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# Changes in soil carbon inventories following cultivation of previously untilled soils

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**Abstract.** Cultivation of previously untilled soils usually results in release of carbon from the soil to the atmosphere, which can affect both soil fertility locally and the atmospheric burden of $CO_2$ globally. Generalizations about the magnitude of this flux have been hampered by a lack of good quality comparative data on soil carbon stocks of cultivated and uncultivated soils. Using data from several recent studies, we have reexamined the conclusions of previous reviews of this subject. The data were divided into subsets according to whether the soils were sampled by genetic horizon or by fixed depths. Sampling by fixed depths appears to underestimate soil C losses, but both subsets of data support earlier conclusions that between 20% and 40% of the soil C is lost following cultivation. Our best estimate is a loss of about 30% from the entire soil solum. Our analysis also supports the conclusion that most of the loss of soil C occurs within the first few years (even within two years in some cases) following initial cultivation. Our analysis does not support an earlier conclusion that the fractional loss of soil carbon is positively correlated to the amount of carbon initially present in the uncultivated soil. We found no relation between carbon content of uncultivated soil and the percentage lost following cultivation.

## Introduction

Net transfer of carbon from the world's terrestrial ecosystems to the atmosphere as a result of changing land uses recently was estimated as 1 to 2 × $10^{15}$ g C $yr^{-1}$ in the early 1980's, about 17% of which is thought to have emanated from soil organic matter (Houghton 1991). Changing land uses include clearing of forests, cultivation of forest and grassland soils, and creation of pastures for grazing, with the recent changes being most pronounced in tropical countries. The estimates of C lost from newly cultivated soils are based on the assumption that 20% of the soil C inventory is lost during the first 5 years following disturbance of natural vegetation and another 5% is lost before a new steady state equilibrium is reached 20 years after tillage began (Houghton et al. 1991). An earlier study estimated greater transfer of C from terrestrial ecosystems to the atmosphere, partly because larger losses of C from soils were assumed (Houghton et al. 1983). Hence, our knowledge of the amount of C lost from soils as a result of human disturbances of natural vegetation clearly affects our characterization of the global carbon budget.

Unfortunately, the estimate for loss of soil C has been based on surprisingly few data. Numerous reviews have been published on the subject (Allen 1985, Detwiler 1986, Johnson 1992, Mann 1986, Schlesinger 1986), but each of these authors has decried the lack of good data on changes of soil C inventories with changing land use. These reviews show that many studies report changes in concentrations of soil C, but few report the data on bulk density and depth that are needed to calculate changes in total carbon inventories of the soil. Several studies have been published in the last five years that significantly increase the meager database available on the effects of cultivation on soil C inventories (Table 1). In this paper, we review the data currently available on soil C inventories of paired comparisons of uncultivated and cultivated soils. We compare the relative importance of changes in the concentration of soil C and changes in soil mass, and we examine the effect of sampling soils by horizons or by fixed depths. We also analyze whether these new data, when combined with the old, support the conclusions of previous reviews that:

1. about 20% to 40% of the soil carbon inventory is usually lost when soil is cultivated;
2. the rate of soil carbon loss is highest in the first 20 years (or sooner) following disturbance; and
3. the fraction of the soil C inventory lost is positively correlated to the amount of C initially present in undisturbed soil.

The first two statements are supported; the third is not.

## Methods

We employed four criteria for selecting studies from our literature search:

1. The study was presented as a paired comparison or a chronosequence of reasonably well matched uncultivated (virgin) and cultivated soils.
2. The uncultivated soil was sampled to at least 30-cm depth.
3. A consistent sampling regime was used for both cultivated and uncultivated soils so that appropriate comparisons could be made either by horizon or by defined sampling depths.
4. For each depth increment sampled, either the carbon inventory was

already calculated or sufficient data on depth, bulk density, and carbon concentration were given to enable calculation of the carbon inventory.

In one case, bulk density was calculated from data given on pore space, assuming a particle density of 2.65 g $cm^{-3}$. Where soil carbon content was expressed as '% organic matter', we assumed a conversion factor of 0.58 g $C \cdot g^{-1}$ organic matter (Nelson & Sommers 1982).

Many of the eighteen studies that met our four criteria included more than one comparison of cultivated and uncultivated soils, yielding a total of 56 such comparisons. For all subsequent discussion of comparisons, the sample size (n) refers to the number of pairwise comparisons of cultivated and uncultivated soil. The study in which each comparison was originally published is indicated with a number used as a plotting symbol in figures and as a reference in tables; the identifying number corresponds to the numbering of studies in Table 1. We divided the 56 comparisons into six overlapping subsets according to how depth increments were sampled (Table 2).

## Results and discussion

### *Types of soils and ecosystems represented*

Not surprisingly, more than half of the studies included in this review were conducted on Mollisols of North American grasslands (Table 1). However, also included were three tropical forest sites and five forests in temperate or boreal regions. Reflecting the international literature sources, reported soil descriptions did not follow a single classification convention; they include Mollisols, Oxisols, Ultisols, Alfisols, brunisols, gleysols, podzols, rendzinas, grey forest soils, and peat. As many of these categories were represented by only one study, we did not attempt to investigate differences among soil types with respect to C loss following cultivation.

### *Carbon concentration vs. carbon inventory*

Carbon concentration (g C/g soil) is an unreliable indicator of C loss because the total amount of C present within the soil also depends on bulk density and soil depth (Schlesinger 1986). Bulk density and C concentration are often negatively correlated, as cultivated soil may become compacted at the same time that C concentration declines. Hence, higher bulk density can partially cancel the effect of lower C concentration, so that the loss of C inventory may be less than indicated from the C concentration

*Table 1.* Comparison of soil carbon and soil mass in cultivated and uncultivated soils.

| Source/ location/ soil type | Treatment | [1]Soil texture | Length of cultivation (yr) | Horizons | Depth (cm) | Bulk density (g $cm^{-3}$) | Mass (kg $m^{-2}$) | Soil C concentration (g $kg^{-1}$) | Soil C inventory (kg $m^{-2}$) |
|---|---|---|---|---|---|---|---|---|---|
| 1. Aguilar et al. (1988), North Dakota, USA, Typic Haplo-borolls, sand-stone summit | Rangeland | — | 0 | A, B, C | 0—48 | — | | — | 7.50 |
| | Wheat-fallow rotation | | ~ 44 | A, B, C | 0—19 | — | | — | 2.92 |
| Typic Ustipsamments, sandstone, shoulder | Rangeland | | 0 | A, B, C | 0—54 | — | | — | 7.86 |
| | Wheat-fallow rotation | | ~ 44 | A, B, C | 0—36 | — | | — | 5.30 |
| Typic Haploboralls sandstone, lower backslope | Rangeland | | 0 | A, B, C | 0—83 | — | | — | 10.50 |
| | Wheat-fallow rotation | | ~ 44 | A, B, C | 0—68 | — | | — | 9.81 |
| Pachic Haploborolls sandstone, footslope | Rangeland | | 0 | A, B, C | 0—85 | — | | — | 13.05 |
| | Wheat-fallow rotation | | ~ 44 | A, B, C | 0—67 | — | | — | 9.24 |
| Typic Haploborolls sandstone, back backslope | Rangeland | | 0 | A, B, C | 0—88 | — | | — | 11.39 |
| | Wheat-fallow rotation | | ~ 44 | A, B, C | 0—59 | — | | — | 6.94 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Pachic Haploborolls sandstone, back footslope | Rangeland | 0 | A, B, C | 0—86 | — | — | 14.22 |
| | Wheat-fallow rotation | ~44 | A, B, C | 0—107 | — | — | 13.48 |
| Typic Haploborolls siltstone, summit | Rangeland | 0 | A, B, C | 0—65 | — | — | 9.70 |
| | Wheat-fallow rotation | ~44 | A, B, C | 0—42 | — | — | 5.96 |
| Typic Haploborolls siltstone, shoulder | Rangeland | 0 | A, B, C | 0—43 | — | — | 10.35 |
| | Wheat-fallow rotation | ~44 | A, B, C | 0—52 | — | — | 11.39 |
| Typic Argiborolls siltstone, lower backslope | Rangeland | 0 | A, B, C | 0—63 | — | — | 12.41 |
| | Wheat-fallow rotation | ~44 | A, B, C | 0—49 | — | — | 5.52 |
| Typic Argiborolls siltstone, footslope | Rangeland | 0 | A, B, C | 0—67 | — | — | 12.91 |
| | Wheat-fallow rotation | ~44 | A, B, C | 0—43 | — | — | 7.81 |
| Typic Argiborolls siltstone, toeslope | Rangeland | 0 | A, B, C | 0—70 | — | — | 15.78 |
| | Wheat-fallow rotation | ~44 | A, B, C | 0—59 | — | — | 10.34 |
| Typic Argiborolls shale, summit | Rangeland | 0 | A, B, C | 0—61 | — | — | 10.92 |
| | Wheat-fallow rotation | ~44 | A, B, C | 0—42 | — | — | 5.62 |
| Typic Argiborolls shale, shoulder | Rangeland | 0 | A, B, C | 0—75 | — | — | 13.55 |
| | Wheat-fallow rotation | ~44 | A, B, C | 0—48 | — | — | 6.93 |

*Table 1 (Continued)*

| Source/ location/ soil type | Treatment | [1]Soil texture | Length of cultivation (yr) | Horizons | Depth (cm) | Bulk density (g $cm^{-3}$) | Mass (kg $m^{-2}$) | Soil C concentration (g $kg^{-1}$) | Soil C inventory (kg $m^{-2}$) |
|---|---|---|---|---|---|---|---|---|---|
| Typic Argiborolls shale, backslope | Rangeland | | 0 | A, B, C | 0—73 | — | | — | 13.87 |
| | Wheat-fallow rotation | | ~ 44 | A, B, C | 0—68 | — | | — | 9.88 |
| Typic Argiborolls shale, footslope | Rangeland | | 0 | A, B, C | 0—87 | — | | — | 19.09 |
| | Wheat-fallow rotation | | ~ 44 | A, B, C | 0—73 | — | | — | 12.67 |
| 2. Blank and Fosberg (1989) | Midgrass prairie | l | 0 | A | 0—15 | 1.33 | 200 | 35 | 6.98 |
| South Dakota, USA | | | | Bt | 15—33 | 1.59 | 286 | 10 | 2.86 |
| Ustic Mollisol | | | | Btk | 33—48 | 1.54 | 231 | 7 | 1.62 |
| | | | | Bk | 48—81 | 1.60 | 528 | 4 | 2.11 |
| | | | | C | 81—127 | 1.67 | 768 | 3 | 2.30 |
| | Common rotation is 2 yr in small grain, 1 yr in corn, 5 yr in pasture | | > 50 | Ap | 0—18 | 1.57 | 283 | 26 | 7.35 |
| | | | | Bt | 18—33 | 1.67 | 251 | 11 | 2.76 |
| | | | | Btk | 33—46 | 1.64 | 213 | 6 | 1.28 |
| | | | | Bk | 46—99 | 1.59 | 843 | 4 | 3.37 |
| | | | | C | 99—150 | 1.67 | 852 | 3 | 2.56 |
| 3. Bouma and Hole (1971) | Prairie | sicl | 0 | A1 | 0—35 | 1.14 | 399 | 24.36 | 9.72 |
| Wisconsin, USA | | | | A3 | 35—50 | 1.22 | 183 | 10.44 | 1.91 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Typic Argiudoll | | | | B1 | 50—65 | 1.21 | 182 | 8.12 | 1.47 |
| | | | | B2t | 65—90 | 1.26 | 315 | 5.80 | 1.83 |
| | | | | B31 | 90—115 | 1.37 | 343 | 3.48 | 1.19 |
| | | | | B32 | 115—140 | 1.37 | 343 | 3.48 | 1.19 |
| | | | | C | 140—150 | 1.39 | 139 | 1.74 | 0.24 |
| | Maize | | ~100 | Ap | 0—20 | 1.04 | 208 | 22.04 | 4.58 |
| | | | | A3 | 20—40 | 1.37 | 274 | 9.86 | 2.70 |
| | | | | B1 | 40—50 | 1.32 | 132 | 6.38 | 0.84 |
| | | | | B2t | 50—80 | 1.35 | 405 | 3.48 | 1.41 |
| | | | | B3 | 80—130 | 1.43 | 715 | 2.90 | 2.07 |
| | | | | C | 130—150 | 1.39 | 278 | 2.90 | 0.81 |
| 4. Bowman et al. (1990) | Rangeland | sl | 0 | | 0—15 | 1.55 | 233 | 10.13[2] | 2.36 |
| Colorado, USA | | | | | 15—30 | 1.55 | 233 | 6.77[2] | 1.58 |
| Aridic Argiustoll | Wheat-fallow rotation | | 3 | | 0—15 | 1.40 | 210 | 6.71[2] | 1.41 |
| | | | | | 15—30 | 1.60 | 240 | 5.63[2] | 1.35 |
| | Wheat-fallow rotation | | 20 | | 0—15 | 1.50 | 225 | 5.73[2] | 1.29 |
| | | | | | 15—30 | 1.62 | 243 | 5.00[2] | 1.22 |
| | Wheat-fallow rotation | | 60 | | 0—15 | 1.51 | 227 | 3.91[2] | 0.89 |
| | | | | | 15—30 | 1.65 | 248 | 4.30[2] | 1.07 |
| 5 Brown and Lugo (1990) | Wet forest | — | 0 | | 0—25 | 1.10[3] | 275 | 32.7[2] | 9.0 |
| Puerto Rico | | | | | 25—50 | 1.25[3] | 313 | 12.8[2] | 4.0 |
| Typic Tropohumult | Crops | | 0.6 | | 0—25 | 0.80[3,4] | 200 | 32.5[2] | 6.5 |
| | | | | | 25—50 | 1.10[3] | 275 | 12.7[2] | 3.5 |

*Table 1 (Continued)*

| Source/ location/ soil type | Treatment | [1]Soil texture | Length of cultivation (yr) | Horizons | Depth (cm) | Bulk density (g cm$^{-3}$) | Mass (kg m$^{-2}$) | Soil C concentration (g kg$^{-1}$) | Soil C inventory (kg m$^{-2}$) |
|---|---|---|---|---|---|---|---|---|---|
| | 6 yr tobacco then 2 yr corn | | 10 | | 0—25 | 0.95[3] | 238 | 14.7[2] | 3.5 |
| | | | | | 25—50 | 1.30[3] | 325 | 10.7[2] | 3.5 |
| 6 Buyanovsky et al. (1987) | Prairie | sil | 0 | A11 | 0—5 | 0.95 | 48 | 37.12 | 1.76 |
| Missouri, USA | | | | A1 | 5—25 | 1.31 | 262 | 20.88 | 5.47 |
| — | | | | A2 | 25—35 | 1.42 | 142 | 12.18 | 1.73 |
| | | | | B1, 2 | 35—50 | 1.35 | 203 | 5.22 | 1.06 |
| | Wheat (4 yr of monoculture) | | ~ 100 | Ap | 0—13 | 1.37 | 178 | 16.80 | 2.99 |
| | | | | A1 | 13—20 | 1.35 | 95 | 14.50 | 1.37 |
| | | | | A2 | 20—28 | 1.33 | 106 | 9.90 | 1.05 |
| | | | | B1 | 28—36 | 1.29 | 103 | 6.40 | 0.66 |
| | | | | B21 | 36—51 | 1.29 | 194 | 7.00 | 1.35 |
| 7. Coote and Ramsey (1983) | Mature trees | sl | 0 | | 0—10 | 1.30 | 130 | 31.2 | 4.06 |
| Ontario, Canada | | | | | 10—20 | 1.33 | 133 | 18.0 | 2.39 |
| Gleyed Melanic Brunisol | | | | | 20—30 | 1.39 | 139 | 12.2 | 1.70 |
| | Corn | | > 34 | | 0—10 | 1.35 | 135 | 25.6 | 3.46 |
| | | | | | 10—20 | 1.44 | 144 | 25.3 | 3.64 |
| | | | | | 20—30 | 1.43 | 143 | 19.2 | 2.75 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Eluviated Melanic Brunisol | Mature trees | ls | 0 | | 0—10 | 1.32 | 132 | 26.1 | 3.45 |
| | | | | | 10—20 | 1.31 | 131 | 17.1 | 2.24 |
| | | | | | 20—30 | 1.29 | 129 | 14.0 | 1.81 |
| | Corn | | > 34 | | 0—10 | 1.45 | 145 | 18.9 | 2.74 |
| | | | | | 10—20 | 1.49 | 149 | 18.9 | 2.82 |
| | | | | | 20—30 | 1.57 | 157 | 9.7 | 1.52 |
| | Mature trees | c | 0 | | 0—10 | 0.90 | 90 | 86.8 | 7.81 |
| | | | | | 10—20 | 1.02 | 102 | 86.2 | 8.79 |
| | | | | | 20—30 | 0.94 | 94 | 83.7 | 7.87 |
| | Small grains | | > 34 | | 0—10 | 1.06 | 106 | 67.8 | 7.19 |
| | | | | | 10—20 | 1.18 | 118 | 62.6 | 7.39 |
| | | | | | 20—30 | 1.18 | 118 | 52.2 | 6.16 |
| | Grasses | cl | 0 | | 0—10 | 1.43 | 143 | 23.7 | 3.39 |
| | | | | | 10—20 | 1.25 | 125 | 17.8 | 2.23 |
| | | | | | 20—30 | 1.30 | 130 | 7.0 | 0.91 |
| | Small grains | | > 34 | | 0—10 | 1.44 | 144 | 14.7 | 2.12 |
| | | | | | 10—20 | 1.60 | 160 | 14.8 | 2.37 |
| | | | | | 20—30 | 1.29 | 129 | 9.1 | 1.17 |
| 8. Kononova (1961) | Cut steppe | — | 0 | A0 | 0—6 | 0.72 | 43 | 75.4 | 3.26 |
| Former Soviet Union | | | | A1 | 6—20 | 0.96 | 134 | 57.5 | 7.73 |
| Chernozem | | | | A2 | 20—42 | 1.02 | 224 | 43.0 | 9.65 |
| | | | | B1 | 42—57 | 1.15 | 173 | 28.4 | 4.9 |
| | | | | B2 | 57—75 | 1.26 | 227 | 19.4 | 4.4 |
| | | | | B3 | 75—100 | 1.58 | 395 | 7.4 | 2.92 |

*Table 1 (Continued)*

| Source/ location/ soil type | Treatment | [1]Soil texture | Length of cultivation (yr) | Horizons | Depth (cm) | Bulk density (g $cm^{-3}$) | Mass (kg $m^{-2}$) | Soil C concentration (g $kg^{-1}$) | Soil C inventory (kg $m^{-2}$) |
|---|---|---|---|---|---|---|---|---|---|
| | Annual crops | | — | A0 | 0—22 | 1.00 | 220 | 44.9 | 9.88 |
| | | | | A1 | 22—37 | 1.10 | 165 | 37.2 | 6.14 |
| | | | | A2 | 37—47 | 1.23 | 123 | 29.8 | 3.67 |
| | | | | B1 | 47—60 | 1.32 | 172 | 15.5 | 2.66 |
| | | | | B2 | 60—80 | 1.37 | 274 | 7.8 | 2.14 |
| | | | | | 80—90 | 1.51 | 151 | 5.2 | 0.79 |
| | | | | B3 | 90—100 | 1.52 | 152 | 5.0 | 0.76 |
| 9. Lamb et al. (1985) | Grassland | 1 | 0 | | 0—10 | — | | — | 1.30 |
| Nebraska, USA | | | | | 10—20 | — | | — | 1.26 |
| Pachic Haplustoll | | | | | 20—30 | — | | — | 1.09 |
| | Wheat-fallow rotation; stubble mulch | | 11 | | 0—10 | — | | — | 1.42 |
| | | | | | 10—20 | — | | — | 1.17 |
| | | | | | 20—30 | — | | — | 0.94 |
| | Wheat-fallow rotation; plow | | 11 | | 0—10 | — | | — | 1.45 |
| | | | | | 10—20 | — | | — | 1.35 |
| | | | | | 20—30 | — | | — | 1.02 |
| | Grassland | 1 | 0 | | 0—10 | — | | — | 1.76 |
| | | | | | 10—20 | — | | — | 1.38 |
| | | | | | 20—30 | — | | — | 1.00 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Wheat-fallow rotation; stubble mulch | | 11 | | 0—10 | — | | — | 1.47 |
| | | | | | 10—20 | — | | — | 1.10 |
| | | | | | 20—30 | — | | — | 1.01 |
| | Wheat-fallow rotation; plow | | 11 | | 0—10 | — | | — | 1.31 |
| | | | | | 10—20 | — | | — | 1.10 |
| | | | | | 20—30 | — | | — | 1.05 |
| 10. Laws and Evans (1949) | Meadow | c | 0 | | 0—15 | 0.98[5] | 149 | 30.2 | 4.50 |
| | | | | | 15—31 | 1.08[5] | 164 | 19.7 | 3.23 |
| Texas, USA | | | | | 31—46 | 1.09[5] | 166 | 16.8 | 2.78 |
| Rendzina | | | | | 46—76 | 1.28[5] | 389 | 11.0 | 4.28 |
| | | | | | 76—107 | 1.31[5] | 398 | 6.4 | 2.55 |
| | Wheat | | 40—50 | | 0—15 | 0.94[5] | 143 | 16.2 | 2.31 |
| | | | | | 15—31 | 1.10[5] | 167 | 12.8 | 2.14 |
| | | | | | 31—46 | 1.08[5] | 164 | 15.1 | 2.48 |
| | | | | | 46—76 | 1.16[5] | 353 | 13.3 | 4.69 |
| | | | | | 76—107 | 1.20[5] | 365 | 7.0 | 2.55 |
| | Meadow | c | 0 | | 0—15 | 1.04[5] | 158 | 32.5 | 5.14 |
| | | | | | 15—31 | 1.11[5] | 169 | 24.4 | 4.12 |
| | | | | | 31—46 | 1.17[5] | 178 | 18.0 | 3.20 |
| | | | | | 46—76 | 1.25[5] | 380 | 11.6 | 4.41 |
| | Cotton | | 90 | | 0—15 | 1.28[5] | 195 | 16.8 | 3.27 |
| | | | | | 15—31 | 1.27[5] | 193 | 16.2 | 3.13 |
| | | | | | 31—46 | 1.33[5] | 202 | 13.9 | 2.81 |
| | | | | | 46—76 | 1.35[5] | 410 | 9.9 | 4.06 |
| 11. Martel and Deschenes (1976), | Forest | cl | 0 | Ah-Aeg | 0—17 | 1.4 | 238 | 67 | 15.95 |

*Table 1 (Continued)*

| Source/ location/ soil type | Treatment | [1]Soil texture | Length of cultivation (yr) | Horizons | Depth (cm) | Bulk density (g $cm^{-3}$) | Mass (kg $m^{-2}$) | Soil C concentration (g $kg^{-1}$) | Soil C inventory (kg $m^{-2}$) |
|---|---|---|---|---|---|---|---|---|---|
| Martel and MacKenzie (1980) | | | | Bg | 17—38 | 1.9 | 399 | 4.2 | 1.68 |
| Quebec, Canada | | | | | | | | | |
| Gleysol | 1 yr cereals, 4 yr hay rotation | | > 50 | Ap | 0—17 | 1.6 | 272 | 37 | 10.06 |
| | | | | Bg | 17—33 | 2.0 | 320 | 5.7 | 1.82 |
| Podzol | Forest | sl | 0 | L-H | 4—0 | 0.42 | 17 | 221 | 3.71 |
| | | | | Ae-Bf1 | 0—15 | 0.96 | 144 | 43 | 6.19 |
| | | | | Bf2 | 15—26 | 1.2 | 132 | 14 | 1.85 |
| | 1 yr cereals, 4 yr hay rotation | | > 50 | Ap | 0—15 | 0.94 | 141 | 37 | 5.22 |
| | | | | Bf | 15—30 | 1.2 | 180 | 17 | 3.06 |
| Podzol | Forest | sil | 0 | Ah-Ae | 0—7 | 0.60 | 42 | 103 | 4.33 |
| | | | | Bf | 7—30 | 1.2 | 276 | 17 | 4.69 |
| | 1 yr cereals, 4 yr hay rotation | | > 50 | Ap | 0—17 | 1.2 | 204 | 24 | 4.90 |
| | | | | Bf | 17—28 | 1.3 | 143 | 6.4 | 0.92 |
| 12. Rhoton and Tyler (1990) | Mixed hardwood forest | — | 0 | A1 | 0—10 | 1.08 | 108 | 28.88 | 3.12 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Tennessee & Mississippi, USA | | | | A2 | 10—20 | 1.08 | 108 | 7.95 | 0.86 |
| | Glossic Fragiudalf | | | | BA | 20—36 | 1.28 | 205 | 4.23 | 0.87 |
| | | | | | BW | 36—48 | 1.44 | 173 | 2.55 | 0.44 |
| | | | | | Bt1 | 48—64 | 1.51 | 242 | 1.57 | 0.38 |
| | | | | | E/Btx | 64—74 | 1.54 | 154 | 1.22 | 0.19 |
| | | | | | Btx1 | 74—127 | 1.58 | 837 | 0.87 | 0.73 |
| | | | | | Btx2 | 127+ | 1.60 | | 0.58 | — |
| | | Cultivation | sl | — | Ap | 0—15 | 1.48 | 222 | 8.41 | 1.87 |
| | | | | | BA | 15—28 | 1.46 | 190 | 2.38 | 0.45 |
| | | | | | Bt1 | 28—43 | 1.37 | 206 | 1.62 | 0.33 |
| | | | | | Bt2 | 43—61 | 1.41 | 254 | 1.16 | 0.29 |
| | | | | | E/Bx | 61—74 | 1.49 | 194 | 0.58 | 0.11 |
| | | | | | Btx1 | 74—88 | 1.52 | 213 | 0.46 | 0.10 |
| | | | | | Btx2 | 88—100+ | 1.60 | 192 | 0.41 | 0.08 |
| | | Cultivation | | — | Ap | 0—11 | 1.43 | 157 | 7.19 | 1.13 |
| | | | | | BW1 | 11—23 | 1.46 | 175 | 1.57 | 0.28 |
| | | | | | BW2 | 23—37 | 1.41 | 197 | 0.93 | 0.18 |
| | | | | | E/Bx | 37—47 | 1.51 | 151 | 0.52 | 0.08 |
| | | | | | Btx1 | 47—75 | 1.55 | 434 | 0.46 | 0.2 |
| | | | | | Btx2 | 75—100+ | 1.58 | 395 | 0.06 | 0.02 |
| | | Cultivation | | — | Ap | 0—10 | 1.44 | 144 | 5.86 | 0.84 |
| | | | | | Bx1 | 10—43 | 1.54 | 508 | 0.64 | 0.33 |
| | | | | | Bx2 | 43—84+ | 1.58 | 648 | 0.81 | 0.52 |
| 13. | Rubilin and Dolotov (1967) | Forest | — | 0 | | 0—50 | — | | — | 0.97 |
| | Russia | | | | | 50—100 | — | | — | 1.36 |

*Table 1 (Continued)*

| Source/ location/ soil type | Treatment | [1]Soil texture | Length of cultivation (yr) | Horizons | Depth (cm) | Bulk density (g $cm^{-3}$) | Mass (kg $m^{-2}$) | Soil C concentration (g $kg^{-1}$) | Soil C inventory (kg $m^{-2}$) |
|---|---|---|---|---|---|---|---|---|---|
| Gray forest | | | | | | | | | |
| | Plowed | | 100+ | | 0—50 | — | | — | 0.58 |
| | | | | | 50—100 | — | | — | 1.26 |
| | Forest | | 0 | | 0—50 | — | | — | 1.39 |
| | | | | | 50—100 | — | | — | 1.86 |
| | Plowed | | 100+ | | 0—50 | — | | — | 0.40 |
| | | | | | 50—100 | — | | — | 0.48 |
| | Forest | | 0 | | 0—50 | — | | — | 1.20 |
| | | | | | 50—100 | — | | — | 1.52 |
| | Plowed | | 100+ | | 0—50 | — | | — | 0.35 |
| | | | | | 50—100 | — | | — | 0.45 |
| | Forest | | 0 | | 0—50 | — | | — | 0.71 |
| | | | | | 50—100 | — | | — | 0.99 |
| | Plowed | | 100+ | | 0—50 | — | | — | 0.46 |
| | | | | | 50—100 | — | | — | 0.59 |
| | Forest | | 0 | | 0—50 | — | | — | 0.53 |
| | | | | | 50—100 | — | | — | 0.83 |
| | Plowed | | 100+ | | 0—50 | — | | — | 0.68 |
| | | | | | 50—100 | — | | — | 0.80 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 14. | Street (1980) | Native | — | 0 | | 0—15 | 0.46 | 69 | 135.1 | 9.32 |
| | New Guinea | | | | | 15—30 | 0.51 | 77 | 85.84 | 6.57 |
| | — | | | | | | | | | |
| | | Gardened | | 0—1 | | 0—15 | 0.54 | 81 | 69.02 | 5.59 |
| | | | | | | 15—30 | 0.59 | 89 | 55.68 | 4.93 |
| | | Gardened | | 1—2 | | 0—15 | 0.49 | 74 | 80.62 | 5.93 |
| | | | | | | 15—30 | 0.54 | 81 | 59.74 | 4.84 |
| 15. | Tiessen et al. (1982) | Prairie | sil | 0 | A | 0—11 | 1.04 | 112 | 47.9 | 5.38 |
| | Saskatchewan, Canada | | | | B | 11—30 | 1.33 | 253 | 15.5 | 3.92 |
| | Typic Cryoboroll | | | | | | | | | |
| | | Cultivation | | 4 | A | 0—13 | 1.04 | 138 | 49.0 | 6.78 |
| | | | | | B | 13—31 | 1.39 | 240 | 18.2 | 4.38 |
| | | Cultivation | | 60 | A | 0—15 | 1.22 | 177 | 32.8 | 5.80 |
| | | | | | B | 15—31 | 1.39 | 232 | 14.8 | 3.44 |
| | | Cultivation | | 90 | A | 0—9 | 1.30 | 117 | 20.0 | 2.34 |
| | | | | | B | 9—20 | 1.38 | 152 | 11.3 | 1.72 |
| | | Prairie | sl | 0 | A | 0—15 | 1.07 | 158 | 32.2 | 5.10 |
| | | | | | B | 15—34 | 1.39 | 265 | 12.6 | 3.35 |
| | | Cultivation | | 65 | A | 0—14 | 1.45 | 200 | 17.4 | 3.48 |
| | | | | | B | 14—36 | 1.42 | 317 | 10.8 | 3.42 |
| | Vertic Cryothent and Vertic | Prairie | c | 0 | A | 0—18 | 0.98 | 176 | 37.7 | 6.65 |
| | Cryoboroll | | | | B | 18—31 | 1.21 | 157 | 22.5 | 3.54 |

*Table 1 (Continued)*

| Source/ location/ soil type | Treatment | [1]Soil texture | Length of cultivation (yr) | Horizons | Depth (cm) | Bulk density (g cm$^{-3}$) | Mass (kg m$^{-2}$) | Soil C concentration (g kg$^{-1}$) | Soil C inventory (kg m$^{-2}$) |
|---|---|---|---|---|---|---|---|---|---|
| | Cultivation | | 70 | A | 0—18 | 1.28 | 230 | 23.7 | 5.46 |
| | | | | B | 18—31 | 1.38 | 179 | 19.6 | 3.52 |
| 16. Vitorello et al. (1989) | Forest | c | 0 | | 0—20 | — | | 22 | 7.4 |
| Brazil | | | | | 20—70 | — | | — | 5.2 |
| Typic Haplorthox | | | | | | | | | |
| | Continuous cultivation of sugar cane | | 12 | | 0—20 | — | | 22 | 3.8 |
| | | | | | 20—70 | — | | — | 4.0 |
| | Continuous cultivation of sugar cane | | 50 | | 0—20 | — | | 15 | 3.6 |
| | | | | | 20—70 | — | | — | 5.6 |
| 17. Voroney et al. (1981) | Prairie | l | 0 | Ah | 0—12 | 0.93 | 112 | 56.99[2] | 6.36 |
| Saskatchewan, Canada | | | | Bm | 12—25 | 1.35 | 176 | 17.44[2] | 3.06 |
| Black Chernozem | | | | Cca | 25—51 | 1.49 | 387 | 5.65[2] | 2.19 |
| | | | | Ck1 | 51—71 | 1.51 | 302 | 1.36[2] | 0.41 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Cereals in 2- and 3-yr grain/summerfallow rotations | ~70 | Ap | 0—9 | 1.15 | 104 | 25.51[2] | 2.64 |
| | | Bmk | 9—25 | 1.30 | 208 | 14.47[2] | 3.01 |
| | | Cca | 25—39 | 1.42 | 199 | 4.98[2] | 0.99 |
| | | Ck1 | 39—49 | 1.45 | 145 | 2.69[2] | 0.39 |
| Prairie | 0 | Ah | 0—15 | 1.11 | 167 | 56.52[2] | 9.41 |
| | | Bm | 15—39 | 1.37 | 329 | 11.56[2] | 3.80 |
| | | Cca | 39—59 | 1.47 | 294 | 5.51[2] | 1.62 |
| | | Ck1 | 59—69 | 1.49 | 149 | 2.62[2] | 0.39 |
| Cereals in 2- and 3-yr grain-summerfallow rotations | ~70 | Ap | 0—13 | 1.17 | 152 | 26.43[2] | 4.02 |
| | | Bm | 13—34 | 1.38 | 290 | 10.28[2] | 2.98 |
| | | Bmk | 34—44 | 1.41 | 141 | 7.59[2] | 1.07 |
| | | Cca | 44—61 | 1.51 | 257 | 4.99[2] | 1.28 |
| | | Ck1 | 61—71 | 1.56 | 156 | 2.12[2] | 0.33 |
| Prairie | | Ah | 0—13 | 1.06 | 138 | 60.45[2] | 8.33 |
| | 0 | Ahe | 13—24 | 1.28 | 141 | 19.18[2] | 2.70 |
| | | Bt | 24—47 | 1.48 | 340 | 7.64[2] | 2.60 |
| | | Cca | 47—71 | 1.59 | 382 | 2.80[2] | 1.07 |
| | | Ck1 | 71—81 | 1.53 | 153 | 2.81[2] | 0.43 |
| Cereals in 2- and 3-yr grain-summerfallow rotations | ~70 | Ap | 0—13 | 1.21 | 157 | 31.28[2] | 4.92 |
| | | Ahe | 13—22 | 1.32 | 119 | 16.25[2] | 1.93 |
| | | Bt | 22—39 | 1.47 | 250 | 11.40[2] | 2.85 |
| | | Cca | 39—47 | 1.57 | 126 | 3.18[2] | 0.40 |
| | | Ck1 | 47—57 | 1.53 | 153 | 1.90[2] | 0.29 |

*Table 1 (Continued)*

| Source/ location/ soil type | Treatment | [1]Soil texture | Length of cultivation (yr) | Horizons | Depth (cm) | Bulk density ($g\ cm^{-3}$) | Mass ($kg\ m^{-2}$) | Soil C concentration ($g\ kg^{-1}$) | Soil C inventory ($kg\ m^{-2}$) |
|---|---|---|---|---|---|---|---|---|---|
| 18. Yefimov and Lunina (1987) | Peat bog | — | 0 | | 20 | 0.18 | 36 | 485.6 | 17.38 |
| Estonia | | | | | 40 | 0.23 | 45 | 523.9 | 23.68 |
| Peat | | | | | 60 | 0.27 | 53 | 521.6 | 27.64 |
| | | | | | 80 | 0.27 | 53 | 549.7 | 29.13 |
| | | | | | 100 | 0.27[6] | 53 | 522.5 | 27.69 |
| | | | | | 120 | 0.27[6] | 53 | 571.6 | 30.29 |
| | Cultivation | | 70 | | 20 | 0.43 | 86 | 570.8 | 49.09 |
| | | | | | 33 | 0.37 | 48 | 543.0 | 26.33 |
| | | | | | 53 | 0.37 | 75 | 658.7 | 49.14 |

[1] si = silt; s = sand; l = loam; c = clay.
[2] data for C concentration ($g\ kg^{-1}$) was not supplied, so it has been calculated from data on C inventory, bulk density, and depth.
[3] approximated from bar graphs.
[4] this site had been tilled just prior to sampling.
[5] bulk density estimated from porosity data.
[6] Bulk density assumed to be the same as the layer above.

*Table 2.* Mean percent change of soil carbon and soil mass for subsets of data grouped according to the method of sampling by depth. Standard errors of the mean are given in parentheses, followed by the number of pairwise uncultivated-cultivated comparisons in *italics*. Negative values indicate a loss when virgin soil is cultivated and positive values indicate a gain.

| Sampling depth | Soil carbon concentration (% change of g C/kg soil) | Soil mass (% change of g soil/m$^2$) | Soil carbon inventory (% change of g C/m$^2$) | References |
|---|---|---|---|---|
| A horizons | −43.3 (4.0, *14*) | −0.6 (5.3, *14*) | −42.7 (5.7, *14*) | 3, 6, 8, 11, 12, 15, 17 |
| A and B horizons | −36.8 (3.7, *14*) | −3.6 (4.4, *14*) | −38.1 (5.1, *14*) | 3, 6, 8, 11, 12, 15, 17 |
| | −31.5 (4.4, *18*) | +0.2 (3.9, *18*) | −30.0 (5.9, *18*) | 2, 3, 6, 8, 11, 12, 15, 17 |
| Entire solum | −14.7 (7.2, *6*) | −9.8 (9.6, *6*) | −30.5 (4.1, *21*) | 1—3, 17, 18 |
| Fixed depth — top layer | −34.0 (4.4, *16*) | +3.6 (4.1, *14*) | −30.9 (4.4, *20*) | 4, 5, 7, 9, 10, 14—16 |
| Fixed depths > 30 cm | −26.2 (4.6, *14*) | +5.5 (3.1, *14*) | −24.2 (4.4, *25*) | 4, 5, 7, 9, 10, 13—16 |
| All data | −25.9 (3.6, *31*) | +0.2 (2.9, *31*) | −27.2 (2.9, *56*) | 1—18 |

data alone. On the other hand, erosion can result in greater loss of soil C than would be indicated by analysis of only data on the C concentration of the remaining soil.

Our analysis reconfirms the need to distinguish between C concentration and C inventory. Although the mean % change in C concentration is very close to the mean % change in C inventory for datasets on A horizons only and A and B horizons (Table 2), the relationship does not follow the 1:1 line when C concentrations are plotted against C inventories (Fig. 1). The slope of this regression is 0.69 ($R^2$ = 0.84), and the residuals of the regression are large relative to the estimated C loss for many of the plotted points. Although the means of % change of C concentrations and of C inventories are fortuitously similar (Table 1), ignoring changes in bulk density would cause important errors in individual estimates of C loss from many soils.

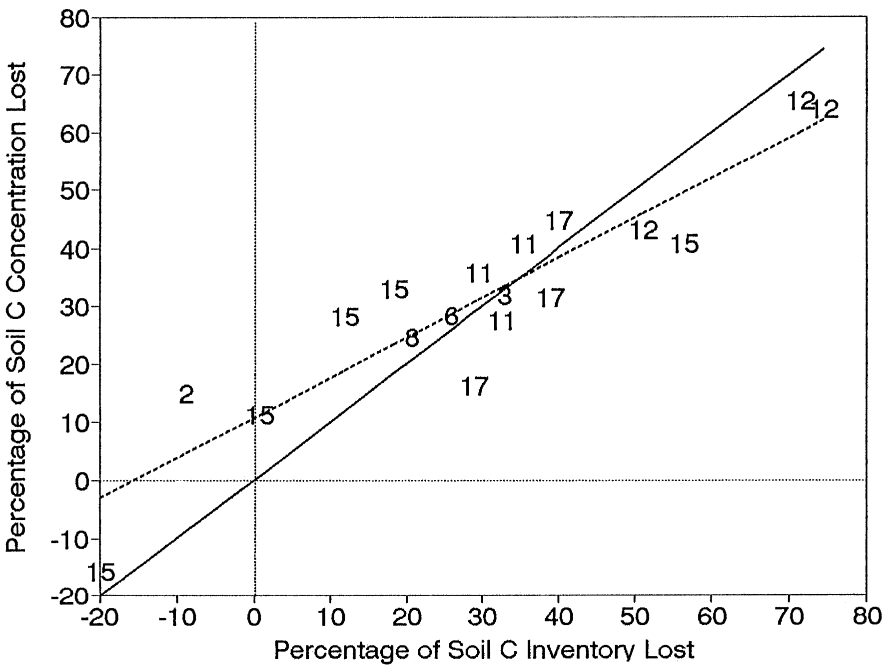


*Fig. 1.* Comparison of the percent of original soil carbon inventory (kg C/m$^2$) lost following cultivation to the percent of original soil carbon concentration (kg C/kg soil) lost following cultivation. Plot symbols refer to the studies numbered in Table 1. The solid line is the 1:1 line. The dashed line is the least squares linear regression line (Y = 0.69X + 10.73; $R^2$ = 0.84).

*Amount of C lost in cultivated soils*

In all subsets of comparisons, the mean loss of soil C inventory ranged from 24% to 43% of the carbon present in the uncultivated soil (Table 2). This result supports earlier generalizations that between 20% and 40% of the C inventory of uncultivated soil is generally lost following cultivation (Detwiler 1986, Mann 1986, Post & Mann 1991, Schlesinger 1986). The highest estimate of loss (43%) is based on the C inventory of the A horizon (Table 2). As most of the C loss occurs within the plow layer, the proportion lost is higher if only the surface horizon is included. When the C inventory of the B horizon is included for the same 14 comparisons used for calculations of loss from the A horizon, the C lost as a percentage of the total inventory drops from 43% to 38% (Table 2).

Four more studies can be included in the subset of A and B horizons, but not the A horizon only, because the plow layers of these soils extended below the shallow A horizon of the native soil (Fig. 2b). Hence the new Ap horizon included some material that was once in the B horizon, and a valid comparison of carbon inventories can be made only if both A and B horizons are summed. For this subset of 18 comparisons and the subset of 21 comparisons of entire solums, about 30% of the original C inventory was lost.

The importance of sampling depth is also apparent in the subset of comparisons using fixed depths. Although we used only studies where the soil had been sampled to at least 30 cm, 20 of the comparisons that used fixed depths $\geqslant 30$ cm also included data on shallower sampling depths. For these 20 comparisons, the mean loss from the surface depth increment was about 31%, whereas the mean loss computed using all depths was about 24% (Table 2).

Although these differences in estimates of mean loss of C are not large relative to the variation among studies (as evidenced by large standard errors of the mean, Table 2), they underscore the importance of defining what is being compared when C loss is reported as a percentage of the original C present. Because the amount of soil included in analyses increases when the soil is sampled to a greater depth, the reported percentage loss declines. If the entire solum is being considered, our analysis indicates a mean loss of about 30% of the original inventory; if only the A horizon is considered, a mean loss of about 40% is indicated.

*Sampling by genetic horizon vs. fixed depths*

Provided that demarcations of horizon boundaries can be identified and sampled consistently for all soil profiles being compared within a study, sampling by genetic horizon provides more reliable data on soil C inventories than does sampling by a fixed depth of a chosen number of centimeters. The bottom of a genetic horizon can be used as a reference point, so that a comparison of C inventories of cultivated and uncultivated soils unambiguously includes all changes that may have occurred above that reference point. If erosion has removed several centimeters of soil from the surface or if compaction has caused the surface horizon to be thinner, these effects are accounted for when the entire genetic horizon is sampled (Fig. 2). As in any pairwise or chronosequence comparison, it must be assumed that the cultivated and uncultivated soil profiles being compared were once identical.

In contrast, when a fixed-depth increment is sampled, soil material that was below that depth before cultivation may be within that depth increment in compacted or eroded cultivated soil (Fig. 2). Hence, the fixed-depth sample from the cultivated soil may include soil from a lower genetic horizon or subhorizon that is not included in the fixed-depth sample from the uncultivated soil. It is useful to think of the fixed-depth increment of the cultivated soil as having a larger 'effective depth,' because the same number of centimeters reaches to deeper genetic horizons in the

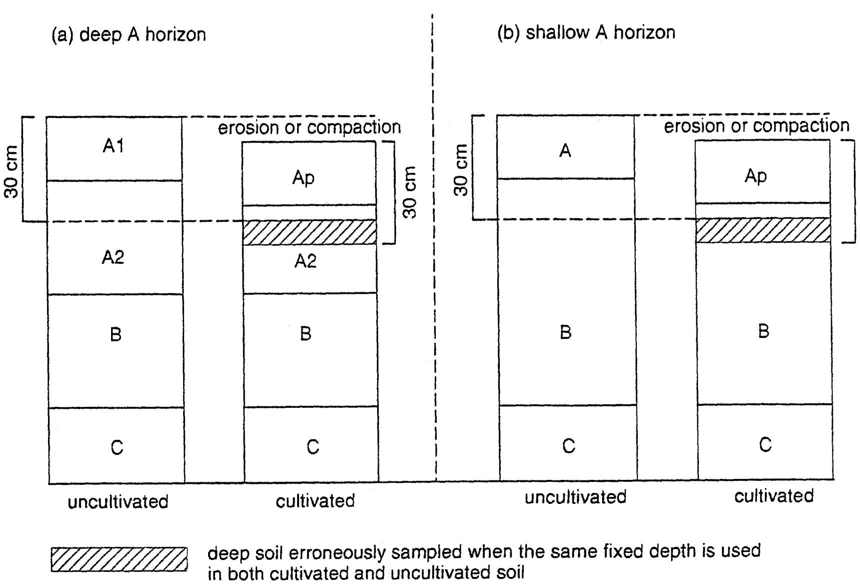


*Fig. 2.* Illustration of the 'effective depth' of a fixed sampling increment of 30 cm in uncultivated and cultivated soils with deep A horizons (a) and shallow A horizons (b). When the cultivated soil is either compacted or eroded, a 30 cm sampling depth penetrates deeper into the A2 or the B horizon in the cultivated soil than in the uncultivated soil.

cultivated soil than in the uncultivated soil. In come cases, this difference in the effective depth of sampling of the soil profile results in greater soil mass in the sample from the cultivated soil than in the sample from the uncultivated soil (studies 7 and 14 in Table 1). In our data set, cultivated soils have slightly increased mean soil mass when fixed depths were sampled, whereas soil mass decreased slightly following cultivation when soils were sampled by genetic horizons (Table 2). Because it is very unlikely that cultivation could cause soil to gain mass, this difference must be considered a sampling artifact caused by use of fixed depths.

When fixed-depth sampling results in greater soil mass being sampled in cultivated soil than in uncultivated soil, then the comparison of C inventories based on this sampling technique is in error. The additional depth increment sampled in the compacted or eroded cultivated soil (Fig. 2) adds additional soil C to its inventory, which lowers the estimated loss of C resulting from cultivation. This sampling artifact results in mean estimates of soil C loss in studies of fixed depths that are at least 6% lower than mean estimates of soil C loss in studies of genetic horizons of similar depths (cf. 'A horizon' vs. 'top layer' and 'A and B horizons' vs. 'fixed-depth > 30 cm' in Table 2). This difference is small, but it is a consistent bias that should not be ignored.

*Erosion vs. mineralization as C loss mechanisms*

A comparison of C losses from erosion cannot be made in this review because only a few authors addressed erosion. Street (1982) indicated that the soils he studied in New Guinea were not prone to erosion and concluded that rapid loss of soil C was primarily the result of mineralization of soil organic matter following cultivation. Aguilar et al. (1988) designed their study to include soils at summit and shoulder landscape positions that were prone to erosion and at footslope positions that received sediments from upslope. They attributed some of the observed variation in C losses (Table 1, plotting symbol '1' in Fig. 3a) to differences in erosion among landscape positions and soil textures. Observing the highest C losses at summit and shoulder positions of a catena derived from shale, they deduced that erosion contributed significantly to C losses in some, but not all, of the cultivated grassland landscapes studied. Narrowing of soil C/N ratios indicated that mineralization also contributed to C loss at all landscape positions.

Changes in soil mass indicate erosional losses, but the means reported in Table 2 are ambiguous. Mean soil mass varied from small increases to a 10% loss in cultivated soils for the subsets of data in Table 2, which contrasts with mean losses of between 24% and 43% of soil C inventories.

If erosion were the dominant mechanism of C loss, decline in soil mass (when sampled by genetic horizon) might be similar to decline in C inventories. On the other hand, erosion removes soil from the surface where the C concentration is highest, and erosion of a small fraction of the soil mass of the A horizon could result in a larger fractional loss of total soil C inventory.

*Rate of C loss following cultivation*

The time interval between initial cultivation and sampling for soil C inventories ranged from <1 year to >100 years (Fig. 3). A plot of the percentage of the original C inventory lost as a function of the time since initial cultivation shows no trend (Fig. 3a). We do not mean to suggest that all of these studies should be viewed as a single chronosequence, but if the duration of cultivation were a factor strongly influencing the percentage of the initial C inventory lost, then a trend of increasing loss with increasing period of cultivation might be apparent despite differences in other factors among study sites. Although this is not the case for the percentage of soil C lost (Fig. 3a), a plot of the average rate of C loss (% C inventory lost divided by years of cultivation) against years of cultivation, reveals that rates of C loss decline sharply during the first few years following initial cultivation (Fig. 3b). In other words, soil C loss occurs so quickly, that even the sites with the shortest period of cultivation have, on the average, lost about as much C as those with longer cultivation periods. It should be noted, however, that the two studies with the shortest period of cultivation and the most rapid rates of C loss (plotting symbols 5 and 14 in Fig. 3a) were conducted in Puerto Rico and New Guinea. Rates of soil C loss may not be as rapid in temperate climates as was observed for these two tropical forest sites.

These results support earlier conclusions that most of the soil C lost following cultivation occurs during the first 5 years (Detwiler 1986) or the first 20 years (Mann 1986, Schlesinger 1986). Although these data provide no strong basis for further refinement, they show that the model used by Houghton et al. (1985, 1987, 1991) is reasonable (at least when it is applied to cultivation as a land use change), which assumes 20% loss of soil C inventory during the first 5 years after initial cultivation and another 5% loss by year 20. A model of almost immediate loss of about 30% and no further significant loss would also be consistent with these data (Table 2, Fig. 3).

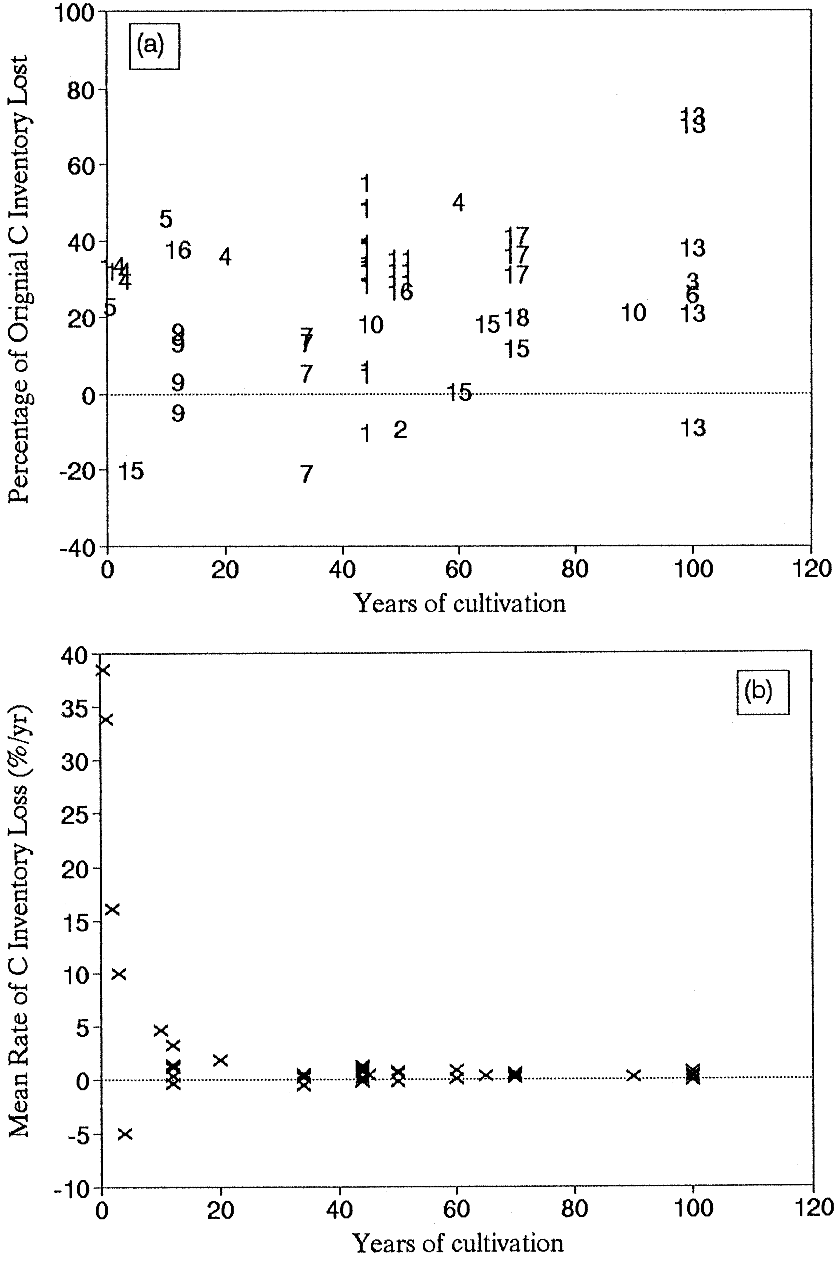


*Fig. 3.* In the upper panel (a), the percentage of the original C inventory (kg C/m$^2$) lost following cultivation is shown as a function of time since the soil was first tilled. Plot symbols refer to the studies numbered in Table 1. In the lower panel (b), the mean annual rate of loss of C inventory is calculated from the data in the upper panel (%loss/year of cultivation) and is shown as a function of time since the soil was first tilled.

*Loss of soil C as a function of the original soil C inventory*

Correlations between soil C inventories of cultivated and uncultivated soils were statistically significant at $\alpha = 0.01$ for all subsets of comparisons (Table 3). This regression equation

$$C_c = B_0 + B_1 \cdot C_u \quad (1)$$

where $C_c$ and $C_u$ are the carbon inventories of the cultivated and uncultivated soils, respectively, was rearranged by Mann (1986) to

$$(C_c - C_u)/C_u = B_0/C_u + B_1 - 1 \quad (2)$$

which was used to show 'that the fractional loss of carbon $[(C_c - C_u)/C_u]$ increases with increasing initial carbon content and approaches a maximum fractional loss equal to $B_1 - 1$.' The right side of the equation becomes a larger negative number (greater fractional loss) as $C_u$ increases, because the y-intercept of Eq. 1 ($B_0$) becomes less important as $C_u$ increases. However, this conclusion holds only if $B_0$ is a positive value that is significantly different from zero. When $B_0$ is negative, then the fractional loss of carbon increases with decreasing initial carbon content ($C_u$), and if

*Table 3.* Regression parameters for the equation $C_c = B_0 + B_1C_u$, where $C_c$ is the carbon content (kg C/m$^2$) of the cultivated soil and $C_u$ is the carbon content of the uncultivated soil.

| Sampling depth | $B_0$ | $B_1$ | $R^2$ | $n$ |
|---|---|---|---|---|
| A horizons | −2.49* | 0.93** | 0.90 | 14 |
| A and B horizons | −2.41* | 0.86** | 0.95 | 14 |
| | −1.26 | 0.83** | 0.84 | 18 |
| Entire solum | −1.44 | 0.81** | 0.99 | 21 |
| Fixed depth — top layer | 0.33 | 0.58** | 0.78 | 20 |
| Fixed depths > 30 cm | −0.07 | 0.77** | 0.92 | 25 |
| All data[1] | −0.38 | 0.77** | 0.85 | 55 |

* significantly different from zero at $\alpha = 0.05$
** significantly different from zero at $\alpha = 0.01$
[1] except the peat soil from reference 18, which was excluded from regression analyses because its high carbon values caused the regression parameters to be strongly influenced by this single point and inflated the apparent $R^2$ value.

$B_0$ is not significantly different from zero, then the initial carbon inventory ($C_u$) has no effect on the fractional loss. Mann (1986) reported statistically significant positive values for $B_0$ for many of the regression analyses of various subsets of data. In contrast, the only $B_0$ values in our analyses that were significantly different from zero were for the subset of 14 comparisons of data on A and A-and-B horizons, and in those cases the $B_0$ values were negative (Table 3). Of course, a soil cannot have negative carbon, nor is a soil with zero C inventory likely to be cultivated. Hence, the importance of a nonzero intercept should be interpreted with caution.

Unlike the criteria for including studies in our analyses, Mann (1986) used data from studies with sampling depths as small as 15 cm, and she assigned random values for bulk density when these data were missing. These less stringent criteria allowed her to include 328 pairwise comparisons of cultivated and uncultivated soils. This large sample size in Mann's analysis affords statistical assertion that many of the reported y-intercepts were significantly greater than zero. Many of Mann's pairwise comparisons, however, used fixed sampling depths, and Mann noted that the y-intercepts were higher for subsets of data from fixed sampling depths than for other subsets. We also see a trend of larger y-intercepts for subsets of data using fixed-depth sampling than for those that were sampled by genetic horizon (Table 3). As we noted above, sampling by fixed depths may cause an underestimation of C loss, but the apparent influence of fixed sampling depths on y-intercepts of regression equations indicates that the error is greatest for soils with low initial C inventories. Shallow depths sample smaller C inventories than larger depths, so we suspect that the underestimation of C loss is greatest when the fixed sampling depths are shallow (e.g. only 15 cm), and that this artifact partly accounts for the apparent positive y-intercepts.

Moreover, a good fit to the original regression equation (Eq. 1) does not necessitate a good fit to the transformed equation (Eq. 2). Using our analyses of data from A and B horizons, a comparison of the fit to the original regression equation (Fig. 4a) and the fit to the transformed equation (Fig. 4b) shows that the fit is much better for the original equation, and that the residuals differ in the two plots. The transformed equation for one of Mann's sets of regression parameters is also plotted for comparison. We do not know how well Mann's data fit this transformed equation.

Determining the y-intercept of Eq. 1 is a rather indirect test of the effects of initial C inventories on C loss. A more appropriate test of the null hypothesis, that the fractional loss of carbon is not related to the initial carbon content, is to compare these data directly in a regression

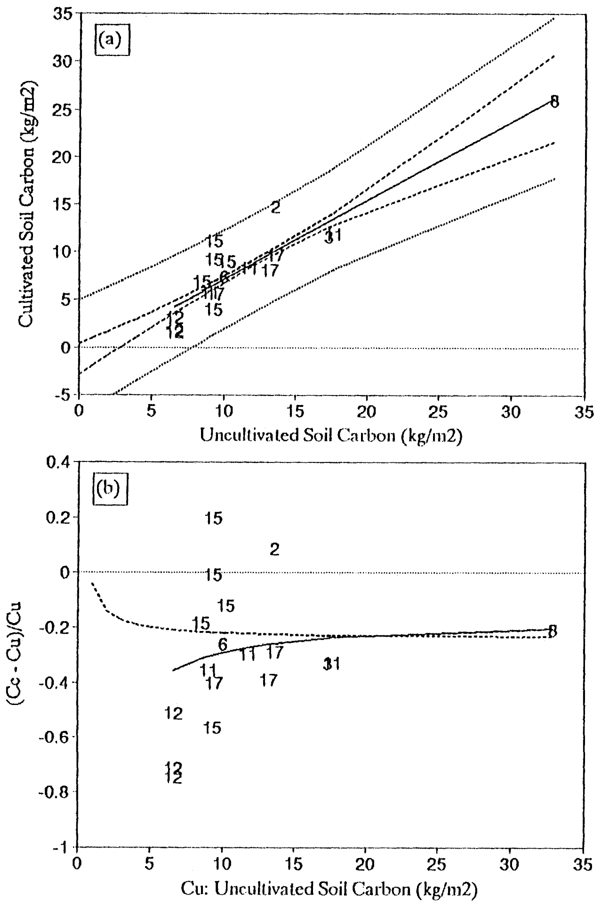


*Fig. 4.* In the upper panel (a), the soil carbon inventories of uncultivated and cultivated soils are shown for 18 pairwise comparisons of data on A-plus-B horizons. Plot symbols refer to studies numbered in Table 1. The least squares linear regression is shown as a solid line (Y = 0.83X − 1.26; $R^2$ = 0.84). The 95% confidence bands for the regression line are shown with dashed lines; note that a y-intercept of zero falls within the confidence bands. Dotted lines show the 95% confidence bands for the predicted-y. In the lower panel (b), the data are transformed as suggested by Mann (1986) to show the fractional loss ($[C_{Cultivated} - C_{Uncultivated}]/C_{Uncultivated}$) as a function of the original C inventory of the uncultivated soil ($C_{Uncultivated}$). In this transformation, a negative value indicates C loss; a positive value indicates C gain. The solid line shows the predicted response using the regression parameters of the regression shown in the upper panel, where $B_0 = -1.26$ and $B_1 = 0.83$. The dotted line shows the predicted response using the parameters of one of the regressions of Mann (1986), where $B_0 = +0.20$ and $B_1 = 0.76$. When the data fit this model and when $B_0$ is positive, the fraction of original soil C lost increases with increasing soil C inventory of the uncultivated soil ($C_u$), and the maximum fractional loss is predicted from the value $B_1 - 1$. When $B_0$ is negative, the fraction of original soil C lost decreases with increasing soil C inventory of the uncultivated soil ($C_u$), and the value $B_1 - 1$ predicts the minimum fractional C loss. However, the data presented here do not appear to fit this model.

analysis. For each of our subsets of data, we applied the regression equation

$$(C_u - C_c)/C_u = B_0 + B_1 \cdot C_u \tag{3}$$

where the variables are defined as before, but $C_u$ and $C_c$ have been reversed within the parentheses so that the fraction lost is expressed as a positive number. The slopes of these regressions were both positive and negative, but only one regression was statistically significant ($R^2 = 0.34$), and the slope for that regression was negative (Table 4). These regression analyses show no positive relation between the fraction of soil C lost following cultivation and the amount of C initially present in the uncultivated soil.

*Table 4.* Regression parameters for the equation $((C_c - C_u)/C_u) \cdot 100 = B_0 + B_1 \cdot C_u)$, where $C_c$ is the carbon content (kg C/m$^2$) of the cultivated soil and $C_u$ is the carbon content of the uncultivated soil.

| Sampling depth | $B_0$ | $B_1$ | $R^2$ | $n$ |
|---|---|---|---|---|
| A horizons | 64.09 | −2.51 | 0.34* | 14 |
| A and B horizons | 53.89 | −1.28 | 0.22 | 14 |
| | 41.23 | −0.94 | 0.05 | 18 |
| Entire solum | 46.73 | −1.21 | 0.04 | 21 |
| Fixed depth — top layer | 18.52 | 2.48 | 0.13 | 20 |
| Fixed depths > 30 cm | 25.39 | −0.14 | 0.00 | 25 |
| All data[1] | 29.39 | −0.19 | 0.00 | 55 |

* significant at $\alpha = 0.05$

[1] except peat soil from reference 18 of Table 1; see footnote in Table 3.

By using more stringent criteria that permit inclusion of fewer data in our analysis, we gain confidence that we avoid some sampling artifacts, such as the problem discussed above regarding shallow fixed sampling depths. As a trade-off, we lose power of our statistical tests and increase the probability of a type II error of accepting an invalid null hypothesis. Both approaches — assembling large datasets to maximize the power of statistical tests or applying stringent criteria to improve quality of smaller datasets — are legitimate. The relative merits of these contrasting approaches are open to debate and individual preference. Using the more stringent criteria to select a smaller database of higher quality, we conclude that the null hypothesis cannot be rejected, and that our data do not support earlier conclusions (Post & Mann 1991, Mann 1986) that the fractional amount of C lost from soil following cultivation is positively correlated with the initial soil C inventory.

*Effects of soil texture on C loss*

We used data on soil texture from those studies where it was provided to divide the comparisons into four classes of clay content of the surface horizon or sampling increment. Using these classes as plotting symbols, clay content appears to have no effect on the relation between C inventories of cultivated and uncultivated soils (Fig. 5). There is scatter about the regression line for all classes; the soils with high clay contents are not clustered on one side of the line as would be expected if clay content

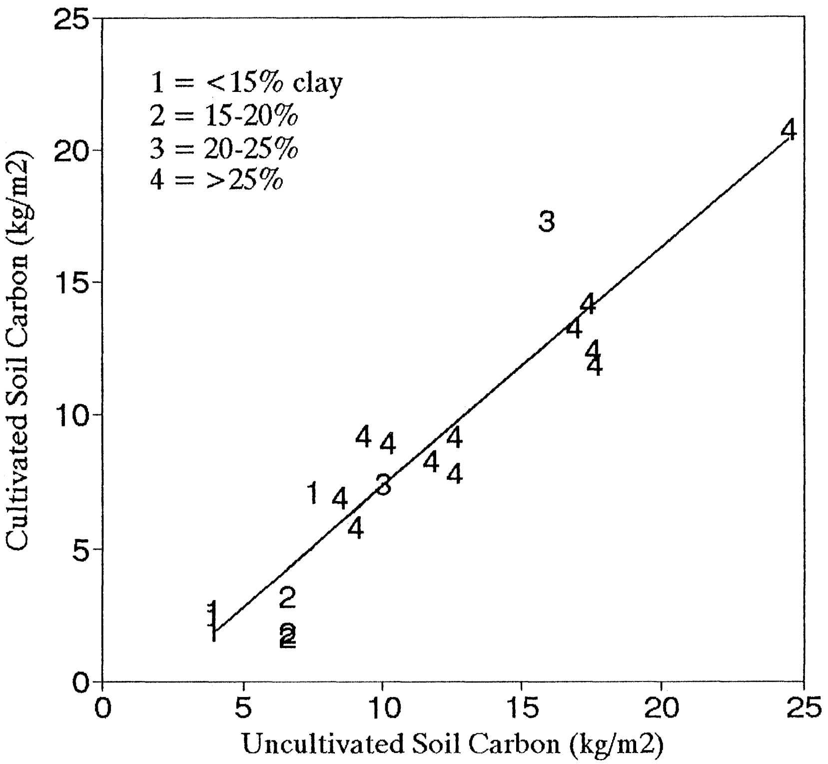


*Fig. 5.* The soil carbon inventories of surface horizons of uncultivated and cultivated soils are shown for the studies in Table 1 for which data on soil texture were provided. The plotting symbols indicate ranges of clay content shown in the figure. The least squares linear regression equation is $Y = 0.90X - 1.64$; $R^2 = 0.89$.

influenced the fractional loss of carbon inventory. Carbon inventories were lower for soils with low clay content and higher for soils with high clay content. This relation probably reflects the importance of clay content as a covariate with carbon content in Mollisols (Burke et al. 1989), which constitute the majority of the data in this analysis. This analysis also supports our earlier conclusion that the fractional loss of C inventory is not related to the initial C inventory of the uncultivated soil.

## Conclusions

Our analyses, that include recently available data on the effects of cultivation on soil C inventories, support two of the three conclusions reached in earlier reviews. First, our data are consistent with an estimate of loss of between 20% and 40% of the initial C inventory following initial cultivation. Our best estimate of mean soil C loss is about 40% in the A horizon and about 30% in the entire solum.

Second, our data support the generalization that most of the C loss occurs soon after initial cultivation. Nearly all of the loss that can be detected by these paired analyses occurs within 20 years, and most occurs within 5 years. Two studies in tropical regions indicate that most of the loss may occur within one or two years.

Our data do not support a third earlier conclusion that the fractional loss of soil C inventory increases with increasing initial C inventory of the uncultivated soil. We show that sampling by fixed depths probably underestimates soil C loss, and that this underestimation is probably greatest when shallow depths are used that sample relatively small C inventories. These sampling artifacts affect regression parameters and can make the effect of the initial C inventory on fractional C loss appear to be statistically significant. By comparing the fractional C loss directly with initial C inventories, we conclude that no relation exists within our dataset.

Our data support the assumptions of present global C budgets, that, on the average, cultivation causes a transfer to the atmosphere of about 25% to 30% of the C inventory of uncultivated soil.

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