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THE EFFECT OF TILLAGE ON SOIL ORGANIC MATTER USING ^{14}C: A CASE STUDY

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ABSTRACT. We compared four adjacent soil plots in an effort to determine the effect of land use on soil carbon storage. The plots were located at the High Plains Agricultural Research Laboratory near Sidney, Nebraska. We measured ^{14}C, total carbon, total nitrogen and ^{137}Ce to determine the size and turnover times of rapid and stable soil organic matter (SOM) pools, and their relation to land-use practices. Results were consistent with the model produced by Harrison, Broecker and Bonani (1993a) in that the ^{14}C surface soil data fell on the time trend plots of world ^{14}C surface soil data, indicating that the natural sod and non-tilled plots had a rapidly turning over SOM pool, comprising *ca.* 75% of surface soil carbon, and the tilled plots had a rapidly turning over SOM pool, comprising only 50% of surface soil carbon.

INTRODUCTION

The role of the terrestrial biosphere remains a major uncertainty in our understanding of the modern carbon cycle. Soil in particular represents a large and potentially variable carbon reservoir. Because soils are heterogeneous, extrapolating global carbon fluxes from limited, existing data can be only tenuous. Thus, it is crucial that we broaden our base of soil carbon data. To this end, we have researched carbon cycling in soils that have been subject to different land-use treatments. Atmospheric CO_2 has been rising as a result of human activities, including fossil-fuel combustion, cement manufacture and land conversion (*i.e.*, deforestation). Further, concentrations of CO_2 in the atmosphere are expected to double in the next century. Because CO_2 is a greenhouse gas that could perturb the global climate, it is important to understand its sources, sinks and controls in the environment.

The loss of soil organic matter (SOM) as a result of the conversion of native land into agricultural land is a well-known phenomenon (Davidson and Ackerman 1993; Harrison 1993; Post and Mann 1990; Schlesinger 1991; Tate 1987). Harrison, Broecker and Bonani (1993a) developed a box model of SOM using surface soil "bomb" ^{14}C data. This model allowed an estimation of soil carbon loss due to changes in land use. Based on the fact that soil pools with short residence times (<100 yr) will record a more pronounced response to atmospheric "bomb" ^{14}C than those with long residence times (~1000 yr), it is possible to partition soils into fast- and slow-cycling soil pools with respect to a time trend of bulk surface soil ^{14}C values (Harrison, Broecker and Bonani 1993a). Soils are a complex system comprised of various pools of organic material with a wide range of turnover times. Here we use "bomb" ^{14}C as a tracer of soil organic carbon. Atmospheric ^{14}C (as $^{14}CO_2$) is incorporated into plant materials during photosynthesis. Death and subsequent decomposition of plant materials incorporates ^{14}C into the SOM pool. Modeling SOM by partitioning it into two pools, a fast and a slow turnover pool, is a simplification, but it is adequate to yield an estimation of changes in carbon storage.

The purpose of this study is to evaluate the effect of land-use practices on carbon storage in cultivated soils subjected to different land-use practices. Related questions are whether agricultural soils have the potential to store excess CO_2, which soils are better candidates for increased carbon storage, and what cultivation/engineering practices would facilitate carbon storage. These questions must be resolved if we hope to understand and possibly mitigate the effects of rising atmospheric CO_2.

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METHODS

Site Description

Samples were collected from the High Plains Agricultural Laboratory near Sidney, Nebraska. The portion of the site used in this study is comprised of four adjacent plots, each 8.5 × 45.5 m. The soil has been characterized as a Duroc loam (fine, silty, mixed, mesic Pachic Haplustoll). The parent material was of mixed loess and alluvium; the site has a slope of <1%. All four plots were covered by native sod until 1970 when they were moldboard-plowed to permit the commencement of a long-term wheat/fallow rotation experiment. One plot was left in its natural sod state and the other three were planted with winter wheat (*Triticum aestivum*). One plot was subjected to plowing (plowing depth ~20 cm, no plant residue on surface), another to sub-till plowing in which most of the plant residue was left on the surface (tilled with V-shaped blades to a depth of 90–150 cm), and the third was a non-plowed plot on which weeds were controlled chemically. Wheat was harvested in odd years and the plots were left fallow in even years (Fenster and Peterson 1979). Samples were collected from each of the four plots (subsequently referred to as plowed, subtilled, sod and non-plowed) using a 5-cm diameter soil auger (hand) to represent depth intervals 0–5 cm, 5–10 cm, 10–20 cm, 20–30 cm, 30–40 cm, 40–50 cm, 50–75 cm and 75–100 cm. Soil was immediately transferred to plastic bags, excess air was expelled and the bags were sealed. Samples were processed following the procedure described by Trumbore (1988). Visible roots, organic debris and pebbles were removed at the time of sample collection. Samples were oven-dried at 60°C within one week of collection. Dry samples were passed through a 2-mm sieve to remove and discard remaining pebbles and bits of plant debris. Samples were further crushed and sieved through a .0092-mm mesh. We used distilled water to float out light organic debris and then added dilute HCl to remove carbonates and, finally, rinsed the samples with distilled water until neutral, at which point we re-dried and crushed the samples.

We measured total carbon and total nitrogen for each depth interval using a Carlo Erba carbon/nitrogen analyzer. Following the acid extraction of carbonates with HCl, we measured the samples' $CaCO_3$ contents on a Coulometrics coulometer. Because residual carbonate was present, we performed a second carbonate extraction and re-analyzed the samples by coulometry to ensure that all carbonate had been removed to avoid distortion of the organic ^{14}C signal. The second acid extraction resulted in complete removal of carbonates.

We prepared the samples for accelerator mass spectrometry (AMS) by sealing them in evacuated quartz tubes with CuO, Ag and quartz wool and combusting at 950°C for 2 h. We sent the CO_2 to the ETH lab in Zürich for target preparation and ^{14}C analysis. We transferred the remaining portion of each sample to aluminum cans and counted them for ^{137}Ce activities on either an intrinsic germanium detector or a lithium-drifted detector.

RESULTS AND INTERPRETATION

Data reported in the study are presented in Figures 1 through 6. ^{137}Cs, total organic carbon (TOC) and "bomb" ^{14}C trends demonstrate the homogenization of the soil profile due to both tillage processes. ^{137}Cs measurements enable the determination of the extent of erosion and physical mixing processes in the soil column because this nuclide tends to be strongly adsorbed onto clay and organic particles (Ritchie and McHenry 1990). Adsorption occurs rapidly after deposition and is, for practical purposes, irreversible. In undisturbed soils, ^{137}Cs shows an exponential decrease in depth. It is useful as a tracer in that its distribution is virtually only a function of mechanical transport. Thus, it clearly reflects disturbance due to plowing and other physical disturbances. As a measure of erosion and deposition, it is useful to calculate the total deposition of ^{137}Cs onto the landscape. In this study, we have integrated the activity of cesium over the entire sampling depth, divided by the cross-sectional area of the sample and compared the result to the known decay-corrected deposition value of 87 m Ci km^{-2} (as of 1993). The total deposition value was determined from measurements of strontium fallout over New York City multiplied by 1.5 (Olsen *et al.* 1978). We assume that the 87 m Ci km^{-2} value is a reasonable value for input to Nebraska soils in that our sample site is in the same latitudinal band as New York City. However, because our study site has a mean annual precipitation of 47 cm compared to a mean annual precipitation of 112 cm for New York City (Bair 1992), the ^{137}Cs input value was validated against Nebraska soil ^{137}Cs measurements reported by Graustein and Turekian (1986). Decay-correcting Graustein and Turekian's data to 1994 yielded a ^{137}Cs inventory of 87 m Ci km^{-2}, implying a deposition rate comparable to that of New York City.

Cesium inventories for 3 of the 4 plots were fairly consistent with one another and concur with atmospheric input. However, an excess in cesium was observed for the sod plot, implying a local input that deviated from the known atmospheric input for this region, or an influx of ^{137}Cs tagged soil particles to the sod plot (Fig. 1). The excess cesium appears to be mainly confined to the 0–5-cm depth interval, correlating well with the high percentage of organic carbon in this stratum (Figs. 2–3). Because cesium is associated with organic materials, mechanical transport could serve to reduce both SOM and ^{137}Cs in the soil profile, *i.e.*, tillage practices are known to promote erosion, providing one explanation of the lower values for the non-tilled plots. Further, some of the soil lost during plowing may have accumulated on the adjacent, grass-covered, natural sod site, its grass cover allowing the entrainment of windblown soil particles. The ^{137}Cs excess observed in the sod plot might also result from the fact that this plot was not plowed in 1970, before which most of the ^{137}Cs had been deposited. The other three plots were plowed, which may have caused some loss of surface soil. The question remains, however, why the sod site has a higher ^{137}Cs inventory than can be explained by the known deposition for this area.

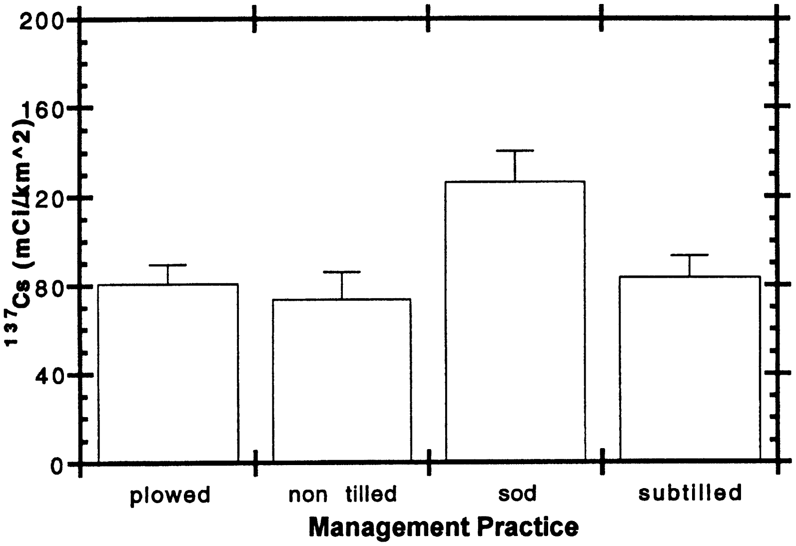

Fig. 1. ^{137}Ce inventories. Three of the four plots show inventories in agreement with the known deposition (corrected to 1993). The sod plot shows excess ^{137}Cs, possibly due to the input of ^{137}Cs tagged organic material. Total inventories with 1 σ errors are as follows (mCi km^{-2}): plowed 82.67 ± 12.20, non-tilled 73.60 ± 12.73, subtill 87.54 ± 17.96, sod 123.34 ± 13.85.

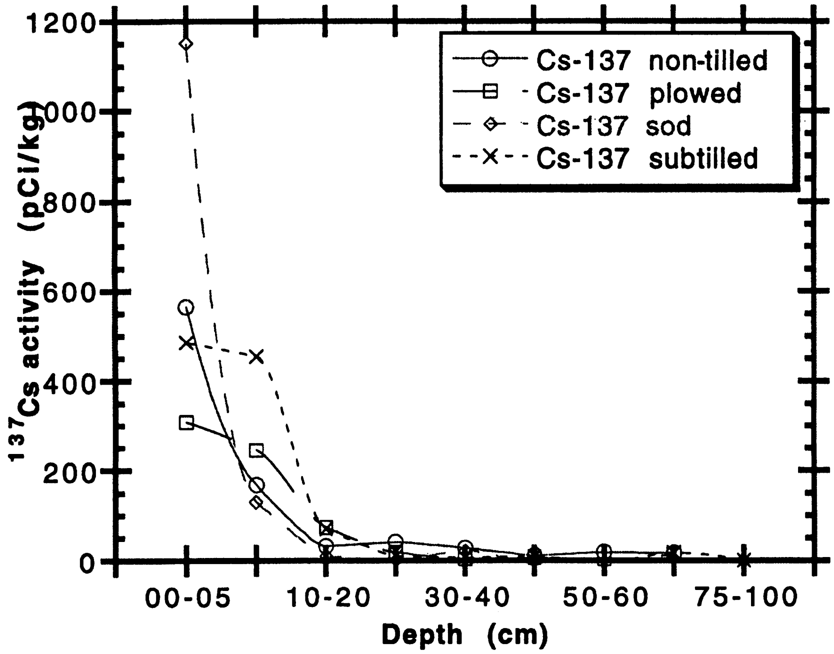

Fig. 2. ^{137}Cs profiles showing exponential decrease with depth

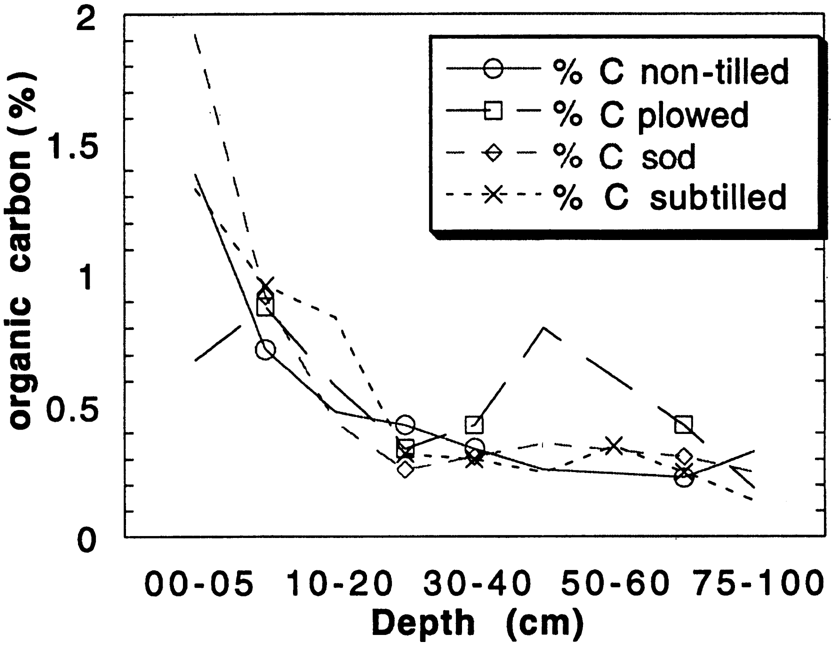

Fig. 3. Organic carbon profiles showing exponential decrease with depth

The ^{137}Cs distribution in the soil profile clearly demonstrates the effect of mechanical mixing. The higher surface values of the non-tilled plots decreased rapidly with depth. The plowed plots show a more homogeneous cesium distribution through the upper 10 cm and a subsequent rapid decline similar to that observed in the non-plowed plots (Fig. 2). Carbon and nitrogen concentration data showed similar trends with depth, decreasing down the soil column (Figs. 3–4). As expected, carbon contents decrease more rapidly in the non-tilled plots.

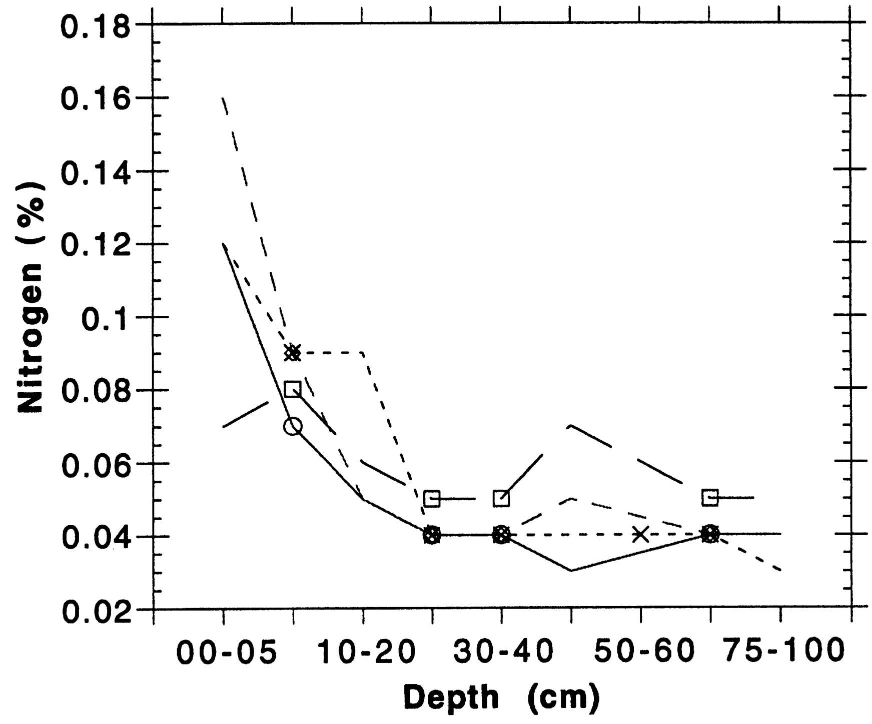

Fig. 4. Percent nitrogen plotted *vs.* depth. Percent nitrogen shows rapid decrease with depth.

^{14}C surface values, expressed as percent modern carbon (pMC), were higher for the non-tilled plots. Furthermore, the non-tilled plots had a steeper gradient in the upper 10 cm than the plowed plots (surface ^{14}C value ranges for non-tilled and tilled plots, respectively, are 102.5–108.2 and 101.8–103.4). The non-tilled plot, however, had a surface R value ($R=(^{14}C/^{12}C)_{sample}/(^{14}C/^{12}C)_{1850\,wood}$, as in Harrison, Broecker and Bonani 1993b) closer to that of the tilled plots than the natural sod (Fig. 5). The removal of vegetation from the non-tilled plot during harvest is a probable cause of the difference between the sod and non-tilled plots' ^{14}C values. All three treatments reduce the input of fresh organic material into the soil, whereas the litter produced on the sod plot is allowed to remain and enter the soil pool. Our deep soil ^{14}C value is within the range of deep soil global ^{14}C measurements (as cited in Harrison (1996)) and can be considered indicative of the presence of only a non-labile organic matter component. The intermediate ^{14}C value (R=.87) for the depth interval 30–40 cm of the sod plot indicates a decreased fraction of fast-turnover SOM at this depth. Taking this value to be a mixture between the fast cycling component and the slow-cycling component, we determine a fast-cycling component R value of 1.20 based on our deep soils measured R value, bulk surface ^{14}C soil value and the assumption that 75% of surface soil is fast-cycling. If the 30–40 cm depth interval R value of 0.87 is taken to represent a mixture between the fast-cycling (R value taken as 1.20) component and the slow-cycling component (R value that of deep soil, 0.71) we can calculate that this depth interval is comprised of roughly 33% fast cycling SOM and 67% slow cycling SOM, demonstrating a decreasing proportion of fast-cycling SOM with increasing depth in the soil column.

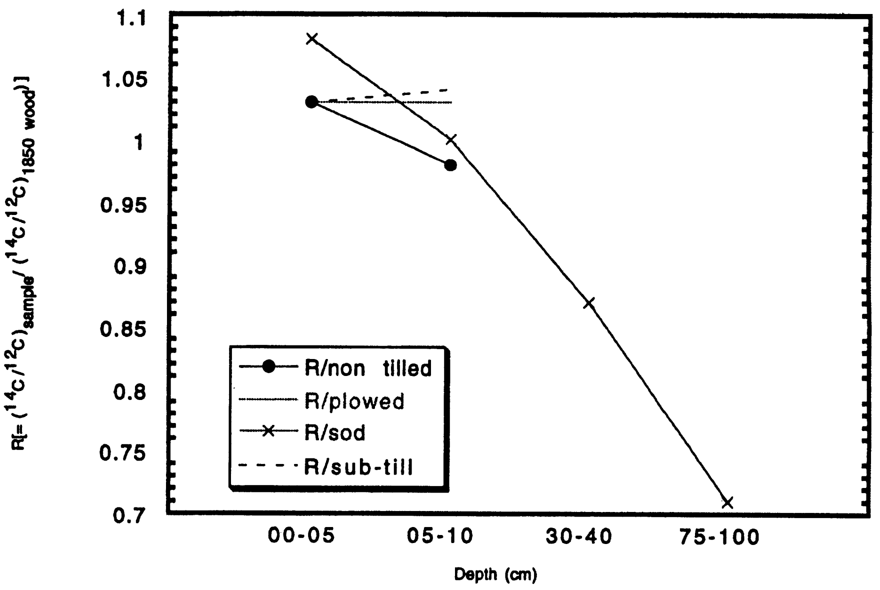

Fig. 5. ^{14}C *vs.* depth. The natural (sod) plot shows a steeper ^{14}C gradient. In addition, the surface ^{14}C data point for the natural plot is also significantly higher than the others, implying a larger component of fast-cycling carbon.

DISCUSSION

Based on a time trend of surface-soil ^{14}C measurements, Harrison, Broecker and Bonani (1993a) showed that surface SOM can be modeled in terms of two pools, a labile pool having a short residence time of ~25 yr, and a slow-turnover pool having a residence time ~3700 yr. Natural (non-cultivated) surface soils were composed on average of ~75% fast turnover SOM and 25% slow turnover SOM. Cultivated surface soils, however, were interpreted to be only 50% fast turnover SOM and 50% slow turnover SOM, indicating the possibility that cultivated surface soils had lost a fraction of their initial fast turnover pool. Although here we use bulk surface ^{14}C measurements to quantify the size and turnover times of carbon in SOM, the exponential decrease of "bomb" ^{14}C in the biosphere has limited its usefulness as a geochemical tracer for future studies. The 1970s would have been the ideal decade in which to collect soil samples and measure their ^{14}C activities, since this was the period when the maximum divergence in the various soil pools' ^{14}C values could be observed. Since then, the difference in ^{14}C values enhanced by the "bomb" ^{14}C spike among individual SOM pools has been decreasing, making interpretation of the data progressively more tenuous (Fig. 6). The ^{14}C data described herein appear to follow the "bomb" ^{14}C surface trends for cultivated (in this case, plowed) and non-cultivated soils indicating a significant decrease in the proportion of fast cycling to slow cycling SOM (*i.e.*, a 3:1 mixture to a 1:1 mixture of fast:slow components). Indeed, the sod site surface ^{14}C value of R=1.08 indicates that the natural site (sod) does have the largest proportion of fast cycling surface SOM of the three plots. All of our surface ^{14}C values follow the expected trends. However, the weighted averages of the ^{14}C values for the cultivated and uncultivated sites are very close together, arguably as a result of the atmospheric ^{14}C inventory decrease as described above (Fig. 7).

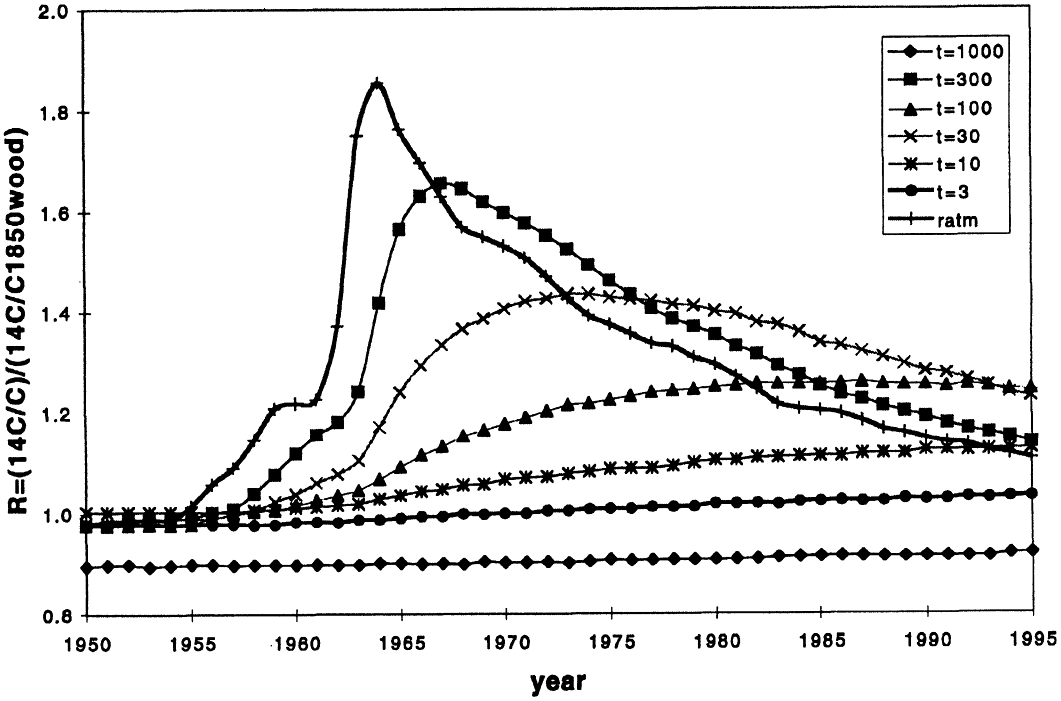

Fig. 6. Plot of ^{14}C over time from 1950–1995 (projected). Atmospheric R shows greatest increase due to direct input. Reservoirs of various turnover times respond to atmospheric trends at different rates, shorter turnover reservoirs having more pronounced, faster responses. R values for different reservoirs had the maximum divergence during the 1970s and since then they appear to be converging, limiting the potential of bomb radiocarbon as a tracer of SOM. (Figure from Harrison, Broecker and Bonani 1993b).

Cultivation reduces SOM by a variety of mechanisms. First and most obvious is that cultivation removes plant debris from the soil, thereby restricting the natural cycling of material in the system. Tilling or plowing incorporates some or all plant residue respectively into the soil column, as well as providing air that enhances the rate of microbial decomposition. Tilling also serves to break up soil-aggregate complexes, which have an important role in stabilizing SOM. When soil aggregates are broken up, SOM becomes much more susceptible to degradation and subsequent loss (Martel and Paul 1974; Schimel *et al.* 1994).

Non-tillage farming systems have been shown to enhance crop production while maintaining SOM levels (Fenster and Peterson 1979; Young 1982). Since enhanced terrestrial carbon storage is an option for mitigating rising CO_2 levels, it would be appropriate to further explore how cultivation practices can be used to facilitate such storage. Because it is the fast turnover pool that responds to atmospheric inputs on relatively short time scales, it is important that methods are developed that not only reduce its loss but possibly increase its proportion of the soil profile by taking advantage of CO_2-related growth enhancement in combination with fertilization.

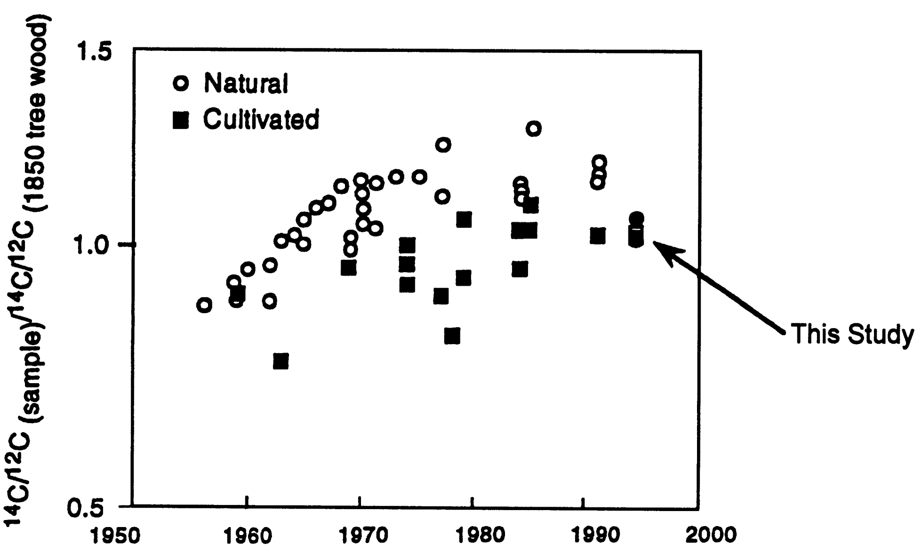

Fig. 7. Summary plot from Harrison *et al.* (1993a) showing the evolution of $^{14}C/^{12}C$ ratios in topsoil from natural and agricultural plots (worldwide) from 1950 to present. The results of the Nebraska soils are shown for comparison.

CONCLUSION

The TOC measurements show that the carbon content in all plots decreases rapidly with depth. Plowing and tilling processes serve to distribute organic material deeper in the soil column, as well as promote decay of detrital material contributing to the partial loss of fast-cycling SOM. These results are as expected, because plowing and tilling serve to physically homogenize the material in the soil column, mixing surface litter with deeper soil, as well as to promote removal of SOM. ^{14}C surface data indicate that the cultivated plots lost a significant fraction of their fast-cycling surface organic matter. Results indicate that a non-tillage cultivation is advantageous in maintaining levels of fast cycling carbon in the soil profile.

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