J. Range Manage.
52:666-670 November 1999

Soil carbon and nitrogen changes following root-plowing of rangeland

W. R. TEAGUE, J. K. FOY, B.T. CROSS AND S.L. DOWHOWER

Authors are associate professor and research associates, Texas Agricultural Experiment Station, P.O. Box 1658, Vernon, Tex.76385

Abstract

The effects of root-plowing on soil organic carbon and nitrogen were investigated by comparing paired undisturbed native rangeland with root-plowed sites in the southern Great Plains. Time since root-plowing ranged from 4 to 22 years. We hypothesized that following root-plowing (1) soil carbon would initially drop but recover to the level of untreated range within a 5–10 year period, and (2) the permanent removal of mesquite trees, which enhance ecosystem carbon and nitrogen and provide shade that lowers soil temperature, would result in a slow decline in soil carbon and nitrogen in this ecosystem.

There were not significant differences due to treatment for either soil carbon mass (g m^{-2}) (P=0.81) or nitrogen mass (P=0.62). There were significant differences in soil carbon mass (P=0.0014) with respect to elapsed time since plowing. The upper soil layer (0–100mm) had higher carbon levels (P=0.0001) than the deeper soil layer (100–200mm)(1422 ± 210 g m^{-2} vs. 1111 ± 206 g m^{-2}). Differences in soil nitrogen were similar to those of soil carbon. There were significant differences in nitrogen among years-since-root-plowing observations (P=0.003) and the upper soil layer had higher nitrogen levels than the deeper soil layer (138 ± 18 g m^{-2} vs. 107 ± 18 g m^{-2})(P=0.0001).

When the data were analyzed using paired native site values as a covariate to account for site differences, the sites that had been root-plowed 4 years previously had higher soil carbon (P<0.08) and nitrogen (P<0.09) than the sites root-plowed 11, 16, and 22 years previously. These results are the opposite of what was hypothesized. This is probably due to root-plowing being a non-recurring treatment that did not invert the soil or remove the perennial grass cover. The slight increase in carbon measured 4 years after root-plowing was possibly caused by the large amount of dead tree roots in the soil after plowing. This would immediately increase the total amount of dead plant material entering the decomposing pool, elevating carbon levels temporarily before they returned slowly to previous levels. There was no trend of decreasing soil carbon or nitrogen over the 22 year period covered. It does not appear that removal of mesquite trees changes soil carbon or nitrogen levels in this ecosystem relative to native rangeland with mesquite trees.

Key Words: Soil, organic carbon, mesquite rangeland, Southern Great Plains

The E. Paul and Helen Buck Waggoner Foundation Inc. and the Texas Agricultural Experiment Station provided funding for this research. We thank Tom Boutton for conducting carbon and nitrogen analyses, Charles Lightfoot for help with sampling and Diane Conover who assisted with bulk density and soil texture analyses. Tom Boutton, Cindy Cambardella, Vince Haby and Don Robinson provided critical review of an earlier draft of the manuscript.

Manuscript accepted 23 Jan. 1999.

Resumen

Los efectos del barbecho de raíz en el carbón orgánico y nitrógeno del suelo se investigaron mediante la comparación de sitios de pastizal apareados con y sin barbecho, localizados en el sudeste de las Grandes Planicies. El tiempo transcurrido desde el barbecho estuvo varió de 4 a 22 años. Hipotetizamos que después del barbecho: (1) el carbón del suelo inicialmente decrecería, pero en un período de 5 a 10 años recuperaría el nivel del pastizal sin disturbio y (2) la remoción permanente de árboles de mezquite, los cuales incrementan el carbón y nitrógeno del ecosistema y proveen sombra que baja la temperatura del suelo, resultaría en una disminución lenta de carbón y nitrógeno del suelo de este ecosistema.

Los tratamientos no tuvieron un efecto significativo ni en la masa de carbón del suelo (g m^{-2}) (P=0.81) ni en la de nitrógeno (P=0.62). El tiempo transcurrido desde el barbecho tuvo un efecto significativo en la masa de carbón (P=0.0014). El nivel de carbón de la capa superior del suelo (0–100 mm) fue mayor (P=0.0001) que el de la capa mas profunda (100–200 mm) (1422 ± 210 g m^{-2} vs 1111 ± 206 g m^{-2}). Las diferencias de nitrógeno en el suelo fueron similares a las del carbón. El contenido de nitrógeno difirió significativamente (P=0.003) debido al tiempo en que ocurrió el barbecho y la capa superior del suelo tuvo mayores niveles de nitrógeno que la capa mas profunda (138 ± 18 g m^{-2} vs 107 ± 18 g m^{-2}) (P=0.0001).

Cuando los datos se analizaron utilizando los valores de sitios nativos apareados como covariable para cuantificar las diferencias por sitio, los sitios con 4 años de haber sido barbechados tenían más carbón (P<0.08) y nitrógeno (P<0.09) que los sitios con 11, 16 y 22 años. Estos resultados son opuestos a lo que se habían hipotetizado. Esto probablemente se debe a que el barbechode raíz es un tratamiento no-recurrente que no invierte el suelo o remueve la cubierta de zacates perennes. El ligero incremento de carbón medido 4 años después del barbecho fue probablemente causado a la presencia en el suelo de una gran cantidad de raíces de arboles muertas después del barbecho. Esto incrementaría inmediatamente la cantidad total de material vegetal muerto que entra a las reservas en descomposición, elevando temporalmente los niveles de carbón antes de que regresen lentamente a los niveles originales. En el período de 22 años cubierto en este estudio, el carbón o el nitrógeno no tuvieron una tendencia a decrecer. En este ecosistema la remoción de árboles de mezquite aparentemente no cambia los niveles de carbón o nitrógeno del suelo en comparación con los niveles del pastizal nativo con árboles de mezquite.

Soil organic carbon is important in range ecosystems since it improves soil structure and enhances infiltration, soil water availability, soil water retention and soil fertility. The fate and status of nitrogen, the prime nutrient limiting productivity in range ecosystems (Risser et al. 1981), is tied closely to soil carbon (Seastedt 1995). Organic matter is also a source of, and temporary sink for, several plant nutrients (Bauer and Black 1994, Tiessen et al. 1994). Soil organic carbon is also significant to global carbon flows since it has been estimated to be 3 times greater than carbon present in biota and twice that in the atmosphere (Bolin 1977, Woodwell et al. 1978).

Root-plowing has been widely used to clear rangeland of unwanted brush. Root-plowing involves pulling a blade, 2.5-m to 4.5-m wide, behind a crawler-tractor at a depth of approximately 350-mm. The blade severs woody plant roots below the bud zone, killing most. The uprooted tree stems and limbs are usually raked into large piles and burned. The soil is loosened but not inverted. Soil micro-relief is disturbed but herbaceous plants are affected very little.

Reductions in soil organic carbon following cultivation of grassland are reasonably well documented (Haas et al. 1957, Aguilar et al. 1988, Burke et al. 1989, Ihori et al. 1995). Soil carbon drops up to 50% in the first 5 years of cultivation then declines more slowly to reach a stable low level after approximately 40 years in the northern Great Plains (Tiessen et al. 1982, Mann 1986, Bowman et al. 1990, Reeder et al. 1995). Conservation tillage lowers carbon less than conventional tillage and has been shown to improve soil organic carbon when implemented after conventional tillage (Wood and Edwards 1992). Root-plowing is more similar to conservation tillage than to conventional tillage.

Following the clearing of woodland and forest, soil organic carbon declines quickly in the first few years (Cerri et al. 1991, Arrouays and Pelissier 1994). Although the major loss of carbon is due to increased oxidation following soil disturbance, significant losses are also due to erosion and changes in plant composition (Richter et al. 1990, Burke et al. 1995). Following either cultivation of grassland or clearing of woodland or forest, there is a quick recovery of soil carbon and nitrogen levels if the area is put back to permanent grass at any stage (Cerri et al. 1991, Gebhart et al. 1994, Burke et al. 1995). It generally takes approximately 40 years under permanent grassland for the total soil carbon to return to undisturbed levels from 60% less than that at undisturbed sites in the Northern Great Plains. However, the proportion of active, slow and passive carbon pools (sensu Parton et al. 1987) changes dramatically. Cultivation lowers the slow pool substantially and recovery of this slow pool takes decades. Soil carbon loss is faster in the southern plains, being dependent on temperature, soil moisture and clay content (Burke et al. 1989). Thus, any treatment that decreases carbon is expected to do so more rapidly in the southern plains.

Plant species differ markedly in the rate and extent that they modify soil carbon and nitrogen. Shrubs, particularly nitrogen fixers such as mesquite (*Prosopis* spp), enhance soil organic carbon and nitrogen substantially, particularly under the canopy (Barth and Klemmedson 1978 1982, Virginia et al. 1992). C_4 grasses, and blue grama (*Bouteloua gracilis*) in particular, result in higher soil carbon than C_3 grasses (Seasted et al. 1994, Burke et al. 1995, Frank et al. 1995, Manley et al. 1995).

This study examines the effect of root-plowing on soil carbon and nitrogen over a period of 22 years. It was hypothesized that following root-plowing (1) soil carbon would initially drop but recover to the level of untreated range within a 5–10 year period, and (2) the permanent removal of mesquite trees, that enhance ecosystem carbon and nitrogen and provide shade to lower soil temperature, would result in a slow decline in soil carbon and nitrogen in this ecosystem.

Materials and Methods

Study Sites

The study was conducted on the Waggoner ranch southeast of Vernon in north central Texas, 34°N, 99°W. The climate is continental with an average 220 frost-free, growing days. Mean annual precipitation is 550 mm varying from 490 mm to 1,000 mm that is bimodally distributed with peaks in May (102 mm) and September (81 mm). Annual mean monthly temperature is 17.4°C, ranging from 36.4°C in July to -2.3°C in January. Elevation ranges from 335 m to 396 m.

The Waggoner ranch is contiguous and 202,000 ha in extent. Sites that had been root-plowed up to 22 years previously were identified on different areas of the ranch. Four replicates of each of 4, 9, 11, 16, and 22 years since root-plowing were located using ranch records. These replicates were each in entirely different pastures at different locations on the ranch. The grazing on all sites has been consistent and light since the early 1960's. Waggoner ranch stocking rates were approximately 12 ha AU^{-1} compared to the Natural Resource Conservation Service recommendation of 7.5 ha AU^{-1} for the area. Grazing in all areas was continuous. At each site, adjacent plowed and native plots were located. These paired plots were chosen to be the same except for the previous root-plow treatment. At each site the paired plots had been part of the same grazing unit for the duration. It is assumed that the vegetation was the same at each set of paired plots prior to root-plowing. Soils at all sites were Tillman clay-loams (fine, mixed, thermic Typic Paleustalf) and slopes were all 1–3%.

Mesquite (*Prosopis glandulosa* Torr.) trees provided 20% ground cover on the native areas. There was no shrub cover on the plowed areas because after root-plowing, any shrubs that appeared were routinely removed by individual plant grubbing. Perennial grasses dominated the herbaceous layers of all sites. Principal species were sideoats grama [*Bouteloua curtipendula* (Michx.) Torr.] buffalograss [*Buchloe dactyloides* (Nutt.) Engelm.], Texas wintergrass [*Nassella leucotricha* (Trin. & Rupr.)], meadow dropseed [*Sporobolus asper* (Michx.) Kunth var. *drummondii*)Trin.) Vasey] and silver bluestem [*Bothriochloa saccharoides* var. *torreyana* (Steud.) Gould].

Field Sampling

Two, 30 m transects were located on each of the native and plowed sites. Transects were parallel to the boundary between the paired native and plowed sites. Ten randomly located soil cores 50 mm in diameter were taken to a depth of 200 mm along each transect. Cores were taken on bare interspaces, midway between grass tufts. The cores were obtained by pounding into the soil a steel coring tube (50 mm i.d.) containing 2 brass cylinder inserts each 100 mm long. Each core was divided into 2 depths (0–100 and 100–200 mm). The samples for each site plot and depth were composited and stored in sealed plastic bags for transport back to the laboratory. Separate cores were sampled for bulk density determinations as above. Sampling took place in late summer and fall.

Laboratory analysis

All analyses were done separately on the 2 depths (0–100 and 100–200 mm) sampled and results either averaged or added for the 2 depths as outlined in each table reporting results. Bulk density was estimated using the core method (Blake and Hartge 1986). Field-moist samples for carbon and nitrogen analysis were pushed through a 10-mm-diameter sieve to remove rocks and root fragments, passed through a 2-mm-diameter sieve and air dried for 3–5 days. Elemental analysis was conducted on two, 10-gram sub-samples from the 2-mm-sieved soil. Each sub-sample was oven dried at 40°C to reduce moisture content to less than 2%.

Soil texture was determined using the 2-mm-sieved samples. The hydrometer method (Bouyocos 1962) was used for the particle-size analysis. Soil texture was determined using the USDA classification (Gee and Bauder 1986). The pH was measured at a soil to solution ratio of 1:1.

Soil total carbon, organic carbon, carbonate carbon and total nitrogen were determined by combustion/gas chromatography with a Carlo Erba NA-1500 elemental analyzer (CE Elantech, Inc., Lakewood, N.J.) using techniques described previously (Nieuwenhuize et al. 1994). Instrument calibration was maintained with acetanilide (NBS-141c). Repeated measurements (n=5) of a soil standard (Leco soil 502-062; Leco Corp., St. Joseph, Mich.) yielded a precision (± 1 S.D.) of 150 mg kg^{-1} for organic carbon and 20 mg kg^{-1} for total nitrogen.

Statistical analysis

We tested the effects of years-since-plowing (n=5) as the main effect, and treatment (n=2, native and root-plowed) and depth (n=2) as blocks, using ANOVA (SAS Institute 1988). Data were also analyzed using paired native plot data as a covariate to account for site differences using the General Linear Model (SAS Institute 1988). Least significant difference tests (Steel and Torrie 1960) were used to separate means. Significance levels are 5% unless otherwise indicated.

Table 1. Soil organic carbon and nitrogen (g kg^{-1} of soil) (mean ± SE) (total to a depth of 200 m of paired native rangeland and root-plowed sites in mesquite rangeland.

Years Since Root-Plowed	Native		Root-Plowed	
	Carbon	Nitrogen	Carbon	Nitrogen
	(g kg^{-1})		(g kg^{-1})	
4	9.6 ± 1.12	0.95 ± 0.088	10.3 ± 1.50	0.99 ± 0.112
9	9.9 ± 0.67	0.93 ± 0.058	9.8 ± 1.11	0.93 ± 0.090
11	9.9 ± 0.91	0.94 ± 0.085	9.5 ± 0.76	0.89 ± 0.047
16	10.3 ± 2.66	0.99 ± 0.221	9.9 ± 2.34	0.95 ± 0.186
22	8.4 ± 0.71	0.86 ± 0.044	8.6 ± 0.37	0.86 ± 0.035

Results and Discussion

There were no significant differences in percentage carbon (g kg^{-1} of soil)(P=0.56) or nitrogen (P=0.68) within or between years or between native and root-plowed sites (Table 1). There were also no significant differences in soil bulk density between and within native and root-plowed sites (Table 2). When the native sites are used as a covariate, year 4 after root-plowing had higher bulk density than the other years (P<0.05) and year 9 had high bulk density than year 22 (P<0.05). It important to note that the native sit were not treated at all so there is r "years since root-plowed" for the native sites. Untreated native sites we "paired" with adjacent plowed sites. appears that bulk density is highest years after root-plowing and the declines with time, presumably to pr root-plowing levels.

Soil carbon and nitrogen mass (g n to 200 mm) is computed by accounti for bulk density and soil textural diffe ences. There were no significant diffe ences in either soil carbon ma (P=0.81) or nitrogen mass (P=0.62) d to treatment (Table 3). However, the were significant differences in soil ca bon mass among years-since-root-plo ing (P=0.0014) and the upper soil lay had higher carbon levels than the deep soil layer (1422 ± 210 g m^{-2} vs. 1111 206 g m^{-2})(P=0.0001). Differences

Table 2. Soil bulk density (g cm^{-3})(mean ± SE)(mean of 0–100 mm and 100–200 mm sample valu of paired native and root-plowed sites in mesquite rangeland.

Years Since Root-Plowed	Native		Root-Plowed With native as covariate
	(g cm^{-3})		
4	1.346^a ± 0.027	1.369^a ± 0.019	1.357^a ± 0.026
9	1.301^a ± 0.036	1.308^a ± 0.036	1.305^b ± 0.034
11	1.294^a ± 0.039	1.278^a ± 0.023	1.286^{bc} ± 0.032
16	1.297^a ± 0.042	1.262^a ± 0.034	1.279^{bc} ± 0.038
22	1.274^a ± 0.032	1.234^a ± 0.036	1.254^c ± 0.035

Means in the same column with the same letters are not significantly different (P<0.05).

Table 3. Soil organic carbon and nitrogen (g m^{-2}) (mean ± SE)(total to a depth of 200 mm) paired native and root-plowed sites in mesquite rangeland.

Years Since Root-Plowed	Carbon Mass		Nitrogen Mass	
	Native	Plowed	Native	Plowed
	(g m^{-2})			
4	2632 ± 160	2861 ± 218	260 ± 12	278 ± 16
9	2611 ± 93	2601 ± 148	246 ± 8	247 ± 12
11	2616 ± 113	2477 ± 115	247 ± 10	232 ± 7
16	2697 ± 326	2528 ± 280	259 ± 27	243 ± 22
22	2167 ± 86	2150 ± 49	222 ± 5	215 ± 4

Table 4. Soil organic carbon and nitrogen (gm^{2}) (mean ± SE)(total to a depth of 200 mm) in root-plowed mesquite rangeland using native paired site values as a covariate to account for site differences.

Years Since Root-Plowed	Carbon Mass	Nitrogen Mass
	------(g cm^{-2}) -----	
4	2790^{a} ± 114	268^{a} ± 110
9	2548^{ab} ± 113	248^{ab} ± 9
11	2419^{b} ± 114	232^{b} ± 9
16	2406^{b} ± 116	234^{b} ± 10
22	2453^{b} ± 129	233^{b} ± 10

Means in the same column with the same letters are not significantly different (P<0.05).

soil nitrogen were similar to those of soil carbon. There were significant differences in nitrogen among years-since-root-plowing (P=0.003) and the upper soil layer had higher nitrogen levels than the deeper soil layer (138 ± 18 g m^{-2} vs. 107 ± 18 g m^{-2})(P=0.0001).

When the data are analyzed using native site values as a covariate to account for site differences, the sites that had been root-plowed 4 years previously had higher soil carbon mass (g m^{-2} (P<0.08) and nitrogen mass (g m^{-2}) (P<0.09) than the sites root-plowed 11, 16, and 22 years previously (Table 4). These differences are partly due to differences in soil bulk density (Table 2) which is used to calculate carbon and nitrogen mass from carbon and nitrogen percentages. The same trends were evident in the percentage carbon and nitrogen data which are not affected by bulk density (Table 5) as for carbon mass and nitrogen mass (Table 4). Therefore, it does not appear that the bulk density values bias these results.

These results refute the *a priori* hypotheses. A decline in soil carbon after cultivation of native grassland and

Table 5. Soil organic carbon and nitrogen (g kg^{-1} of soil)(mean ± SE)(total to a depth of 200 mm) following root-plowing of mesquite rangeland using native paired site values as a covariate to account for site differences.

Years Since Root-Plowed	Carbon Mass	Nitrogen Mass
	--------(g kg^{-1}) --------	
4	10.3^{a} ± 0.43	0.99^{a} ± 0.042
9	9.6^{ab} ± 0.43	0.93^{a} ± 0.042
11	9.3^{b} ± 0.44	0.89^{a} ± 0.042
16	9.4^{ab} ± 0.44	0.91^{a} ± 0.043
22	9.5^{ab} ± 0.47	0.91^{a} ± 0.044

Means in the same column with the same letters are not significantly different (P<0.05).

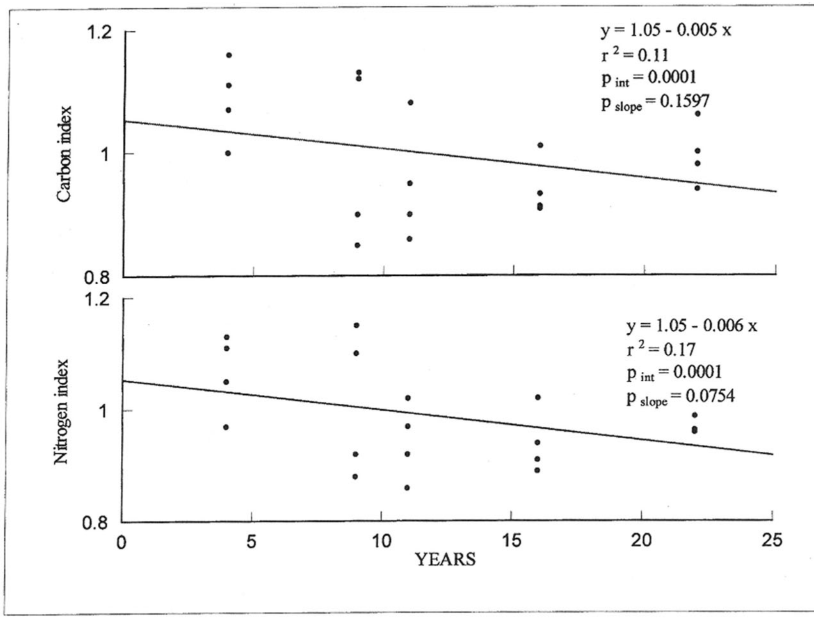

Fig. 1. Soil carbon and nitrogen at root-plowed sites as an index of paired native site values in mesquite rangeland of the southern Great Plains.

woodland is well documented (Haas et al. 1957, Aguilar et al. 1988, Burke et al. 1989, Cerri et al. 1991, Arrouays and Pelissier 1994, Ihori et al. 1995). Usually a large decline in carbon takes place in the first 3–5 years of continuous, conventional tillage. This decline continues with annual tillage until a low-level equilibrium is approached after approximately 40 years in the northern Great Plains.

A lesser decline was expected following root-plowing than would be expected from conventional tillage since root-plowing occurs once, not annually, and root-plowing does not invert the soil. In addition, root-plowing does not pulverize the soil, but leaves it in large aggregates with some fractures. The inversion and mixing of the soil with conventional tillage improves aeration which allows considerably more oxidation of organic matter than does conservation tillage and root-plowing. Lower oxidation is the main reason that conservation tillage does not decrease soil carbon where conventional tillage does (Wood and Edwards 1992). In addition, most established perennial grasses are not killed and remain dominant after root-plowing. Perennial grass growth following either cultivation of grassland or clearing of woodland or forest causes a quick recovery of soil carbon and nitrogen levels (Cerri et al. 1991, Gebhart et al. 1994, Burke et al. 1995). Although the major cause of carbon loss is due to increased oxidation following soil disturbance, significant losses can occur due to erosion (Burke et al. 1995) and the replacement of perennial grasses with annual herbs that do not produce as much below-ground carbon (Richter et al. 1990). The maintenance of permanent grass cover after root-plowing would minimize erosion or a change of species composition to annuals.

It is clear that root-plowing had no detrimental effect on soil carbon or nitrogen levels in this ecosystem. A possible explanation is that root-plowing leaves a large amount of dead tree and herbaceous roots in the soil, which would immediately increase the total amount of dead plant material entering the decomposing pool to elevate carbon levels temporarily before they returned slowly to previous levels. Nine years after root-plowing (this study), carbon and nitrogen levels had declined but were still higher (but P>0.05) than the areas that had been root-plowed earlier. This result is consistent with the above explanation.

A regression of soil carbon and nitrogen mass at root-plowed sites as an index of paired native site values indicated no decline in either parameter over the 22 years (Fig. 1). A curvilinear plot did not improve the regression r^2. The intercepts were significantly different from 0 (P=0.0001) but only because carbon and nitrogen were higher on root-plowed sites in year 4 than in all other years, as reported above. There is a slight negative slope between carbon and years (P=0.16) and between nitrogen and years (P=0.08), but it was only the elevated values in year 4 that gave the regression a slope. In addition, the regressions had very low r^2 values, so little weight should be given to them. If carbon and nitrogen levels in the ecosystem had declined because of the removal of mesquite trees, this regression would have had a significant negative slope. These data indicate that, at least over a period of 22 years, no such decline took place in this ecosystem. Over a longer period, soil carbon and nitrogen may decline without the presence of mesquite since mesquite elevates carbon and nitrogen levels at least in subcanopy positions (Barth and Klemmedson 1978, 1982, Virginia et al. 1992) and provides shade that lowers soil temperature. Maintenance of carbon and nitrogen in the absence of mesquite in this study is at least partly due to the fact that root-plowed areas remained dominated by the same C4 perennial grasses. Permanent C4 perennial grassland soils have been shown to maintain high carbon and nitrogen levels except under heavy continuous grazing (Frank et al. 1995, Manley et al. 1995, Berg et al. 1997).

Both of the stated hypotheses are refuted in this study and it appears that both root-plowing and mesquite removal have no detrimental effect on soil carbon and nitrogen storage.

Literature Cited

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

Arrouays, D. and P. Pelissier. 1994. Changes in carbon storage in temperate humic loamy soils after forest clearing and continuous corn cropping in France. Plant and Soil 160:215–223.

Barth, R.C. and J.O. Klemmedson. 1978. Shrub-induced spatial patterns of dry matter, nitrogen and organic carbon, Soil Sci. Soc. Amer. J. 42:804–808.

Barth, R.C. and J.O. Klemmedson. 1982. Amount and distribution of dry matter, nitrogen and organic carbon in soil-plant systems of mesquite and Palo-verde. J. Range Manage. 35:412–418.

Bauer, A. and A.L. Black. 1994. Quantification of the effect of soil organic matter content on soil productivity. Soil Sci. Soc. Amer. J. 58:185–193.

Berg, W.A., J.A. Bradford, and P.L. Sims. 1997. Long-term soil nitrogen and vegetation change on sandhill rangeland. J. Range Manage. 50:482–486.

Blake, G.R. and C.H. Hartge. 1986. Bulk density. In: A. Klute (ed.) Methods of soil analysis. Part 1. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, Wisc.. p. 363–375.

Bolin, B. 1977. Changes of land biota and their importance for the carbon cycle. Sci. 196:613–615.

Bowman, R.A., J.D. Reeder, and R.W. Lober. 1990. Changes in soil properties in a central Plains rangeland soil after 3, 20 and 60 years of cultivation.. Soil Sci. Soc. Amer. J. 150:851–857.

Bouyocos, G.J. 1962. Hydrometer method improved for making particle size analysis of soils. Agron. J. 54:464–465.

Burke, I.C., W.K. Lauenroth, and D.P. Coffin. 1995. Soil organic matter recovery in semiarid grasslands: implications for the conservation reserve program. Ecol. Appl. 5:793–801.

Burke, I.C., C.M. Yonker, W.J. Parton, C.V. Cole, K. Flach and D.S. Schimel. 1989. Texture, climate and cultivation effects on soil organic matter content in U.S. grassland soils. Soil Sci. Sci. Amer. J. 5:800–805.

Cerri, C.C., B. Volkoff, and F. Andreaux. 1991. Natural behavior of organic matter in soils under natural forest, and after deforestation, burning and cultivation, near Manous. For. Ecol. Manage. 38:247–257.

Frank, A.B., D.L. Tanaka, L. Hoffmann, and R.F. Follett. 1995. Soil carbon and nitrogen of Northern Great Plains grasslands as influenced by long-term grazing. J. Range Manage.. 48:470–474.

Gebhart, D.L., H.B. Johnson, H.S. Mayeux, and H.W. Polley. 1994. The CRP increases soil organic carbon. J. Soil and Water Cons. 49:488–492.

Gee, G.W. and J.W. Bauder. 1986. Particle-size analysis. In: A. Klute (ed.). Methods of soil analysis. Part 1: Physical and mineralogical methods. Second Edition. ASA/SSSA, Madison, Wisc.

Haas, J.H., C.F. Evans, and E.F. Miles. 1957. Nitrogen and carbon changes in Great Plains soils as influenced by cropping and soil treatments. United States Technical Bulletin Number 1164, USDA, Washington, D.C., USA.

Ihori, T., I.C. Burke, W.K. Lauenroth and D.P. Coffin. 1995. Effects of cultivation and abandonment on soil organic matter in northeastern Colorado. Soil Sci. Soc. Amer. J. 59:1112–1119.

Manley, J.T., G.E. Schuman, J.D. Reeder , and R.H. Hart. 1995. Rangeland soil carbon and nitrogen responses to grazing. J. Soil and Water Cons. 50:294–298.

Mann, L.K. 1986. Changes in soil carbon storage after cultivation. Soil Sci. Soc. Amer. J. 142:278–288.

Nieuwenhuize, J., Y. Maas, and J. Middleburg. 1994. Rapid analysis of organic carbon and nitrogen in particulate materials. Marine Chemis.. 45:217–224.

Parton, W.J., D.S. Schimel, C.V. Cole and D.S. Ojima. 1987. Analysis of factors controlling soil organic matter levels in Great Plains grasslands. Soil Sci. Soc. Amer. J. 51:1173–1179.

Reeder, J.D., G.E. Schuman, and R.A. Bowman. 1995. Soil carbon and nitrogen changes on CRP land in the central great Plains. Agronomy Abstracts, St. Louis, Missouri, Oct. 29–Nov. 3.

Richter, D.D., L.I. Babbar, M.A. Huston, and M. Jaeger. 1990. Effects of annual tillage on organic carbon in a fine-textured Udalf: the importance of root dynamics to soil carbon storage. Soil Sci. 149:78–83.

Risser, P.G., E.C. Birney, H.D. Blocker, S.W. May, W.J. Parton, and J.A. Wiens. 1981. The True Prairie Ecosystem. US/IBP synthesis series, no 16. Hutchinson Ross Publishing Company, Stroudsburg, Penns.

SAS Institute. 1988. SAS/STAT User's Guide. SAS Institute, Cary, N.C.

Schimel, D.S., M.A. Stillwell, and R.G. Woodmansee. 1985. A soil catena of the shortgrass steppe. Ecol. 66:276–282.

Seastedt, T.R. 1995. Soil systems and nutrient cycles of the North American Prairie. *In:* A. Joern and K.H. Keeler (eds). The Changing Prairie: North American Grasslands. Oxford University Press, New York.

Seastedt, T.R., C.C. Coxwell, D.S. Ojima and W.J. Parton. 1994. Controls of plant and soil carbon in a sub-humid temperate grassland. Ecol. Appl.. 4:344–353.

Steel, R.G.D. and J.H. Torrie. 1980. Principles and procedures of statistics. McGraw-Hill Co. Inc., N.Y.

Tiessen, H., E. Cuevas, and P. Chacon. 1994. The role of soil organic matter in sustaining soil fertility. Nature 371, Oct 1994.

Tiessen, H., J.W.B. Stewart, and J.R. Bettany. 1982. Cultivation effects on the amounts and concentration of carbon, nitrogen and phosphorus in grassland soils. Agron. J. 74:831–835.

Virginia, R.A., W.M. Jarrell, W.G. Whitford, and D.W. Freckman. 1992. Soil biota and soil properties in the surface rooting zone of mesquite (*Prosopis glandulosa*) in historical and recently desertified Chihuahuan desert habitats. Biol. Fertil. Soils. 14:90–98.

Wood, C.W. and J.H. Edwards 1992. Agroecosystem management effects on soil carbon and nitrogen. Agr., Ecosystems and Environ.. 39:123–38.

Woodwell, G.M., R.H. Whittaker, W.A. Reiners, G.E. Likens, C.C. Delwiche and D.B. Botkin. 1978. The biota and the world carbon budget. Science. 199:141–146.