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Soil carbon and nitrogen pools under long-term productivity of rhizoma peanut and perennial weeds management systems

(Kohlenstoff- und Stickstoffpools im Boden bei Langzeitanbau von Futterleguminosen (*Arachis glabrata* Benth.) bzw. mehrjährigen Grasanbausystemen)

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Abstract
The effects of a 10-year-old rhizoma peanut (RP) (*Arachis glabrata* Benth.), a perennial legume forage, and perennial weeds (PW) management systems on soil organic C (SOC), total N (STN), NH_4-N, NO_3-N, potential C and N mineralization (PCM and PNM), microbial biomass C and N (MBC and MBN), and particulate organic C and N (POC and PON) were evaluated in a Norfolk loamy fine sand (fine-loamy, siliceous, thermic Typic Kandiudult) in 2000 and 2001 in Georgia, USA. Aboveground biomass yield and N accumulation increased from June to October in 2000 and 2001, were greater in RP than in PW from July to October, and were greater in 2000 than in 2001 in RP. Root length density increased from June to September, and was greater in RP than in PW in September. The SOC, STN, POC, PON, MBC, MBN, PCM, and PNM varied seasonally but in different trends than those of biomass yield and root length density. In contrast, soil NH_4-N in 2001 and NO_3-N contents in 2000 and 2001 increased from June to September similar to those of biomass yield and N accumulation. Averaged across sampling dates, SOC, STN, POC, PON, MBC, MBN, PCM, PNM, and NO_3-N were greater in RP than in PW and greater in 2000 than in 2001. Short-term productivity of RP may enrich soil mineral N by supplying N from above- and belowground residues and long-term productivity may improve soil quality and productivity by increasing microbial activities, N mineralization, and C and N sequestrations compared with PW.

Keywords: *Rhizoma peanut, biomass yield, carbon pools, nitrogen pools, soil quality*

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Introduction

Rhizoma peanut (RP) (*Arachis glabrata* Benth.) is a perennial legume forage that survives well in the Coastal Plain of southeast USA (Prine et al. 1986; Terrill et al. 1996, 2000). Once the forage is planted, roots start to grow to a depth >70 cm (Terrill et al. 2000), thereby enabling it to produce biomass year after year and meeting the demand of high-quality forage (Terrill et al. 1996, 2000). Although the aboveground biomass is harvested for forage every year, belowground biomass, such as roots, continues to grow and becomes the main source of C and N inputs in the soil. Roots of RP not only sequester C, but also fix N from the atmosphere. As much as 7 – 43% of C and N from total above- and belowground plant biomass can be contributed by roots (Kuo et al. 1997a, 1997b). Roots may play a dominant role in soil C cycle (Gale et al. 2000; Puget & Drinkwater 2001; Wedin & Tilman 1990) and may have relatively greater influence on soil organic C (SOC) level than the aboveground plant biomass (Boone 1994; Milchumas et al. 1985; Norby & Cotrufo 1998). Balesdent and Balabane (1996) observed that corn (*Zea mays* L.) roots contributed 1.6 times more C to SOC than that by stover. When C contribution from rhizodeposition, such as root exudates, mucilages, and sloughed cells, along with roots was considered, corn roots contributed from 1.7 – 3.5 times more C to SOC than that by stover (Allmaras et al. 2004; Wilts et al. 2004). Therefore, long-term productivity of RP may continually supply C and N inputs from plant and root residues and rhizodeposition, which may improve soil quality and fertility by increasing organic matter, microbial activities, and nitrogen mineralization and availability.

Gentile et al. (2005) emphasized the importance of perennial forages in sequestering C in the subsoil. They observed that perennial forages, because of their ability to develop extensive root systems, increased SOC and particulate organic C (POC) levels at 20 – 60 cm depth after 38 years. The increased levels of SOC and POC under grassland occur not only due to continuous addition of C from above- and belowground residues over the several years (Chan 1997; Gentile et al. 2005; Paustian et al. 1997), but also due to their slower rates of mineralization because of decreased soil disturbance (Cambardella & Elliott 1992; Elliott 1986; Gill et al. 1999; Six et al. 1998). Therefore, grassland soil has been identified as one of the potential sites to sequester atmospheric CO_2 in the terrestrial ecosystem for helping to reduce some of the deleterious effects of greenhouse gases (Bouwman 1990). Because of the long-term (>10 years) growth of RP, this study provides a unique opportunity to study C and N sequestrations in the soil under perennial legume forages.

Although increased C and N sequestrations or organic matter level can improve soil quality, their measurements alone do not adequately reflect changes in soil quality and nutrient status (Bezdicek et al. 1996; Franzluebbers et al. 1995). This is because SOC and soil total N (STN) have large pool size and inherent spatial variability (Franzluebbers et al. 1995). Measurement of biologically active fractions of soil organic matter, such as microbial biomass C and N (MBC and MBN) and potential C and N mineralization (PCM and PNM) could better reflect changes in soil quality that alter nutrient dynamics (Bremner & Van Kissel 1992; Powlson et al. 1987; Saffigna et al. 1989). These fractions can vary seasonally due to changes in soil temperature, moisture, rhizodeposition, and amount of plant residue and roots returned to the soil (Bonde & Rosswall 1987; Franzluebbers et al. 1995). Since above- and belowground biomass of RP contain a higher concentration of N than those of perennial weeds (PW) (Sainju et al. 2003), differences in the amount of C and N supplied by RP and PW residues, rhizodeposition, and temporal changes in temperature and rainfall can influence seasonal variations of MBC, MBN, PCM, PNM, NH_4-N, and NO_3-N levels, due to changes in microbial activities and N mineralization.

Little is known about the seasonal, annual, and long-term effects of RP and PW management systems on soil C and N pools. While SOC and STN are regarded as recalcitrant pools of soil C and N that change slowly over time (Franzluebbers et al. 1995; Salinas-Garcia et al. 1997), PCM, PNM, MBC, and MBN are considered as labile pools that change rapidly during plant growing season (Franzluebbers & Arshad 1997; Franzluebbers et al. 1999). Similarly, POC and particulate organic N (PON) are considered as intermediate pools for changes in soil C and N over time and provide substrates for microbes (Beare et al. 1994; Franzluebbers et al. 1999; Six et al. 1999). Available forms of N that influence plant growth are NH_4-N and NO_3-N. Because of deep root growth and N fixing ability (Sainju et al. 2003; Terrill et al. 2000), we hypothesized that RP management system will increase seasonal, annual, and long-term levels of soil C and N pools compared with PW system. In order to measure the long-term effects of RP on soil quality, the naturally occurring grassland system, such as PW, adjacent to RP plots were chosen for comparison. The objective of the study was to evaluate the long-term productivity of RP and PW management systems on seasonal and long-term levels of soil C and N pools, such as SOC, STN, POC, PON, MBC, MBN, PCM, PNM, NH_4-N and NO_3-N contents.

Materials and methods

Climate in the experimental site

Average monthly temperature near the experimental site during the growing season of RP and PW from June to October was similar in 2000 and 2001 and close to the normal of 41-year average (see Figure 1A). Total monthly rainfall, however, was lower in June, but higher from July to October in 2000 than in 2001 (Figure 1B). Similarly, monthly rainfall was higher in June and September but lower in July, August, and October in 2000 than in the 41-year average. Total rainfall from June to October was higher in 2000 (400 mm) than in 2001 (304 mm) but was lower than in the 41-yr average (473 mm). It is expected that growing-season variations in temperature and rainfall would influence the growth of above- and belowground biomass of RP and PW, which would affect seasonal levels of soil C and N pools due to variations in C and N inputs from plant residue, roots, and rhizodeposition.

Field experiment

The experiment was established by Terrill et al. (1996). Eight RP (*Arachis glabrata* Benth, variety Florigraze) and eight PW plots (6×2 m) were randomly established in April 1991 on a Norfolk loamy fine sand (fine-loamy, siliceous, thermic, Typic Kandiudult) at Fort Valley State University, Agricultural Research Station farm, Fort Valley, Georgia, USA. The RP management system consisted of vegetatively transplanted rhizomes, fertilized with P and K fertilizers, sprayed with herbicides to control weeds, and aboveground biomass harvested for forage every year. The PW management system consisted of naturally grown weeds from established seed bank that resembled natural grassland, which was neither fertilized nor sprayed with herbicides and where aboveground biomass was mowed and left in the soil every year. The soil had 750 g sand kg^{-1}, 150 g silt kg^{-1}, and 100 g clay kg^{-1} soil at the 0- to 30-cm depth. The SOC content at the initiation of the experiment in 1991 was 7.3 g kg^{-1}, STN 515 mg kg^{-1} soil, and pH 6.9 (1:2 soil/water ratio). Below 30 cm depth, clay content increased to >300 g kg^{-1} soil.

The RP was vegetatively transplanted at 5.25 m^3 ha^{-1}. The PW was dominated by henbit (*Lamium amplexicaule* L.), cut-leaf evening primrose (*Oenothera laciniata* L.), and wild

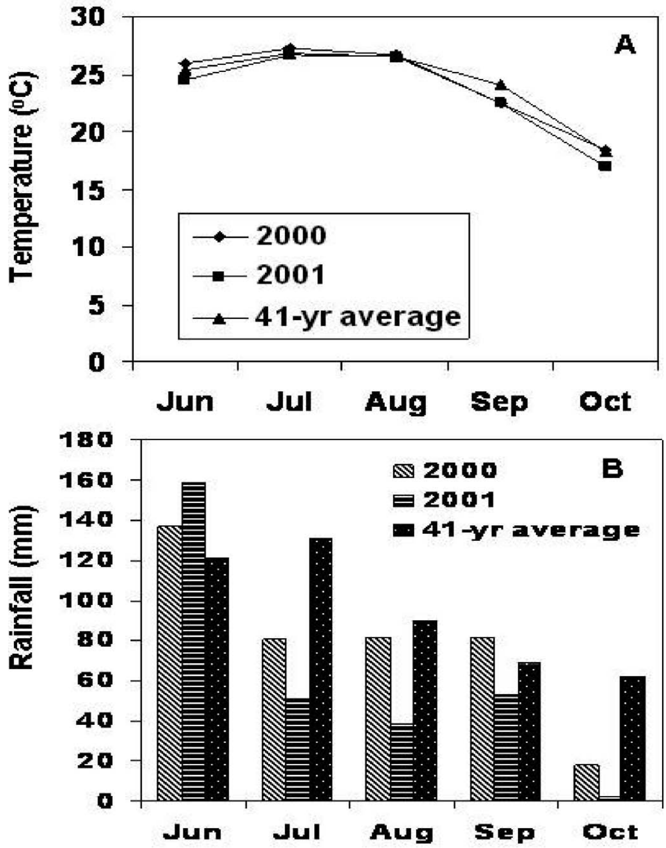

Figure 1. Average monthly temperature (A) and total monthly rainfall (B) from June to October in 2000, 2001 and the 41-year average at the study site.

mustard (*Brassica juncea* L.). The RP and PW plots were arranged in a randomized complete block with eight replications. Based on the annual soil test conducted in the spring and crop requirement, RP plots were fertilized with 0–67 kg ha^{-1} P (as triple superphosphate, $Ca[H_2PO_4]_2$, 48% P) and 146 to 224 kg ha^{-1} K (as muriate of potash, KCl, 60% K) every year from 1991–2000. No N fertilizer was applied. Weeds in RP plots were controlled by applying sethoxydim {2-(1-[ethoxyimino] butyl)-5-(2-[ethylthio] propyl)-3-hydroxy-2-cyclo-hexen-1-one} at 3.5 L ha^{-1} in mid to late summer every year. In PW plots, no fertilizer or herbicide was applied. The RP and PW were grown under natural rainfall and no irrigation was applied.

Measurement of observations

A strip (0.8 × 6.0 m) was allocated within each plot under RP and PW to measure monthly observations of aboveground biomass and root length density and to collect soil samples. Within the strip, aboveground biomass of RP and PW was harvested from two 900 cm^2 areas from June to October in 2000 and 2001. These were composited, oven-dried at 60°C for 3 d, and weighed for dry matter yield determination. Samples were collected every month from a different area within the strip. Dried samples were ground and passed through a 1 mm screen to determine N concentration. In the remaining area of RP plot, aboveground biomass was harvested twice a year (July and October) to measure forage yield and nutrient composition (as a part of another study) when plants were 30 – 35 cm tall. The data on forage yield had been measured since 1991 when RP was transplanted. A strip, 4 – 5 m long and 0.9 m wide, was cut with a sickle-bar mower for biomass yield determination after which the rest of the biomass was removed from the plot. Similarly, in the remaining area of PW plot, weeds were also mowed with a sickle bar mower but residues were left at the soil surface.

For measuring root length density, two minirhizotron acrylic tubes (5 cm internal diameter by 91 cm long) were installed to a 70 cm depth at an angle of 15° with the vertical and 15 cm away from the base of the plant inside the strip of each plot (Box et al. 1989). Images of roots taken by a camera (1.8 × 1.25 cm) attached to a rod at every 6.5 cm interval from 0 – 70 cm depth were recorded in a VCR attached to a back pack. Observations of root images were taken at the same time as aboveground biomass collection every month from June to October in 2000 and 2001. Images of roots were displayed in a monitor in the laboratory and number of roots at a depth was counted. From this, root length density was calculated by multiplying the number of roots by a factor of 3.4, as suggested by Merrill and Upchurch (1994). Total root length density from 0 – 70 cm depth was obtained by summing up length densities at individual depths.

At the same time as aboveground biomass and root observations were measured, soil samples from 0 – 30 cm depth were collected from five places with a soil core (5 cm internal diameter) within the strip of each plot under RP and PW. These were composited, air-dried, ground, and passed through a 2-mm sieve. A separate core (5 cm internal diameter) of soil was taken from 0 – 30 cm depth from each plot to measure bulk density and to convert soil parameters from mass to volume basis.

Chemical analysis

Nitrogen concentration in the aboveground biomass of RP and PW was determined by the H_2SO_4-H_2O_2 method as described by Kuo et al. (1997b). Nitrogen accumulation in RP and PW was determined by multiplying biomass yield by N concentration. The SOC concentration was determined by the Walkley-Black method (Nelson & Sommers 1996). The STN was determined by the Kjeldahl method (Bremner 1996). The NH_4-N and NO_3-N concentrations in the soil were determined by using steam distillation after extracting the soil with 2 *M* KCl for 1 h (Mulvaney 1996).

The PCM and PNM in air-dried soils were determined by the method modified by Haney et al. (2004). Two ten gram soil subsamples were moistened with water at 50% field capacity and placed in a 1 l jar containing beakers with 4 ml of 0.5 *M* NaOH to trap evolved CO_2 and 20 ml of water to maintain high humidity. Soils were incubated in the jar at 21°C for 10 d. At 10 d, the beaker containing NaOH was removed from the jar and PCM was determined by measuring CO_2 absorbed in NaOH, which was back-titrated with 1.5 *M* $BaCl_2$ and 0.1 *M* HCl. One beaker containing soil was removed from the jar and extracted with 100 ml of 2 *M* KCl for 1 h. The NH_4-N and NO_3-N concentrations in the extract were determined by using steam distillation as above. The PNM was calculated as the difference between the sum of NH_4-N and NO_3-N concentrations in the soil before and after incubation.

The other beaker containing moist soil and incubated for 10 d for determining PCM above was fumigated with ethanol-free chloroform for 24 h and placed in a 1 l jar containing beakers with 2 ml of 0.5 *M* NaOH and 20 ml water for determining MBC and MBN by the modified fumigation-incubation method for air-dried soils (Jenkinson & Powlson 1976; Shen et al. 1987; Franzluebbers et al. 1996). As with PCM, fumigated moist soil was incubated for 10 d and CO_2 absorbed in NaOH was back-titrated with $BaCl_2$ and HCl. The MBC was calculated by dividing the amount of CO_2-C absorbed in NaOH by a factor of 0.41 (Voroney & Paul 1984) without subtracting the values from non-fumigated control (Franzluebbers et al. 1996). For MBN, the fumigated-incubated sample at 10 d was extracted with 100 ml of 2 *M* KCl for 1 h and NH_4-N and NO_3-N concentrations were determined by the steam distillation. The MBN was calculated by the difference between the sum of NH_4-N and NO_3-N concentrations in the sample before and after fumigation-incubation and divided by a factor of 0.41 (Carter & Rennie 1982; Brookes et al. 1985). Specific respiratory activity (SPRAC) of MBC and specific mineralization activity (SPMAN) of MBN were calculated by dividing PCM and PNM by MBC and MBN, respectively (Franzluebbers et al. 1995).

The POC and PON were determined by the method described by Cambardella and Elliott (1992). Ten grams of soil was dispersed with 30 ml (1:3 soil/solution ratio) of 5 g l^{-1} of sodium hexametaphosphate for 16 h and the solution was poured through a 0.05-mm sieve. After washing with deionized water, soil particles that passed through the sieve were oven-dried at 50°C and organic C and total N were determined as above. The POC and PON were determined by subtracting SOC and STN concentrations in the particles that passed through the sieve from that in the original soil before dispersion after correcting for the sand content. All soil C and N parameters were converted from mass to volume basis to determine their contents (kg ha^{-1}) by multiplying their concentrations (g kg^{-1} soil) by an average soil bulk density of 1.49 Mg m^{-3} and depth of 30 cm.

Data analysis

Treatment (RP and PW management systems) was considered as the main plot factor and date of soil sampling or date of biomass or root length measurement as the split plot factor for analysing data for aboveground biomass yield, N accumulation, root length density, and soil C and N pools. Data were analysed using the Analysis of Repeated Measures in MIXED procedure of SAS after testing for homogeneity of variance (Littell et al. 1996). Treatment and date of sampling were considered as the fixed effects and replication and treatment × replication were considered as random effects. Means were separated by using the least square means test. Statistical significance was evaluated at $p \leqslant 0.05$.

Results and discussion

Aboveground biomass yield and nitrogen accumulation

Aboveground biomass yield and N accumulation in RP and PW increased from June to October in 2000 and 2001 (data not shown). Biomass yield was greater in RP than in PW from July to October 2000 and in October 2001. Nitrogen accumulation was greater in RP than in PW from July to October 2000 and from August to October 2001. A higher biomass yield and N accumulation in RP than in PW may have resulted from application of P and K fertilizers, followed by increased N fixation and reduced competition from weeds, since herbicides were applied regularly to control weeds in RP plots. The PW plots represented a natural grassland area without application of fertilizers and herbicides, where nutrients are recycled from the addition of above- and belowground biomass residue to the soil. Although legumes, such as RP, can fix N in the above- and belowground biomass in nutrient-deficient soils, application of P and K fertilizers can enhance its N fixing ability (Collins et al. 1986; Mullen et al. 2001).

Root length density

Similar to aboveground biomass, root length density from 0 – 70 cm depth in RP and PW increased from June to October in 2000 and 2001 (data not shown). Root length density was higher in RP than in PW in September and October 2000 and September 2001. As with aboveground biomass yield, increased root length density in RP compared to PW could be due to P and K fertilization, followed by reduced competition from weeds. Since distribution of root length density in the soil profile is proportional to root biomass (Wilhelm et al. 1982; Qin et al. 2004), it may be possible that variations in root growth and rhizodeposition during the growing season also influence seasonal variations of C and N pools. Roots can have a greater role in soil C cycle than shoots (Gale et al. 2000; Puget & Drinkwater 2001; Wedin & Tilman 1990).

Soil carbon pools

Soil C pools, such as SOC, POC, MBC, and PCM, varied seasonally in 2000 and 2001, with significantly ($p \leqslant 0.05$) greater values in RP than in PW at different times of the year (see Figures 2, 3, 4, and 5). The SOC was greater in RP than in PW in June 2000 and September 2001 (Figures 2A and 2B). Similarly, POC was greater in RP than in PW in June, July, and October 2000 and from July to September 2001 (Figures 3A and 3B), MBC was greater in July and September 2001 (Figure 4B), and PCM was greater in July 2001 (Figure 5B). Averaged across sampling dates, SOC was 8 – 17%, POC 26 – 35%, MBC 23%, and PCM 29% greater in RP than in PW in 2000 and 2001 (see Table I). The POC/SOC ratio, representing the proportion of SOC in POC, was also greater in RP than in PW in 2000 and 2001. However, the MBC/SOC and PCM/SOC ratios were similar between RP and PW and between 2000 and 2001. Averaged across treatments, SOC, POC, MBC, PCM, and POC/SOC ratio were greater in 2000 than in 2001.

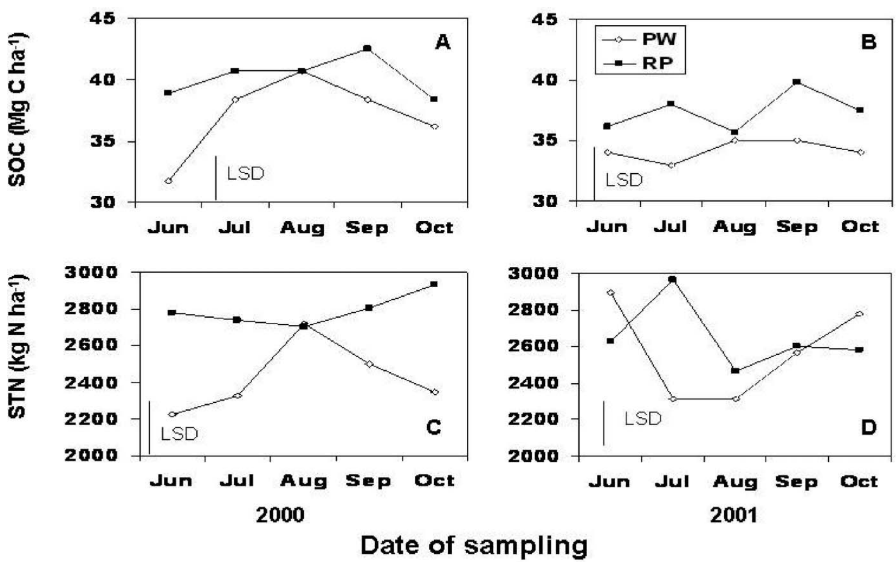

Figure 2. Soil organic C (SOC) (A) and (B) and total N (STN) (C) and (D) concentrations in perennial weeds (PW) and rhizoma peanut (RP) from June to October in 2000 and 2001. LSD denotes least significant difference between treatments at $p \leqslant 0.05$.

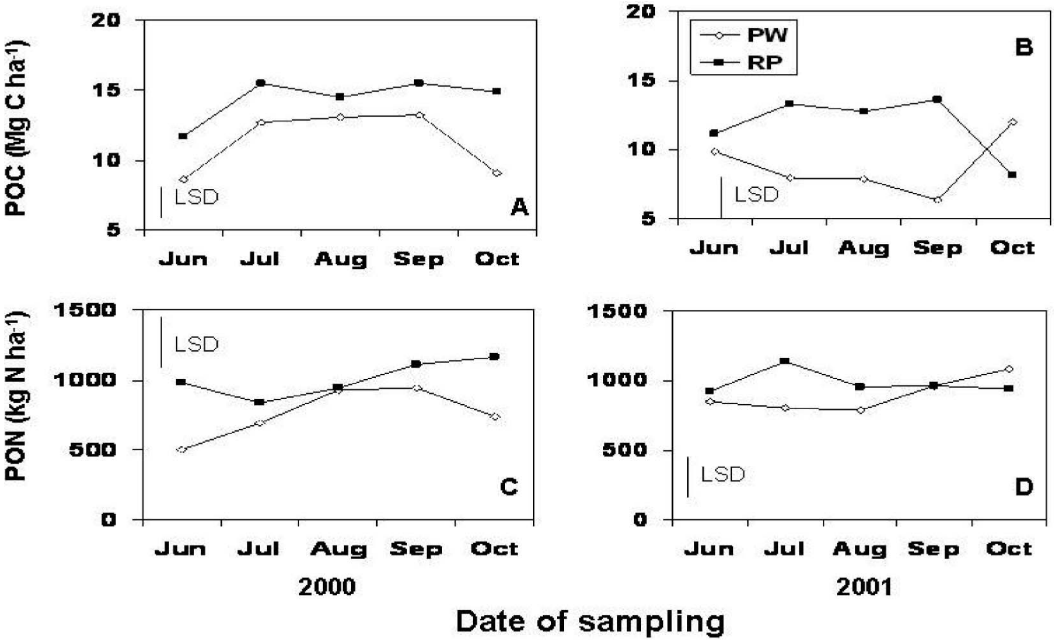

Figure 3. Soil particulate organic C (POC) (A) and (B) and particulate organic N (PON) (C) and (D) in perennial weeds (PW) and rhizoma peanut (RP) from June to October in 2000 and 2001. LSD denotes least significant difference between treatments at $p \leqslant 0.05$.

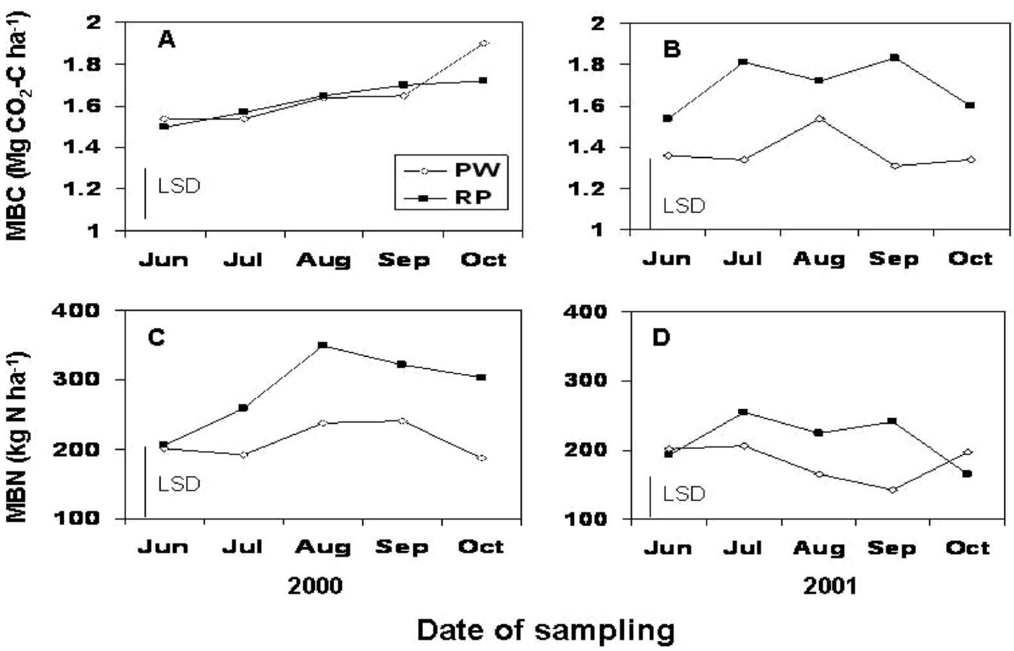

Figure 4. Soil microbial biomass C (MBC) (A) and (B) and microbial biomass N (MBN) (C) and (D) in perennial weeds (PW) and rhizoma peanut (RP) from June to October in 2000 and 2001. LSD denotes least significant difference between treatments at $p \leqslant 0.05$.

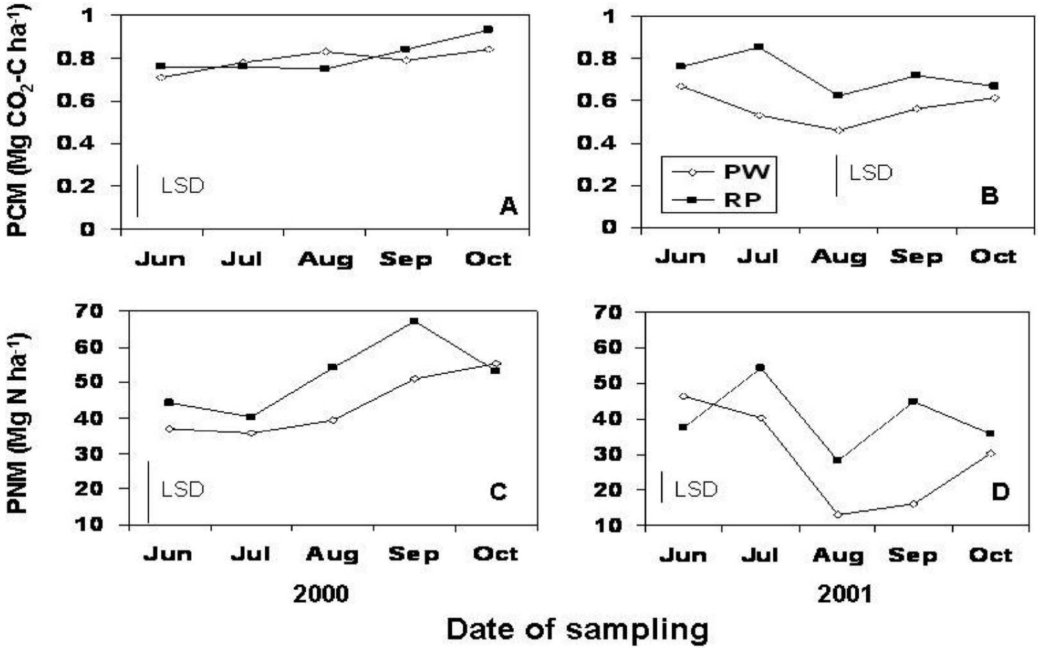

Figure 5. Soil potential C mineralization (PCM) (A) and (B) and potential N mineralization (PNM) (C) and (D) in perennial weeds (PW) and rhizoma peanut (RP) from June to October in 2000 and 2001. LSD denotes least significant difference between treatments at $p \leqslant 0.05$.

Table I. Soil organic C (SOC), particulate organic C (POC), microbial biomass C (MBC), and potential C mineralization (PCM) under perennial weeds (PW) and rhizoma peanut (RP) averaged across sampling dates in 2000 and 2001.

	2000			2001		
Soil C pool	PW	RP	Mean	PW	RP	Mean
SOC, Mg C ha^{-1}	37.1b[a]	40.2a	38.9A[b]	32.2y	37.5x	34.9B
POC, Mg C ha^{-1}	11.4b	14.4a	13.1A	8.7y	11.7x	10.4B
MBC, Mg CO_2-C ha^{-1}	1.65a	1.63a	1.64A	1.38y	1.70x	1.54B
PCM, Mg CO_2-C ha^{-1}	0.79a	0.80a	0.80A	0.56y	0.72x	0.64B
POC/SOC, g kg^{-1} SOC	307b	359a	333A	270y	312x	299B
MBC/SOC, g kg^{-1} SOC	44a	41a	43A	43a	45a	44A
PCM/SOC, g kg^{-1} SOC	21a	20a	21A	17a	19a	18A
SPRAC, g kg^{-1} MBC	479a	491a	485A	406x	424x	415B

[a]Numbers followed by different lower case letter between PW and RP treatments within a year are significantly different at $p \leqslant 0.05$ by the least square means test; [b]Numbers followed by different upper case letter between years are significantly different at $p \leqslant 0.05$ by the least square means test.

The seasonal variation of soil C pools may depend on cropping systems, management practices used and growing season climate. Franzluebbers et al. (1995) and Lynch and Panting (1980, 1982) observed that soil C pools, such as MBC and PCM, increased from planting to harvest under wheat (*Triticum aestivum* L.) and sorghum (*Sorghum bicolor* L.) in the summer, regardless of tillage practices, probably due to rhizodeposition and crop residue addition. In contrast, Granastein et al. (1987) and Van Gestel et al. (1992) found either a decrease on no change in MBC level from spring to autumn in wheat-barley (*Hordeum vulgare* L.) -pea (*Pisum sativum* L.) and wheat-legume rotations, regardless of tillage. Similarly, Staley (1999) reported that MBC decreased in the surface soil (0- to 3.8-cm depth) during the corn (*Zea mays* L.) growing season in no-till but increased in the subsurface soil in no-till and surface and subsurface soils in conventional till system. Since our cropping system is perennial forage, difference in seasonal variations in soil C pools between RP and PW systems could be due to variation in C inputs from previous plant and root residues, rhizodeposition during the growing season, or availability of fresh residue at plant maturity. The biomass production was higher in RP than in PW. Besides the variation in the amount of residue input, residue quality (such as C/N ratio) and difference in temperature and rainfall during the growing season can also influence the seasonal variation in soil C pools between RP and PW due to difference in mineralization rates of plant residue and soil organic matter. Because of higher N concentration, RP had lower C/N ratio than PW. As a result, higher POC, MBC, and PCM in RP than in PW at different times of the year could be due rapid mineralization of RP residue. Also greater POC, MBC, and PCM levels from July to September than in June and October, regardless of treatments, could be due to warmer temperature (see Figures 1A, 3, 4, and 5).

The increased levels of SOC, POC, MBC, and PCM in RP compared with PW (see Table I) suggests that long-term RP management system can improve soil quality and C sequestration by increasing soil organic matter and microbial activities. Gentile et al. (2005) reported that perennial forages in rotations with cereal crops increased POC in the subsurface soil (20- to 60-cm depth) after 38 years. Our study showed that both SOC and POC increased with RP compared with PW management system in the surface soil after 10 years. Since the soil sample collected in 1991 before the initiation of the experiment contained 32.6 Mg C ha^{-1} SOC, the RP management system increased SOC by 23% in 2000 and 15% in 2001. With PW system, the increases in SOC were 14% in 2000 and −1% in 2001. The reasons for the lower increases in SOC or lower C pools in 2001 than in 2000 were not known, but could have resulted from declined C input from reduced growth of above- and belowground biomass yield, followed by continuous mineralization of soil organic matter from 2000 to 2001.

The POC/SOC, MBC/SOC, and PCM/SOC ratios have been termed as enlarging pools of soil organic matter that are more sensitive to changes than SOC alone (Anderson & Domsch 1989; Powlson et al. 1987). Although MBC/SOC and PCM/SOC ratios were similar between treatments, greater POC/SOC ratio (see Table I) suggests that the RP system contained a greater proportion of SOC to POC, which can change rapidly due to changes in C inputs from plant residue and roots than the PW system. The SPRAC was not different between RP and PW systems but was greater in 2000 than in 2001, probably due to small, infrequent C input, indicating a stressed ecosystem that underwent a recession in the active soil organic matter pool (Visser & Parkinson 1992).

Soil nitrogen pools

Labile and non-labile nitrogen pools. Similar to C pools, soil N pools, such as STN, PON, MBN, and PNM varied seasonally at different times of the year (see Figures 2, 3, 4, and 5). The STN was greater in RP than in PW in June, July, and October 2000 and in July 2001 (Figures 2C and 2D). Similarly, PON was greater in RP than in PW in June and October 2000 and in July 2001 (Figures 3C and 3D), MBN was greater from August to October

2000 and from July to September 2001 (Figures 4C and 4D), and PNM was greater in September 2000 and from July to September 2001 (Figures 5C and 5D). Averaged across sampling dates, STN was 10–15%, PON 10–33%, MBN 17–39%, and PNM 18–38% greater in RP than in PW in 2000 and 2001 (Table II). The PON/STN, MBN/STN, and PNM/STN ratios were also greater in RP than in PW. Averaged across treatments, MBN, PNM, MBN/STN, and PNM/STN ratios were greater in 2000 than in 2001 but PON/STN ratio was greater in 2001 than in 2000. The SPMAN of MBN was greater in PW than in RP in 2000 but was greater in RP than in PW in 2001.

Although STN and PON levels varied in different patterns in RP and PW from June to October in 2000 and 2001, MBN and PNM tended to increase from late spring to summer and then declined in autumn. Carter and Rennie (1982) and Franzluebbers et al. (1995) reported that MBN and PNM under wheat and sorghum decreased from planting to harvest due to immobilization of N from increased addition of crop residue in the soil. While the crops in their study were non-legumes with high C:N ratio, the increase in MBN and PNM levels from spring to summer in RP plots in our study could be due to increased fixation of atmospheric N by RP at flowering. As the N fixing ability decreased at maturity, MBN and PNM may have decreased from summer to autumn. Besides, changes in temperature, rainfall (Figure 1), and crop rooting during the growing season could also have influenced seasonal levels of MBN and PNM, which may affect nutrient availability to plants through soil organic matter turnover (Bonde & Rosswall 1987; Bonde et al. 1988; Kaiser & Heinemeyer 1993). For example, increased MBN and PNM levels in the summer compared with spring and autumn, regardless of treatments, could have resulted from increased mineralization of plant residue and STN due to increased temperature. The increased levels of STN, PON, MBN, and PNM in RP compared with PW (Table II) may have resulted from increased N addition from above and belowground biomass residue. Sainju et al. (2003) reported that N input from belowground biomass of RP to a depth of 15 cm was greater than N input from above- and belowground biomass of PW.

Similar to soil C, the results showed that long-term management of RP can increase N sequestration as well as mineralization in the soil compared with PW system. Since the soil

Table II. Soil total N (STN), particulate organic N (PON), microbial biomass N (MBN), potential N mineralization (PNM), NH_4-N, and NO_3-N contents under perennial weeds (PW) and rhizoma peanut (RP) averaged across sampling dates in 2000 and 2001.

	2000			2001		
Soil C pool	PW	RP	Mean	PW	RP	Mean
STN, kg N ha^{-1}	2423b[a]	2794a	2610A[b]	2333x	2570x	2454A
PON, kg N ha^{-1}	761b	1009a	885A	895y	982x	939A
MBN, kg N ha^{-1}	210b	286a	250A	183y	215x	199B
PNM, kg N ha^{-1}	44b	52a	48A	29y	40x	34B
PON/STN, g kg^{-1} STN	314b	361a	339B	383a	382a	383A
MBN/STN, g kg^{-1} STN	87b	102a	95A	78a	84a	81B
PNM/STN, g kg^{-1} STN	18a	19a	19A	12b	16a	14B
SPMAN, g kg^{-1} MBN	210a	182b	196A	158y	186x	172B
NH_4-N, kg N ha^{-1}	22a	24a	23A	18a	18a	18B
NO_3N, kg N ha^{-1}	17b	25a	21B	24y	29x	27A

[a]Numbers followed by different lower case letter between PW and RP treatments within a year are significantly different at $p \leqslant 0.05$ by the least square means test; [b]Numbers followed by different upper case letter between years are significantly different at $p \leqslant 0.05$ by the least square means test.

sample collected before the initiation of the experiment in 1991 contained 2302 kg N ha^{-1}, the RP management system increased STN by 21% in 2000 and 12% in 2001. With PW system, the increases in STN were 5% in 2000 and 1% in 2001. Like soil C, the reasons for the decrease in the amount of N sequestration or N pools in 2001 compared with 2000 were not known, but could be due to lower biomass yield and N accumulation and continuous N mineralization from 2000 to 2001.

The increased PON/STN, MBN/STN, and PNM/STN ratios in RP compared with PW (Table II) indicates that the RP system contained enlarged pools of N that can change rapidly with changes in N inputs from plant residues or changes in soil temperature and moisture. As a result, N mineralization and availability in RP system can vary seasonally, which could probably be related to N fixing and supplying ability of RP during and after the growing seasons. The change from lower, to higher SPMAN of MBN in RP than in PW between 2000 and 2001 respectively could be due to difference in reimmobilization of mineralized N between RP and PW systems in 2000 and 2001 as a result of changes in environmental condition, since growing season rainfall was higher in 2000 than in 2001 (see Figure 1B).

Available nitrogen pools

Unlike other C and N pools, NH_4-N and NO_3-N contents significantly ($p \leqslant 0.05$) increased from late spring to late summer and tended to follow the growth pattern of aboveground biomass, N accumulation, and root length density in RP and PW (see Figure 6). The NH_4-N was greater in PW than in RP in June 2000 but was greater in RP than in PW in October 2000

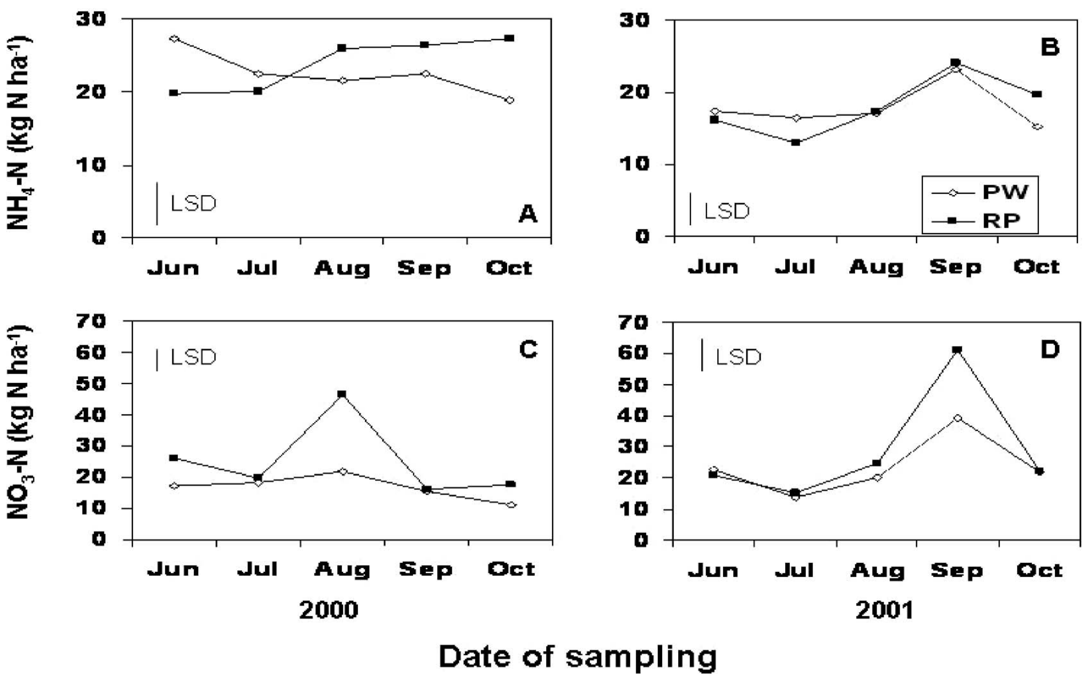

Figure 6. Soil NH_4-N (A) and (B) and NO_3-N (C) and (D) contents in perennial weeds (PW) and rhizoma peanut (RP) from June to October in 2000 and 2001. LSD denotes least significant difference between treatments at $p \leqslant 0.05$.

and 2001 (Figures 6A and 6B). Similarly, NO_3-N was greater in RP than in PW in August 2000 and September 2001 (Figures 6C and 6D). Averaged across treatments, NH_4-N was at greater in September than in other sampling dates in 2001 and NO_3-N was greater in August 2000 and September 2001 than at other dates. Averaged across date of sampling, NO_3-N was 21 – 51% greater in RP than in PW in 2000 and 2001 (Table II). Similarly, NH_4-N was 30% greater in 2000 than in 2001, but NO_3-N was 26% greater in 2001 than in 2000.

The increased levels of NH_4-N and NO_3-N contents from June to September could be due to increased mineralization of N from soil organic matter, as temperature increased (Figure 1A). There was a tendency to increase PNM level during the same period (Figures 5C and 5D). The greater level of NO_3-N in RP than in PW in August 2000 and September 2001 may have resulted from increased N mineralization from above- and belowground biomass of residue, since RP contained higher concentration of N. Soil NO_3-N level is closely correlated with the amount of N supplied by plant residue (Kuo et al. 1996). As with other N pools, greater NH_4-N level in 2000 than in 2001 could be due to greater biomass yield and N accumulation, followed by greater PNM level (Table II). In contrast, lower NO_3-N level in 2000 than in 2001 may have resulted from increased N leaching due to higher rainfall (Figure 1B).

Conclusions

Results of this study showed that long-term productivity of Rhizoma Peanut (RP) increased soil C and N pools due to its greater C and N contributions and its lower C: N ratio than in Perennial Weeds (PW). The levels of C and N pools between RP and PW varied with the season probably due to difference in mineralization rates of the residue as temperature and rainfall varied. The available pools of N may be used to increase forage production by growing non-legume forages together with RP, thereby reducing N leaching. The RP management system may be used not only to produce high quality nutritious forage but also to improve soil quality and productivity by increasing C and N sequestrations, organic matter content, microbial activities, and N mineralization. As a result, it may also help to mitigate some of effects of deleterious effects of global warming.

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