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Soil organic matter stratification ratio as an indicator of soil quality

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Abstract

Soil quality is a concept based on the premise that management can deteriorate, stabilize, or improve soil ecosystem functions. It is hypothesized that the degree of stratification of soil organic C and N pools with soil depth, expressed as a ratio, could indicate soil quality or soil ecosystem functioning, because surface organic matter is essential to erosion control, water infiltration, and conservation of nutrients. Stratification ratios allow a wide diversity of soils to be compared on the same assessment scale because of an internal normalization procedure that accounts for inherent soil differences. Stratification ratios of soil organic C were 1.1, 1.2 and 1.9 under conventional tillage (CT) and 3.4, 2.0 and 2.1 under no tillage (NT) in Georgia, Texas, and Alberta/British Columbia, respectively. The difference in stratification ratio between conventional and NT within an environment was inversely proportional to the standing stock of soil organic C to a depth of 15–20 cm across environments. Greater stratification of soil C and N pools with the adoption of conservation tillage under inherently low soil organic matter conditions (i.e., warmer climatic regime or coarse-textured soil) suggests that standing stock of soil organic matter alone is a poor indication of soil quality. Stratification of biologically active soil C and N pools (i.e., soil microbial biomass and potential activity) were equally or more sensitive to tillage, cropping intensity, and soil textural variables than stratification of total C and N. High stratification ratios of soil C and N pools could be good indicators of dynamic soil quality, independent of soil type and climatic regime, because ratios >2 would be uncommon under degraded conditions. Published by Elsevier Science B.V.

Keywords: Conservation tillage; Cropping intensity; Potential nitrogen mineralization; Soil microbial biomass; Soil organic carbon; Soil quality

1. Introduction

Soil is an essential natural resource that provides several important ecosystem functions, e.g. (1) a medium for plant growth, (2) regulation and partitioning of water flow in the environment and (3) an environmental buffer in the formation, attenuation, and degradation of natural and xenobiotic compounds (Larson and Pierce, 1991). Management that causes a decline in soil quality reduces these functional abilities, whereas stewardship preserves these abilities. Given the resiliency of nature, appropriate soil management techniques can be expected to restore ecosystem functions once degraded.

The organic contents of soil are vitally important in providing energy, substrates, and the biological diversity necessary to sustain numerous soil functions. The concept of ‘‘soil quality’’ has recognized soil organic matter as an important attribute that has a great deal of

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control on many of the key soil functions (Doran and Parkin, 1994). However, soil organic matter varies among environments and management systems, generally increasing with higher mean annual precipitation (Burke et al., 1989), with lower mean annual temperature (Jenny, 1980), with higher clay content (Nichols, 1984), with an intermediate grazing intensity (Parton et al., 1987; Schnabel et al., 2001), with higher crop residue inputs and cropping intensity (Franzluebbers et al., 1998), with native vegetation compared with cultivated management (Burke et al., 1989), and with conservation tillage compared with conventional tillage (CT) (Rasmussen and Collins, 1991).

A criticism of recent developments in the soil quality concept has been aimed at more clearly defining the role of soil organic matter towards increasing agricultural productivity and environmental quality (Sojka and Upchurch, 1999). The criticism questions the "Mollisol-centric" view that soil quality literature has taken and refer readers to a strong correspondence between soil taxonomy and the USDA–Natural Resource Conservation Service's use of soil property data, crop performance, and evaluator perceptions to model and map "a relative index of inherent soil quality" for the USA (Sinclair et al., 1996). Sojka and Upchurch (1999) stressed that regions of the world with low soil organic matter (i.e., Aridisols, Entisols and Inceptisols) are also highly productive and that total soil organic matter is unreliable as a predictor of soil and crop performance. Obviously, external inputs of irrigation and fertilization contribute much more to productivity in these more typically arid environments than in temperate environments with Mollisols and Alfisols.

Stratification of soil organic matter pools with soil depth is common in many natural ecosystems (Prescott et al., 1995) and managed grasslands and forests (Van Lear et al., 1995; Schnabel et al., 2001), as well as when degraded cropland is restored with conservation tillage (Dick, 1983). The soil surface is the vital interface that receives much of the fertilizers and pesticides applied to cropland, receives the intense impact of rainfall, and partitions the flux of gases into and out of soil. It is hypothesized that the degree of stratification can be used as an indicator of soil quality or soil ecosystem functioning, because surface organic matter is essential to erosion control, water infiltration, and conservation of nutrients. My objectives were to (1) develop the concept of using a stratification ratio as an indicator of dynamic soil quality, (2) test the capability of several different soil properties to express the extent of stratification, and (3) illustrate the potential of soil organic matter stratification ratio to detect management-induced changes in dynamic soil quality.

2. Materials and methods

Data from several long-term comparisons between CT and no tillage (NT) were compiled in this analysis. On a Weswood silty clay loam (fine-silty, mixed, superactive, thermic Udifluventic Ustochrept) in southcentral Texas, soil was collected at depths of 0–5, 5–12.5, and 12.5–20 cm in the 10th year of an experiment comparing (1) tillage [conventional disk and bed (CT) and NT], (2) crop sequence [wheat (*Triticum aestivum* L.), wheat/soybean (*Glycine max* (L.) Merr.)-sorghum (*Sorghum bicolor* (L.) Moench), and wheat/soybean], and (3) N fertilization (0 and 68 kg N ha^{-1}). Absolute concentrations of soil properties were reported in Franzluebbers et al. (1994a,b).

In Alberta and British Columbia, soil was collected at depths of 0–5, 5–12.5, and 12.5–20 cm under conventional shallow tillage (CT) and NT in small-grain cropping systems at the end of the 7th year on a Donnelly loam (sandy-skeletal, mixed, frigid Typic Eutrocryept), at the end of the 16th year on a Donnelly silt loam, at the end of the 4th year on a Hythe clay loam (fine, montmorillonitic, frigid, Mollic Cryoboralf), and at the end of the 6th year on a Falher clay (fine, montmorillonitic, frigid, Typic Natriboralf). Absolute concentrations of soil properties were reported in Franzluebbers and Arshad (1996a,b,c).

In Georgia, soil was collected at depths of 0–2.5, 2.5–7.5, and 7.5–15 cm under CT, paraplowing with NT planting, shallow cultivation with NT planting, and in-row chisel at planting alternated with NT planting at the end of 4 years in a millet (*Panicum miliaceum* L.)/clover (*Trifolium incarnatum* L.)/cotton (*Gossypium hirsutum* L.)/rye (*Secale cereale* L.) cropping system. Absolute concentrations of soil properties were reported in Franzluebbers et al. (1999).

Stratification ratios were calculated from soil properties at 0–5 cm divided by those at 12.5–20 cm in

Texas and Alberta/British Columbia and from soil properties at 0–2.5 cm divided by those at 7.5–15 cm in Georgia. A complete description of methods employed for soil analyses can be found in original reports. Briefly, soil organic C was determined by the modified Mebius method or dry combustion, particulate organic C and N were from the dispersed soil collected on a 0.05 mm screen, soil microbial biomass C was determined with the chloroform fumigation–incubation method without subtraction of a control, potential C and N mineralization were from aerobic incubations at 25 °C for either 10 or 24 days, the flush of CO_2 following rewetting of dried soil was from an aerobic incubation at 25 °C for 3 days, and water-stable aggregate fractions were from soil collected on screens with openings of 0.05, 0.25, and 1.0 mm following slaking and vertical stroking for 10 min.

3. Results and discussion

3.1. Soil organic C under conventional and NT in diverse environments

Soil organic C concentration was relatively uniformly distributed within the surface 15–20 cm under long-term CT in Georgia and Texas (Fig. 1). In contrast, NT management resulted in a significant increase in soil organic C at the soil surface at both these locations. Accumulation of soil organic C at the soil surface was a result of surface placement of crop residues and a lack of soil disturbance that kept residues isolated from the rest of the soil profile. Greater soil organic C under CT compared with NT at a depth of 7.5–15 cm in Georgia was a result of tillage operations that incorporated surface organic C throughout the 15 cm tilled zone. Decomposition of surface-placed residues is often slower than when incorporated in the soil profile (Brown and Dickey, 1970; Ghidey and Alberts, 1993), primarily because of less optimal moisture conditions (Franzluebbers et al., 1996). Due to the less than optimal decomposition environment when soil is left undisturbed and residues are at the surface compared with disturbance and incorporation with tillage, transformation of organic C from plant-derived residues into soil organic C may be more effective under NT than under CT (Franzluebbers et al., 1998).

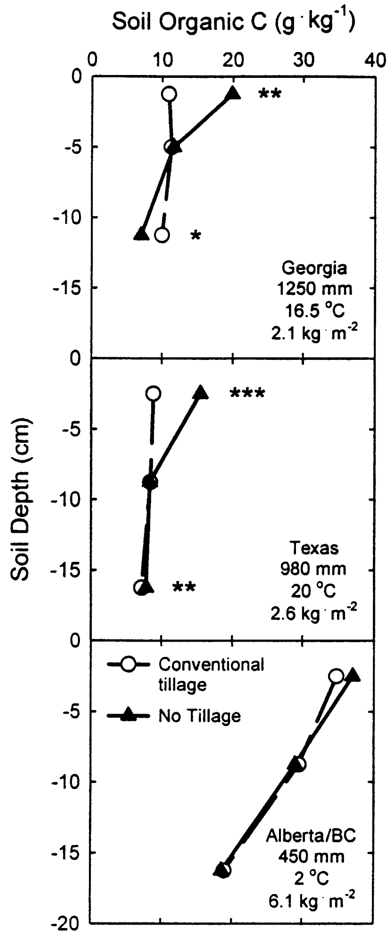

Fig. 1. Soil organic C depth distribution under conventional and NT in Texas, Georgia, and Alberta/British Columbia. *, ** and *** indicate significance between tillage systems within a depth at $P \leq 0.1$, $P \leq 0.01$, and $P \leq 0.001$, respectively.

Soil organic C concentration decreased with increasing soil depth under both CT and NT in Alberta/British Columbia (Fig. 1). Unlike in Texas and Georgia, NT management did not significantly increase soil organic C at the soil surface compared with CT. The cold, dry climatic conditions and shallow tillage depth (10–15 cm with CT) probably did not offer a significant decomposition advantage to CT over NT, as is often observed in warmer and wetter climates.

Decreasing mean annual precipitation and temperature tended to increase soil organic C concentration within a soil depth increment, irrespective of tillage management (Fig. 1). If absolute soil organic C concentration alone were a determinant of soil quality, then CT management could be considered as beneficial as NT in Georgia, because of the same total amount of soil organic C in the 0–15 cm soil profile [2.1 kg m^{-2} under both management systems (Franzluebbers et al., 1999)]. This same approach would indicate that soil quality in Texas and Georgia, irrespective of tillage management, would be less than half of that in Alberta/British Columbia under CT. However, comparison of absolute amounts of soil organic C across regions does not seem to be an appropriate approach for assessing soil quality, since the driving variables of mean annual temperature and precipitation would never allow soil organic C in warmer and drier climates to accumulate to the same level as in cooler and moister climates. To circumvent these environmental limitations, it has been suggested that minimum and maximum values of key soil properties could be established for various climatic regions, in order to develop quantitative relationships between these key soil properties and soil function (Doran and Parkin, 1994). It would be an enormous task to accurately define the minimum and maximum levels of soil properties under the multitude of climatic regions and various other factors such as soil texture, native fertility, soil mineralogy, slope, and aspect, which all control steady-state levels of dynamic soil properties, independent of management. Ultimately, land managers need to know the *effect of their management on soil ecosystem functioning*, in addition to the effect of environmental factors beyond their control. The concept of soil organic matter stratification is offered as an alternative soil quality assessment protocol to overcome these inherent differences in soil capability among environments. Stratification, in this context, is defined as a soil property at the soil surface divided by the same soil property at a lower depth, such as the bottom of the tillage layer. This lower depth is used to normalize the assessment so that soils from different ecoregions or landscape positions varying in inherent soil capability can be fairly compared.

The stratification ratio of soil organic C varied from 1.1 to 1.8 under CT and increased with decreasing mean annual precipitation, decreasing mean annual temperature, and increasing standing stock of soil organic C (Fig. 2). The stratification ratio of soil organic C was greater under NT compared with CT in Georgia and Texas and tended to be greater in Alberta/British Columbia ($P = 0.11$), but the difference between tillage systems decreased with increasing standing stock of soil organic C. Contrary to absolute quantities of soil organic C, the stratification ratio of soil organic C indicated that NT management might improve soil quality the most in Georgia and Texas, where the high temperature limits soil organic C accumulation. High stratification ratios of soil C and N pools should reflect relatively undisturbed soil with a high quality soil surface that leads to (1) improved water infiltration, (2) better macropore development for rapid water transmission into the soil profile, (3) more stable aggregates, (4) an abundant supply of organically bound slow-release nutrients, and (5) a diverse food supply for beneficial soil organism activities.

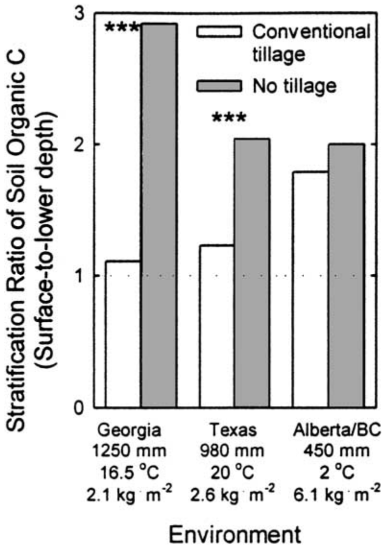

Fig. 2. Stratification ratio of soil organic C under conventional and NT in Georgia, Texas, and Alberta/British Columbia. *** indicates significance between tillage systems within an environment at $P \leq 0.001$. Environmental variables for each site are mean annual precipitation (mm), mean annual temperature (°C), and standing stock of soil organic C (kg m^{-2}) to a depth of 15 cm in Georgia and to a depth of 20 cm in Texas and Alberta/British Columbia.

3.2. *Stratification ratio of soil properties in Texas*

Increasing cropping intensity would be expected to supply greater quantities of crop residues to soil, which should improve soil organic matter in the long

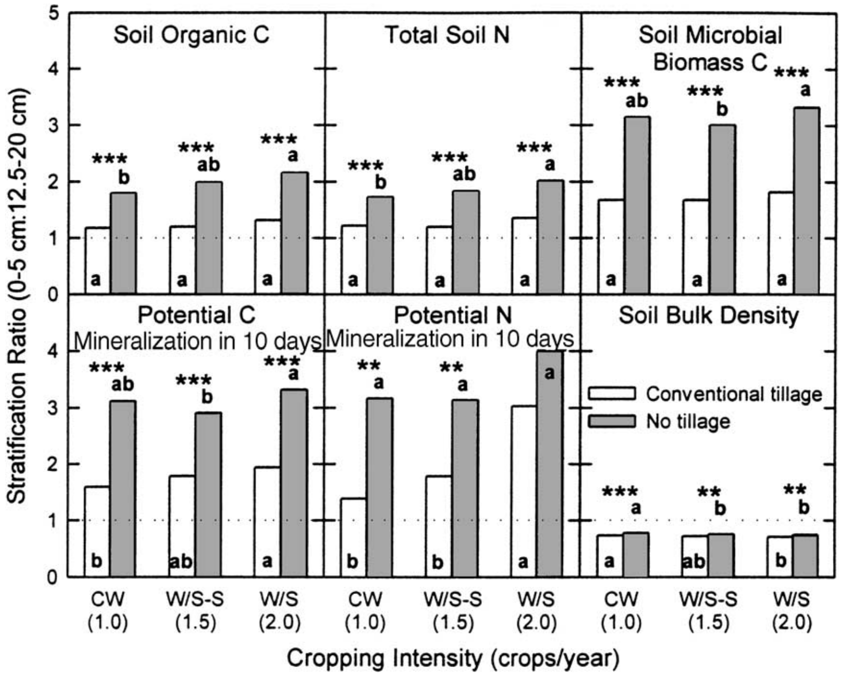

Fig. 3. Stratification ratio of soil properties under conventional and NT in Texas as affected by cropping intensity (CW is continuous wheat, W/S–S is wheat/soybean–sorghum rotation, and W/S is wheat/soybean double crop). Within a tillage system, bars with different letters indicate significance at $P \leq 0.1$. Within a cropping intensity, ** and *** indicate significance between tillage systems at $P \leq 0.01$ and $P \leq 0.001$, respectively.

term. Under CT, the stratification ratio of soil organic C, total soil N, and soil microbial biomass C tended to increase with increasing cropping intensity, but was not significant (Fig. 3). However, the stratification ratio of the more biologically active pools of potential C and N mineralization did increase with increasing cropping intensity. Under NT, stratification ratios of soil C and N pools also tended to increase with increasing cropping intensity. The greater stratification ratios with increasing cropping intensity were probably due to greater C inputs with more intensive cropping (Franzluebbers et al., 1998) and reduced soil water available for decomposition by soil microorganisms because of greater crop water uptake (Franzluebbers et al., 1995a,b). Irrespective of cropping intensity, stratification ratios of soil C and N pools were greater under NT than under CT.

Time of soil sampling could influence estimates of biologically active soil C and N pools because fresh roots and their decomposition products would accumulate during the growing season. Stratification ratios of potential C and N mineralization tended to be greater at wheat flowering in March than at planting in November, irrespective of tillage system (Fig. 4). However, the significantly higher stratification ratio of soil microbial biomass and potential C and N mineralization under NT than under CT was maintained, independent of sampling time. Seasonal variability in the stratification ratio of soil microbial biomass C was small (3–6%) compared with seasonal variation in absolute estimates of soil microbial biomass C (8–13%) (Franzluebbers et al., 1994b). This consistency in stratification ratio of biologically active soil C and N pools with respect to long-term tillage management suggests that sampling time would not be a critical issue if this approach were used to estimate long-term changes in soil quality.

Stratification ratio of soil bulk density was lower under CT than under NT in all cropping intensities (Fig. 3). Soil bulk density is considered a negative soil attribute under most conditions, since high bulk density limits soil porosity and subsequent water

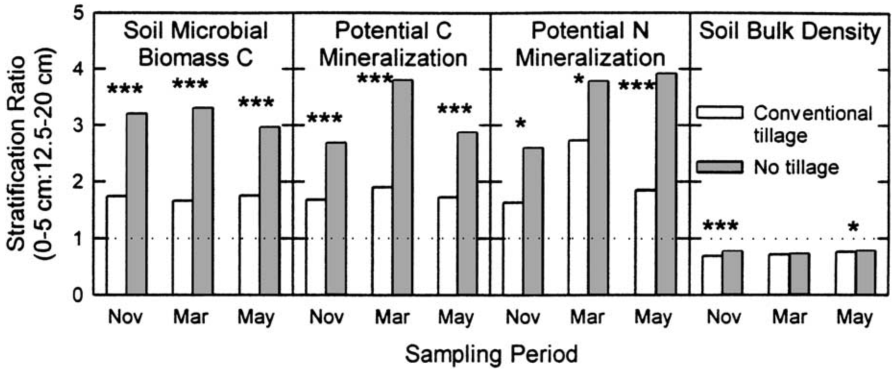

Fig. 4. Stratification ratio of soil properties under conventional and NT in Texas as affected by sampling period (Nov is at wheat planting, Mar is at wheat flowering, and May is at wheat maturity). Within a sampling period, * and *** indicate significance between tillage systems at $P \leq 0.1$ and $P \leq 0.001$, respectively.

movement and plant root development. Therefore, a lower stratification ratio of soil bulk density should reflect improved soil quality. One of the primary reasons for tillage is to loosen soil for better seedling and root development. This function of tillage was adequately expressed in this study in Texas, especially early in the growing season at wheat planting (Fig. 4). The diminishing effect of surface soil loosening with tillage as the growing season progresses reflects the need for frequent tillage to restore this loose condition because of the enhanced decomposition of soil organic matter that would otherwise help to alleviate soil compaction.

3.3. Stratification ratios of soil properties in Georgia

The type and frequency of tillage would be expected to alter the depth distribution of soil properties because of differences in the amount of soil disturbance. Stratification ratios of soil C and N pools were lowest with yearly CT and increased with decreasing frequency of paraplow tillage (Fig. 5). Highest stratification ratios were obtained for particulate organic C and N, although large random variability did not allow significant distinction between CT and paraplow tillage each year. Particulate organic C and N are coarse physical fractions of organic matter that represent an intermediate stage of residue decomposition (Cambardella and Elliott, 1992). Stratification ratios of soil microbial biomass C were lower than of particulate organic C and N, but the lower random variability in the stratification ratio of soil microbial biomass C was more sensitive to differences among tillage variables. The flush of CO_2 in 3 days following rewetting of dried soil was equally sensitive to tillage variables as other soil C and N pools. The flush of CO_2 is a simple microbial activity assay that requires minimal equipment and time and relates well to other biologically active soil organic matter pools, including longer term potential C and N mineralization and soil microbial biomass (Franzluebbers et al., 2000).

Stratification ratios of soil C and N pools were also lowest under CT compared with other tillage types and increased along a gradient with less soil disturbance (Fig. 6). Paraplowing loosened soil in the autumn followed by NT planting. Shallow cultivation controlled weeds in the summer following NT planting. In-row chisel loosened the soil zone immediately below the seed only. Paraplowing likely incorporated some surface residues and, therefore, is a more disruptive soil management operation than in-row chiseling.

Stratification ratios of clay content and soil bulk density decreased with reduced frequency of tillage and reduced disturbance level (Figs. 5 and 6). Stratification ratios of these soil properties are negatively associated with soil quality, and therefore, responded in a manner consistent with soil C and N pools to the gradients in soil disturbance. Soil mixing would be expected to uniformly distribute the high clay content of the argillic horizon of this Cecil soil with that of the sandy surface soil. Unlike other soil properties, stratification ratios of water-stable macroaggregates and soil inorganic N were not particularly sensitive to the gradients in soil disturbance, and therefore, their

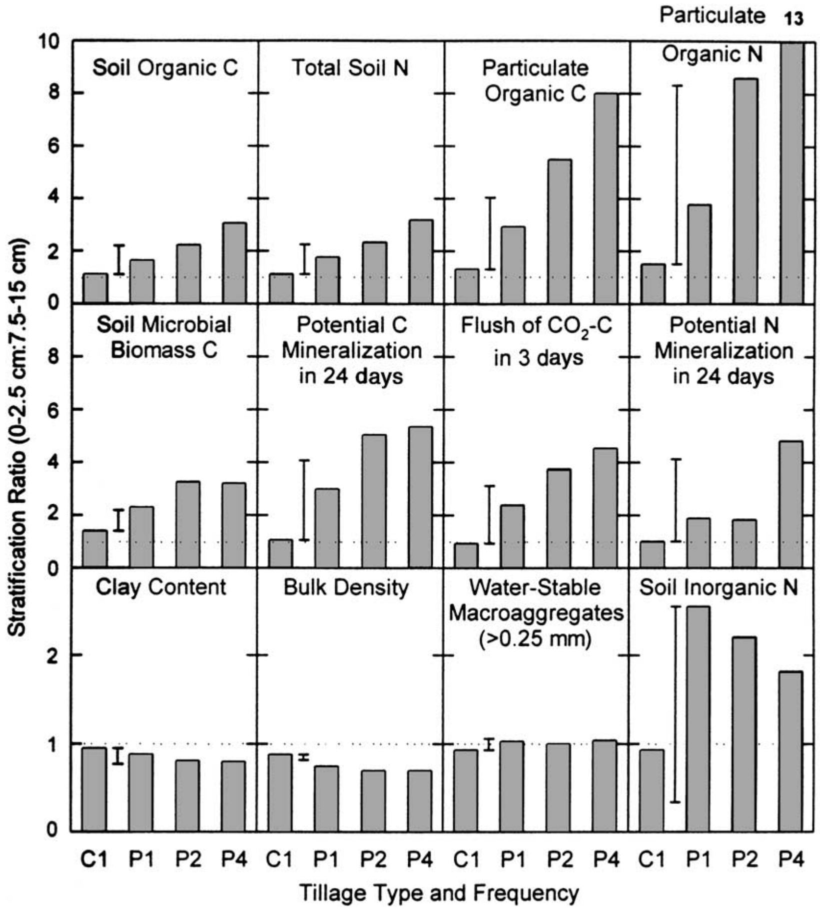

Fig. 5. Stratification ratio of soil properties in Georgia in response to tillage type and frequency (C1 is CT each year, P1 is paraplow each year with NT planting, P2 is paraplow every 2 years with NT planting, and P4 is paraplow every 4 years with NT planting). Error bar in each panel is LSD at $P = 0.1$.

value for assessing changes in soil quality appears questionable.

3.4. Stratification ratios of soil properties in Alberta/British Columbia

In general, stratification ratios of soil C and N pools for the four soils in Alberta and British Columbia were minimally and variably affected by tillage system (Fig. 7), which was unlike that observed for soils in Texas and Georgia. One of the most consistent properties with respect to tillage system was the stratification ratio of potential N mineralization, where it was numerically higher under NT than under CT in all soils, but significantly higher in the loam and silt loam soils.

A feature that set the stratification ratios of soil C and N pools from Alberta/British Columbia apart from those in Texas and Georgia was the relatively high ratio even under CT. The high stratification ratio of soil C and N pools under CT in Alberta/British Columbia suggests that soil degradation with inversion tillage may not have proceeded to near the extent that it has in other regions. There may be several reasons for this difference among regions. Firstly, soils in the Peace River region of northern Alberta and British Columbia have been under cultivation for less than a century, while soils in the southern USA have

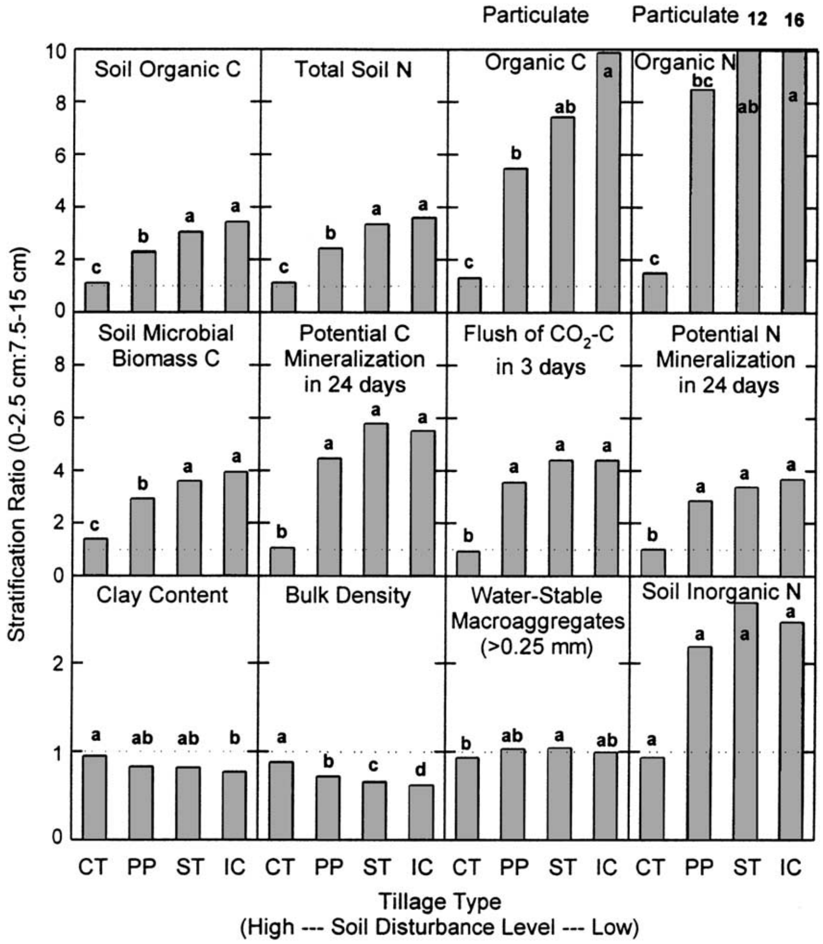

Fig. 6. Stratification ratio of soil properties in Georgia as affected by tillage type (CT is conventional tillage, PP is paraplow with NT planting, ST is non-inversion sweep cultivation with NT planting, and IC is in-row chisel at planting without further disturbance). Bars with different letters indicate significance at $P \leq 0.1$.

been cultivated for up to several centuries. Long-term cultivation would be expected to deplete organic matter reserves to a greater extent. Secondly, the CT operation in Alberta/British Columbia has been shallow disk tillage (10–15 cm) for decades, while deeper inversion tillage systems were historically employed in the regions examined in Texas and Georgia, although the recent CT systems from experiments in Texas and Georgia were intermediately deep disk systems (15–20 cm). Another reason, and thought to be the major factor, is the difference in climate among regions. Alberta/British Columbia has a cold and dry climate with a short growing season, while Texas and Georgia have warm and relatively moist climates with a long growing season. The cold and dry climate limits decomposition of organic matter, resulting in a high standing stock of soil organic C. The same climatic controls that result in overall greater standing stock of soil organic C in cold and dry regions are hypothesized to also minimize the stimulatory effect of tillage on soil organic matter decomposition (Franzluebbers and Arshad, 1996b). In warm and moist climates, incorporation of plant residues results in more rapid decomposition than those exposed at the soil surface.

The stratification ratio of water-stable aggregation and potential N mineralization indicated that coarse-textured soils responded to NT management more

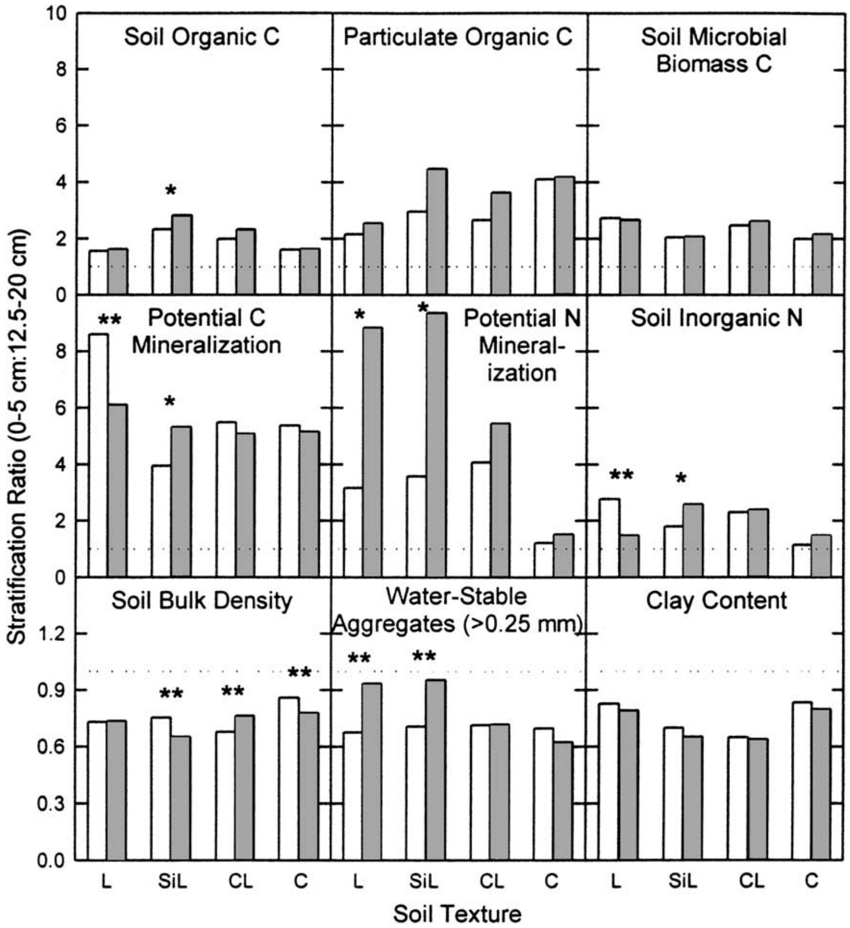

Fig. 7. Stratification ratio of soil properties under conventional and NT in Alberta/British Columbia as affected by soil texture (L is a Donnelly loam, SiL is a Donnelly silt loam, CL is a Hythe clay loam and C is a Falher clay). Within a soil texture, * and ** indicate significance between tillage systems at $P \leq 0.1$ and $P \leq 0.01$, respectively.

than fine-textured soils (Fig. 7). This soil textural interaction with tillage management occurred, perhaps because coarse-textured soils are generally lower in the degree of aggregation and organic matter, and therefore, had a greater potential to respond to non-disturbance effects from transient and temporary binding agents (Franzluebbers and Arshad, 1996c). The stratification ratio of these two properties was significantly greater under NT than under CT in the loam (18% clay, 4.3 kg soil organic C m^{-2}) and the silt loam (28% clay, 5.1 kg soil organic C m^{-2}), but not in the clay loam (37% clay, 6.8 kg soil organic C m^{-2}) and the clay (63% clay, 8.2 kg soil organic C m^{-2}). The greater stratification ratio under NT than under CT in response to the inverse gradient in the standing stock of soil organic C (controlled by soil texture) is consistent with the tillage effect in response to the inverse gradient in the standing stock of soil organic C (controlled by climate) (Fig. 2).

The cementing of soil particles and organic materials together into water-stable aggregates via soil biological activity results in increased concentration of total and mineralizable C and N with increasing aggregate size (Elliott, 1986). Stratification ratio of soil C pools also tended to increase with increasing aggregate size (Fig. 8). Although the tillage effect was variable or not significant, the stratification ratios of soil microbial biomass C and potential C mineralization were

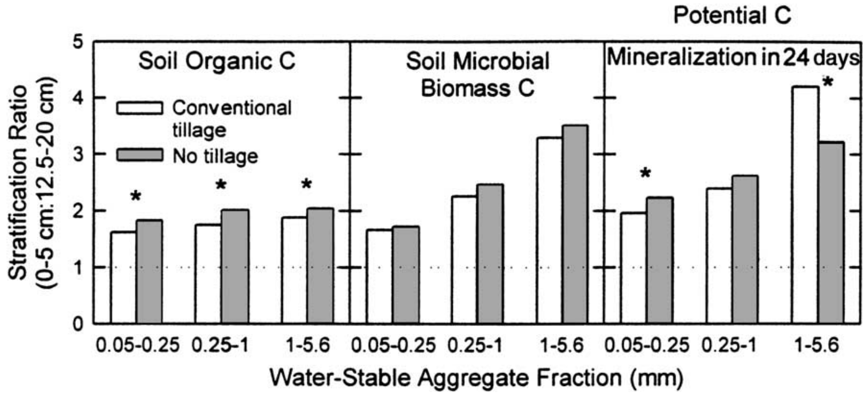

Fig. 8. Stratification ratio of soil properties from water-stable aggregate fractions under conventional and NT in Alberta/British Columbia. Within a water-stable aggregate fraction, * indicates significance between tillage systems at $P \leq 0.1$.

more strongly related to aggregate size fraction, independent of tillage system, than was the stratification ratio of soil organic C. The high stratification ratios with large water-stable aggregates under both CT and NT suggests that soil quality improvements are likely to be preferentially expressed in labile soil organic matter associated with transient aggregation processes.

4. Summary and conclusions

Stratification ratios of most soil properties were greater under NT compared with CT, with the greatest difference between tillage systems occurring in Texas and Georgia (hot, wet, and low soil organic matter environments) and the least difference in Alberta/British Columbia (cold, dry, and high soil organic matter environment). This interaction between tillage and environment suggests that conservation tillage management systems may have the most benefit to soil quality in climatic regions and soil conditions with the lowest native soil organic matter. This conclusion supports the criticism of Sojka and Upchurch (1999), which argued that too often environments high in total standing stock of soil organic matter have been preferentially identified as high in soil quality. The concept of stratification ratio of soil organic matter pools presented here does rely on an increase in soil organic pools, but primarily at the soil surface, because this is the vital interface that (1) receives much of the fertilizers and pesticides applied to cropland, (2) receives the intense impact of rainfall, and (3) partitions the flux of gases into and out of soil. The mechanisms that affect productivity and environmental quality begin at the soil surface.

Stratification ratios of soil organic C and N pools (i.e., total and particulate organic C and N, soil microbial biomass C, and potential C and N mineralization) under NT management were always >2, while they were often <2 under CT. The exception to this general relationship occurred in soils from Alberta/British Columbia, in which stratification ratios of soil organic C and N pools were also ≥ 2 under CT. Because of high 'native' stratification ratios under CT in Alberta/British Columbia, NT management often did not lead to increases in stratification ratios. Certainly more research is needed, but preliminary analyses indicate that stratification ratios of soil organic C and N pools >2 would be an indication that soil quality might be improving, and therefore, the economic and ecological impacts of that particular land management system should be more fully analyzed for its contribution to agricultural sustainability.

Further research is needed to (1) test the applicability of this soil quality indicator approach in different agroecological zones, (2) determine the most appropriate sampling depths for calculating a stratification ratio in diverse environments, and (3) make quantitative relationships between changes in stratification ratios of soil C and N pools and the ability of the soil to function, especially since several different relationships might be possible (Fig. 9).

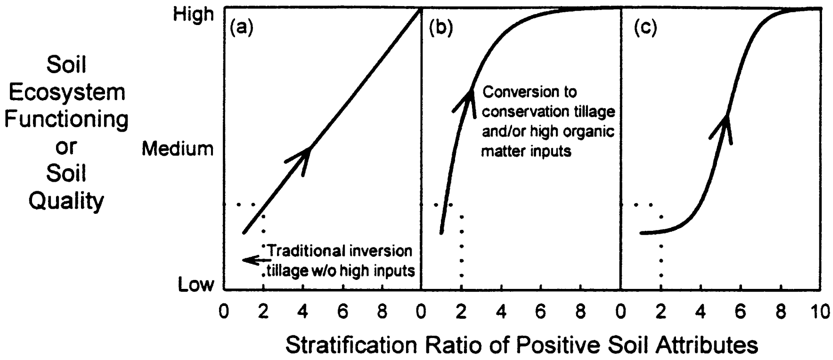

Fig. 9. Conceptual illustration of how stratification ratio of positive soil attributes (e.g., soil organic C, soil microbial biomass C, potential N mineralization) could be related to soil ecosystem functioning or an estimate of soil quality. Traditional inversion tillage without high organic matter inputs would have a low stratification ratio (<2) and low to medium soil quality. By increasing the stratification ratio of positive soil attributes with conservation tillage, ecosystem functioning and soil quality should improve. Three relationships are hypothesized, i.e. as the stratification ratio increases soil ecosystem functioning could (a) increase linearly, (b) increase rapidly initially and then plateau, or (c) not respond initially and increase logarithmically later.

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