions in no–tillage and plowed soils. Biol. Fertil. Soils **5:** 68–75.

Gregorich, E. G. and Anderson, D. W. 1985. Effect of cultivation and erosion on soils of four toposequences in the Canadian Prairies. Geoderma **36:** 343–354.

Henzell, E. F., Fergus, I. F. and Martin, A. E. 1967. Accretion studies of soil organic matter. J. Aust. Inst. Agric. Sci. **33:** 35–37.

Jenkinson, D. S. and Johnston, A. E. 1976. Soil organic matter in the Hoosfield continuous barley experiment. Pages 87–101 *in*

Rothamsted Experiment Station Report for 1976, Part 2. Harpenden, U.K.
Laws, W. D. and Evans, D. D. 1949. The effects of long–time cultivation on some physical and chemical properties of two Rendzina soils. Soil Sci. Soc. Am. Proc. **14:** 15–19.
Lawes, J. B. and Gilbert, J. H. 1885. On some points in the composition of soils; with results illustrating the sources of the fertility of Manitoba prairie soils. J. Chem. Soc. **XLVII:** 380–422.
Martel, Y. A. et Deschenes, J. M. 1976. Les effets de la mise en culture et de la prairie prolongée sur le carbone, l'azote et la structure de quelques sols due Québec. Can. J. Soil Sci. **56:** 373–383.
Newton, J. D., Wyatt, F. A. and Brown, A. L. 1945. Effects of cultivation and cropping on the chemical composition of some western Canada prairie province soils. Part III. Sci. Agric. **25:** 718–737.
Nye, P. H. and Greenland, D. J. 1964. Changes in the soil after clearing tropical forest. Plant Soil **21:** 101–112.
Post, W. M., Peng, T–H., Emanuel, W. R., King, A. W., Dale, V. H. and DeAngelis, D. L. 1990. The global carbon cycle. Am. Sci. **78:** 310–326.
Powlson, D. S. and Jenkinson, D. S. 1981. A comparison of the organic matter, biomass, adenosine triphosphate and mineralizable nitrogen contents of ploughed and direct–drilled soils. J. Agric. Sci. (Camb.) **97:** 713–721.
Roberts, T. L., Bettany, J. R. and Stewart, J. W. B. 1989. A hierarchical approach to the study of organic C, N, P and S in western Canadian soils. Can. J. Soil Sci. **69:** 739–749.
Schlesinger, W. H. 1986. Changes in soil carbon storage and associated properties with disturbance and recovery. Pages 194–220 *in* J. R. Trabalka and D. E. Reichle, eds. The changing carbon cycle — A global analysis. Springer–Verlag, New York, NY.
Slater, C. S. and Carleton, E. A. 1938. The effect of erosion on losses of soil organic matter. Soil Sci. Soc. Am. J. **3:** 123–128.
Tiessen, H., Stewart, J. W. B. and Bettany, J. R. 1982. Cultivation effects on the amounts and concentration of carbon, nitrogen, and phosphorus in grassland soils. Agron. J. **74:** 831–835.
Voroney, R. P., Van Veen, J. A. and Paul, E. A. 1981. Organic C dynamics in grassland soils. 2. Model validation and simulation of long–term effects of cultivation and rainfall erosion. Can. J. Soil Sci. **61:** 211–224.