RESEARCH SUB-PROGRAM

Effects of Crop Residue in Conservation Tillage Systems on Soil Quality and Crop Productivity

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FORWARD

This report is one of a series of COESA (Canada-Ontario Environmental Sustainability Accord) reports from the Research Sub-Program of the Canada-Ontario Green Plan. The GREEN PLAN agreement, signed Sept. 21, 1992, is an equally-shared Canada-Ontario program totalling $64.2 M, to be delivered over a five-year period starting April 1, 1992 and ending March 31, 1997. It is designed to encourage and assist farmers with the implementation of appropriate farm management practices within the framework of environmentally sustainable agriculture. The Federal component will be delivered by Agriculture and Agrifood Canada and the Ontario component will be delivered by the Ontario Ministry of Agriculture and Food and Rural Assistance.

From the 30 recommendations crafted at the Kempenfelt Stakeholders conference (Barrie, October 1991), the Agreement Management Committee (AMC) identified nine program areas for Green Plan activities of which the three comprising research activities are (with Team Leaders):

1. Manure/Nutrient Management and Utilization of Biodegradable Organic Wastes through land application, with emphasis on water quality implications
   A. Animal Manure Management (nutrients and bacteria)
   B. Biodegradable organic urban waste application on agricultural lands (closed loop recycling) (Dr. Bruce T. Bowman, Pest Management Research Centre, London, ONT)

2. On-Farm Research: Tillage and crop management in a sustainable agriculture system. (Dr. Al Hamill, Harrow Research Station, Harrow, ONT)

3. Development of an integrated monitoring capability to track and diagnose aspects of resource quality and sustainability. (Dr. Bruce MacDonald, Centre for Land and Biological Resource Research, Guelph, ONT)

The original level of funding for the research component was $9,700,000 through Mar. 31, 1997. Projects will be carried out by Agriculture and Agri-Food Canada, universities, colleges or private sector agencies including farm groups.

This Research Sub-Program is being managed by the Pest Management Research Centre, Agriculture and Agri-Food Canada, 1391 Sandford St., London, ONT. N5V 4T3.

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EXECUTIVE SUMMARY

No-tillage systems have not worked very well for corn which is a problem as corn is commonly used in a rotation with wheat and soybean. Furthermore, when corn follows winter wheat there may be an additional problem associated with residue management during the early stages of corn growth. The objectives were to determine the effects of no-tillage systems on soil physical, biological and chemical properties and to identify the problems associated with planting corn into wheat stubble.

Treatments included conventional versus no tillage both with and without red clover in a wheat-corn-soybean rotation in a clay loam soil. Results have been reported for the corn year of the rotation. No-tillage treatments improved soil structure and when red clover was included further improvements occurred. No-tillage treatments increased soil water content and reduced soil temperatures by 2-3 ^{0}C in June. Soil drying occurred along the planting slot of the no-tillage treatments which enabled the soil seed furrow to open and the corn seedling to become water stressed; even though the no-tillage treatments were wetter in the spring. The net result was that the corn in the no-tillage treatment (without red clover) was significantly delayed (emergence and early vegetative growth) and was never able to catch up to the corn in the conventional tillage treatments.

The soil respiration rates were 30% greater in conventional tillage than no-tillage treatments. Hence, residue decomposition was considerably greater with the conventional tillage treatments. The no-tillage treatment (without red clover) had lower corn grain yields than the conventional tillage treatment in all three years of the study. However, in both 1994 and 1996, when red clover was included in the crop rotation, corn grain yields in the no-tillage treatment were similar to conventional tillage treatments. Red clover improved soil structure and accelerated the decomposition of the crop residue which contributed to the yield improvement in the no-tillage treatments.

A weed species shift from predominantly summer annuals to winter annuals and perennials

was evident in the early stages of the switch to no-tillage on this clay loam soil. The presence or absence of red clover in rotation did not have a substantial impact on the number and types of weeds found.

In summary, the combination of no-tillage and under-seeding red clover in a winter wheat -corn-soybean rotation worked very well for improvements in soil structural and microbial biomass C which resulted in increased corn grain yields and profitability. The no-tillage treatments with red clover had lower amounts of straw residue on the surface which also improved corn germination and emergence compared to the no-tillage treatment without red clover. When red clover was not included, the wheat straw residues insulated the soil surface which led to wetter and cooler soil conditions and reduced grain yields. No-tillage practices have to be modified by using techniques such as cover crops to ensure long-term soil quality and improved crop productivity on these poorly drained soils in southern Ontario. Additional research to enhance cover crop establishment, growth and management in a wheat crop would also ensure an improvement in soil quality under no-tillage conditions. Further, zone tillage systems should be investigated as they may improve seed bed conditions in the seed row while maintaining the benefits of no-tillage between corn rows.

2. Introduction

Sustainable crop production systems must maintain or enhance the quality of soil resources while simultaneously providing sufficient economic return to the producer (Miller et al. 1992). The deterioration of soil and water quality associated with crop production is a major concern in Southern Ontario. Conventional production practices (mouldboard plow followed by secondary cultivation) expose the soil to the forces of wind and water erosion especially during the winter and spring months, and reduce the organic matter content of the soil. The reduction of organic matter results in poor soil structure and aggregate stability, and increases the susceptibility of the soil to compaction.

2.1 Tillage effects on soil quality and crop productivity

Surface soil structural deterioration contributes to increased soil erosion, runoff and compaction. Deterioration of surface soil structure in heavy textured soils is believed to be the result of mouldboard plough based, intensive row crop production (Ketcheson, 1980; McKeague et al. 1987). Long-term production of the clay and clay loam soils in southwestern Ontario appears to be dependent upon the development of soil and crop management systems which optimize improvements in soil structure (Stone, 1989).

Conservation tillage is associated with greater surface crop residue levels, larger and more stable surface aggregates, increased infiltration, decreased runoff and erosion, and higher surface soil water contents compared to conventional tillage (Baumer and Bakermans, 1973; Blevins et al. 1971, 1983). A review of the impacts of conservation tillage on soil and water quality has been given by Baker and Laflen (1983). In general, improved soil structure or stability of structure means better infiltration, less surface runoff, and better subsurface drainage, all viewed as positive benefits with respect to crop production and soil erosion control. The importance of timely planting and rapid germination on yields is well documented (Imholte and Carter, 1987). Poor emergence has been attributed to lower seed bed temperatures with conservation tillage (Gupta et al. 1988; Hayhoe et al. 1993). The delay in emergence was related mainly to a reduction in soil temperature. The effect of cover crop residue on the temperature and water regime in clay soils during the spring and its effect on timely planting has not been studied in detail.

One of the major difficulties encountered by growers using a no-till management on clay soil is the problem of good establishment of a corn crop in wheat stubble. It is believed that the major contributor to this problem is the lack of soil drying in the spring as a result of high levels of residue cover. Management of the cover crop and residue through a combination of mechanical and chemical techniques has not been adequately evaluated.

2.2 Cover crop effects on soil quality and crop productivity

The most practical method of improving soil structure is by including a forage in the cropping system (Lynch and Bragg, 1985). Intercrops and cover crops have been suggested as a promising method of incorporating forages into an intensive row crop production system (Scott et al. 1987). Improvements in soil structure and aggregate stability were found to occur after only one season of forage (Stone, 1990). Rasiah and Kay (1990) showed an increase in aggregate stability after two years of red clover under-seeded to corn and maintained as an intercrop. They also showed that two years of under-seeded red clover was equally effective in improving soil aggregation, particularly under minimum tillage, as pure stands of brome grass or alfalfa.

Cover crops have been shown to increase water infiltration rates due to deeper rooting systems and improved soil structure (Lal, 1979, Yaacob and Blair, 1981). The effects of changes in soil and crop management practices in Ontario, and the results on soil and water resources have also been studied extensively in recent years (Ketcheson, 1980; Kay et al. 1988). Short term improvement in the stability of aggregates following the introduction of forage crops into a rotation has been linked to increased carbohydrates (Angers and Mehuys, 1989) and, in some cases, to simple physical enmeshment by roots (Tisdall and Oades, 1982). Existing cover crop research has been conducted mainly on silt loam and sandy textured soils, and the effect on heavy clay soils needs to be studied.

Surface soil water content affects many soil processes including microbial biomass activity (Sommers et al. 1980; Harris, 1980), nutrient uptake by plants, and N-cycling (Stanford and Epstein, 1974). Cover crops have been shown to use stored soil water which can have either a beneficial or deleterious effect on the subsequent crop, depending on the weather conditions. In a dry spring, the cover crop can accelerate soil water use and result in a lower subsequent crop yield (Campbell et al., 1984, Gillespie et al. 1992). Munawar et al. (1990) concluded that in a high rainfall spring, it may be advantageous to allow the cover crop to grow longer to dry out the soil and produce dry matter for surface mulch which would conserve water for the corn crop during the summer. Several studies have shown that the presence of residue, or mulch left on the soil surface increases soil water content (Jones et al., 1969) and decreases soil temperature in relation to bare soil (Griffith et al. 1973).

The use of cover crops as methods of weed control appear to offer great promise as a method of weed management (Altieri and Lieberman, 1986). A major problem with this technique is that in addition to suppressing the weeds, the main crop yield may suffer. The use of winter-rye as a cover crop in no-till soybeans was found to reduce weed biomass (Samson et al. 1992). This was attributed to the physical mulch effect, and lower nutrient availability. Red clover has been used to suppress annual weed growth and showed a trend to suppress weed growth at cereal harvest, and greatly restrict weed growth after harvest (Samson et al., 1989). Other researchers have found a reduction in perennial weed growth and reproduction after harvest from the use of inter-seeded cover crops in cereals. The use of red clover as a cover crop in the wheat-corn-soybean rotation and its effect on weed control needs further examination.

2.3 The effects of red clover under-seeded in wheat on soil quality and crop productivity

The wheat-corn-soybean rotation has become an increasingly common crop rotation in Southern Ontario in recent years. In Essex county, corn, wheat and soybean crops make up 90% of the land in agricultural crop production. Under-seeding red clover into the spring or winter cereal crop is also a common practice. Red clover under-seeded in cereals has been shown to provide large quantities of fall biomass and supply much of the N required by corn (Bruulsema and Christie, 1987). Other studies have shown however that the N from red clover may not be available to corn grown in no-till systems. It is not clear however whether the N was limited or was released after the corn crop had matured.

The stage of red clover growth and the kill method can have a major impact on residue left on the soil surface, and the timely release of N to the subsequent crop. In most experiments or field evaluations, it has been killed (fall or spring) prior to planting. Studies have indicated that ploughing down the red clover in late October or early November resulted in the greatest corn yield but was unacceptable in terms of erosion control (Sweep-TED #36, 1992). Miller et al. (1992) showed that ploughed down red clover was very effective in retaining N through the winter and spring and in releasing it to the subsequent crop. Meissinger (1991) also showed significantly more nitrate leaching from fields planted with leguminous cover crops. Clearly more long term studies of the impact of cover crops to N availability to the crop and to N leaching are necessary before any conclusive management decisions can be made.

2.4 The interactions between cover crops and reduced tillage systems

Cover crops in association with reduced tillage, and a crop rotation appear to be a promising approach both in reducing soil and chemical runoff, and in maintaining or improving soil quality. Advantages of cover crops include increased soil organic matter content, improved soil structure and stability, nitrogen fixation, nutrient cycling, weed suppression, and increased biomass production (Samson, 1990). Some cover crops are particularly effective in concurrently increasing microbial biomass and improving soil structure (Drury et al. 1991). Much of the existing cover crop research has been conducted on continuous spring cereal or corn systems, and the use of cover crops in rotation systems requires further evaluation.

The contribution of organic matter from a cover crop under no-till conditions can play a significant role in improving and maintaining soil structure. Structural stability represents the ability of a soil to resist changes in structural form when a stress is applied (eg. raindrop impact, wheel traffic). Structural form can significantly affect the storage and infiltration of water, and root development (Hamblin, 1985). Soil management practices have been shown to significantly impact soil structural form and soil stability (Kay et al. 1988).

A crop rotation production system involving conservation tillage has been suggested as one of the best management practices for sustainable agriculture. This system provides for an improvement of soil structure and concomitantly, a better environment for soil flora and fauna. Careful management of the cover crop can result in a better C:N ratio, hence increased biological activity and improved conditions for seed germination and plant growth. Increased knowledge on the integration of crop rotation, minimum tillage, vegetation and residue management on soil structure and biological activity is essential for developing recommendations on the long term impact of conservation tillage on fine textured soils.

3. Objectives

1. To measure the effect of the red clover cover crop on the changes in soil structure, water and nitrogen dynamics, and the influence on soil biomass in a wheat-corn-soybean rotation.
2. To evaluate vegetation management strategies and determine factors limiting no-till corn planting into wheat and red clover residue.
3. To evaluate the impact of the red clover cover crop on weed management during corn production in a clay soil.

4. Materials and Methods

4.1. Tillage and red clover effects on crop performance

Three adjacent fields were used in this study on a Brookston clay loam soil (Humic Gleysol). Weather data was obtained from a weather station located ~ 0.5 km from these sites. This study involved a three year rotation of wheat, corn and soybean with one crop per field. There were 5 treatments with 4 replicates in a randomized complete block design. The treatments included fall conventional moldboard plow tillage with and without red clover under-seeded in wheat (CT-RC and CT, respectively) and no-tillage with and without red clover under-seeded in wheat (NT-RC and NT, respectively). In addition, there was a no-tillage red clover treatment which had the wheat straw baled (NT-RC-B) and removed after harvest to reduce the amount of residue on the soil surface.

Corn (Zea mays L., pioneer 3573) was planted (65,000 plants ha^{-1}) in 75 cm row with a John Deere 6 row no-till MaxEmerge planter. One 18" ripple coulters and one bubble coulter were used to open the seed furrow and apply dry fertilizer and residue managers were also used to improve seedbed conditions. Planting dates were May 19, 1994; May 17,1995 and May 28,1996. Nitrogen was split between planting (40 kg N ha^{-1}) and sidedress (115 kg N ha^{-1}) application. Phosphorus (40 kg P_2O_5 ha^{-1}) and potassium (40 kg K_2O ha^{-1}) were added at soil test recommended rates. Row areas (four 1M strips per plot) were measured and marked with flags after planting and both the rate and final crop emergence values were determined. Plants were counted every 1-2 days in the marked areas until emergence was complete for that particular treatment. Days to 100% silking were also determined. Total grain yields were measured at harvest and subsamples were dried and ground. Grain samples were analyzed for total N by performing a Kjeldahl digestion. The digests were analyzed for ammonium on a TRAACS 800 autoanalyzer using the Berthelot reaction (Tel and Heseltine, 1991). Total N uptake was calculated from the dry grain yield and the N concentration in the grain.

All plots were sprayed with 1.8 kg ai ha^{-1} glyphosate plus 1.0 kg ai ha^{-1} 2,4-D in the fall to control perennial weeds, red clover and volunteer wheat. In the spring, at the time of corn planting, all plots were sprayed with 1.68 kg ai ha^{-1} pendimethalin plus 1.0 kg ai ha^{-1} atrazine preemergence. Within each main plot, a 2 m strip was left unsprayed in each of two corn rows to serve as a control. Approximately 6 weeks after planting in each year, weeds were counted in 0. 25 m x 0.25 m quadrats. Three replicate quadrats were placed in the corn row and three quadrats between the row in both sprayed and unsprayed areas of each of two corn rows within each main plot, giving a total of 480 quadrats per year.

4.2. Soil physical properties

Volumetric soil water content was measured using the Time Domain Reflectometry method (Topp et al., 1980). Measurements were made 3 times per week at the 0-10 and 0-30 cm depths in four replications of each treatment. Soil temperature was measured continuously and integrated hourly using thermocouples during the growing seasons in 1995 and 1996. Four thermocouples each were inserted horizontally into the undisturbed soil profile at 5 and 10 cm depths on two replications of each treatment. Two CR-10 microloggers and four multiplexers were used to record the soil temperatures. Daily, monthly and seasonal temperature and moisture averages were calculated.

Representative soil samples were collected after harvest each year from experimental sites at depths of 0-5 cm and 10-15 cm for wet aggregate stability (WAS) and mean weight diameter (MWD) analyses. Wet aggregate stability (WAS) was determined on 0.25 mm to 4.69 mm air dry aggregates wetted by immersion using the method described by Kemper and Rosenau (1986). The size distribution of aggregates was characterized by determining the mean weight diameter (MWD; Kemper and Roseau 1986).

4.3. Soil biological properties

Crop residue degradation was measured two ways. Surface residues were measured 3 to 4 times during the growing season by collecting, drying and weighing the crop residue in a 30 cm quadrant. In addition, residue decomposition was estimated during the growing season by determining the CO_2 flux from 60 cm diameter cylinders that were installed to a soil depth of ~ 8 cm at the beginning of the growing season. Two cylinders were placed in each plot and three replicates were used for these measurements. Hence there were 6 estimates per treatment per sampling date. Chamber height was also estimated several times during the growing season by placing a wooden board on top of the chambers with 20 holes to allow a bolt to be placed in these holes and rest on the soil surface. Chamber height was estimated by subtracting the height of the bolt above the bottom of the wooden board from the total bolt height. Carbon dioxide flux was measured with a LICOR photosynthesis instrument. Measurements were taken between 10 to 15 times during the growing season and soil respiration rates were determined. Average fluxes were also calculated over each growing season for each treatment. Average fluxes over the growing season were presented to determine the overall effect of a particular treatment, although it is recognized that the soil water, temperature, and availability of residue all influence soil respiration rates.

Microbial biomass carbon (MBC) levels were determined on soil samples taken at 0-10 cm depths in all years and in 1995 and 1996 microbial biomass levels were also determined at 10-20 cm depth. Microbial biomass was measured at monthly intervals over the growing season. Microbial biomass carbon was determined using a fumigation-extraction method (Vance et al., 1991). Both fumigated and non-fumigated samples were extracted with 0.25 M K_2SO_4 and analyzed for total C (TC) and inorganic C (IC) on a total organic carbon analyzer (Shimadzu TOC 5000). Microbial biomass carbon was determined as follows:

$$MBC = ((TC\text{-}IC)_{fumigated} - (TC\text{-}IC)_{non\text{-}fumigated})/0.45$$

Soil samples were taken 1-2 days prior to planting, before and after sidedress application and at the end of the growing season at 0-30 and 30-60 cm depths. These samples were extracted with 2M KCl, shaken for 1 hr on a rotary shaker, filtered through Whatman 40 filter papers and analyzed on a TRAACS 800 autoanalyzer for NH_4^+ using the Berthelot reaction and for NO_3^- plus NO_2^- using a cadmium reduction method (Tel and Heseltine, 1991).

Analysis of variance was conducted using a randomized complete block design with 4 replicates for crop performance data (emergence, residue decomposition, % silking, yields, N uptake and microbial biomass C). Three replicates were used for the temperature, moisture, and respiration rates. When significant differences occurred at ($P<0.05$), a Least Squares Difference (LSD) test was used to determine which treatments were significantly different from each other.

Weed counts were log transformed and data for each weed species were subjected to an analysis of variance with position (in or between the rows) nested within herbicide application (sprayed or unsprayed), and herbicide application nested within tillage main plots. A multivariate canonical discriminant analysis was also conducted on the combined weed species data within each year to detect overall differences.

5. Results and Discussion

5.1. Tillage and red clover effects on emergence and initial soil conditions

The rainfall in both 1994 (305 mm) and 1995 (290 mm) growing seasons was considerably below the 30 year long term average of 422 mm (Fig. 1). There were several months in both years that received less than half of the 30 year average. In 1994, these deficit months were in July and September and in 1995 these months were in June and September. Despite the average precipitation amount for the 1996 growing season (412 mm), it was very dry during June, July and August. The month of August was the driest, receiving only 18 mm of precipitation compared to a long-term average of 82 mm. In 1996, there was 197 mm of precipitation in the month of September which was over twice the average rainfall (81 mm). However, this rainfall occurred too late to be of much benefit for most of the crop since there had been three consecutive dry months which limited crop growth. Hence, both the rainfall distribution and totals are important for optimal corn growth and yields.

The rate of corn emergence was measured in 1995 and 1996 growing seasons (Fig. 2). In 1995, CT treatments achieved 75% emergence by about 12 days whereas 18 days were required for NT treatments. The total number of emerging plants was between 93-95% for the CT treatments whereas in the NT treatment only 75% of the plants emerged and survived. In contrast, when red

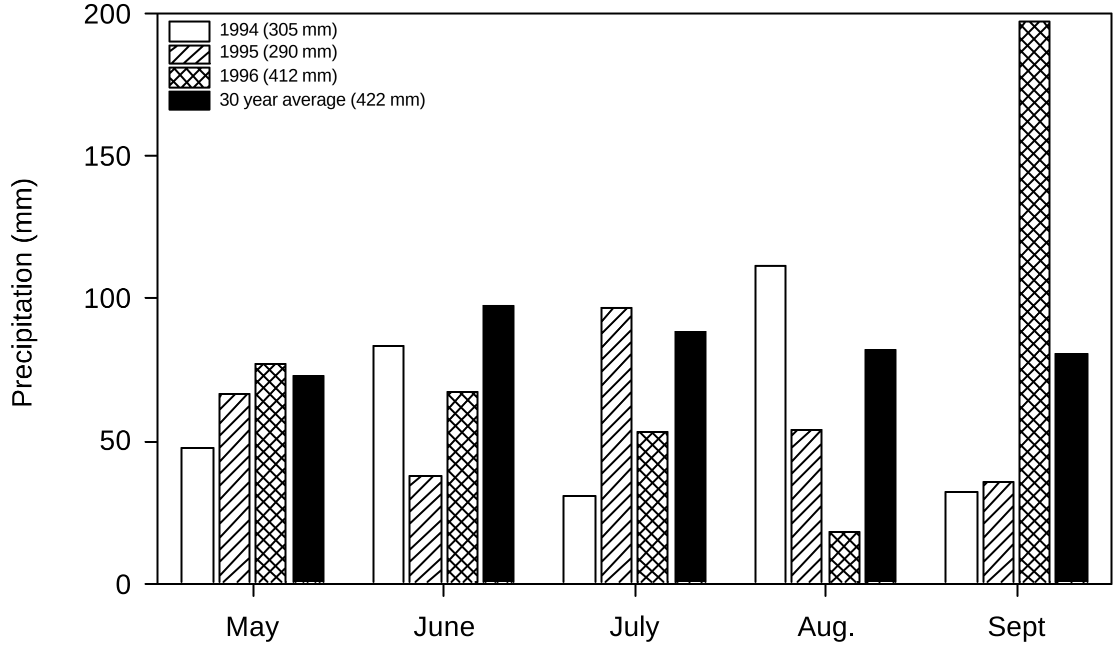

Figure 1. Seasonal (May to September) and monthly precipitation for 1994, 1995, 1996 and the thirty year average.

clover was included in the rotation with the NT treatment, about 100% of the plants emerged. In addition to the moisture and treatment effects which will be described in the following sections, the planting slot reopened in the NT treatment which caused the corn roots to desicate even though there was more moisture in the NT soils. In 1996, it required about 13-14 d for 75% of plants to emerge from the CT treatments whereas it took about 19 days for the NT-RC treatment and 27 d for the NT treatment to reach 75% emergence. The CT treatments had between 92 and 96% of the seeds emerge, the NT-RC treatment had a 84% emergence rate whereas the NT treatment had only 76% of the seeds emerge by 27 d. In 1996, the planting slot was also found to reopen in the NT treatments. This problem was partially due to the lack of measurable rainfall within 3 weeks after planting in both years.

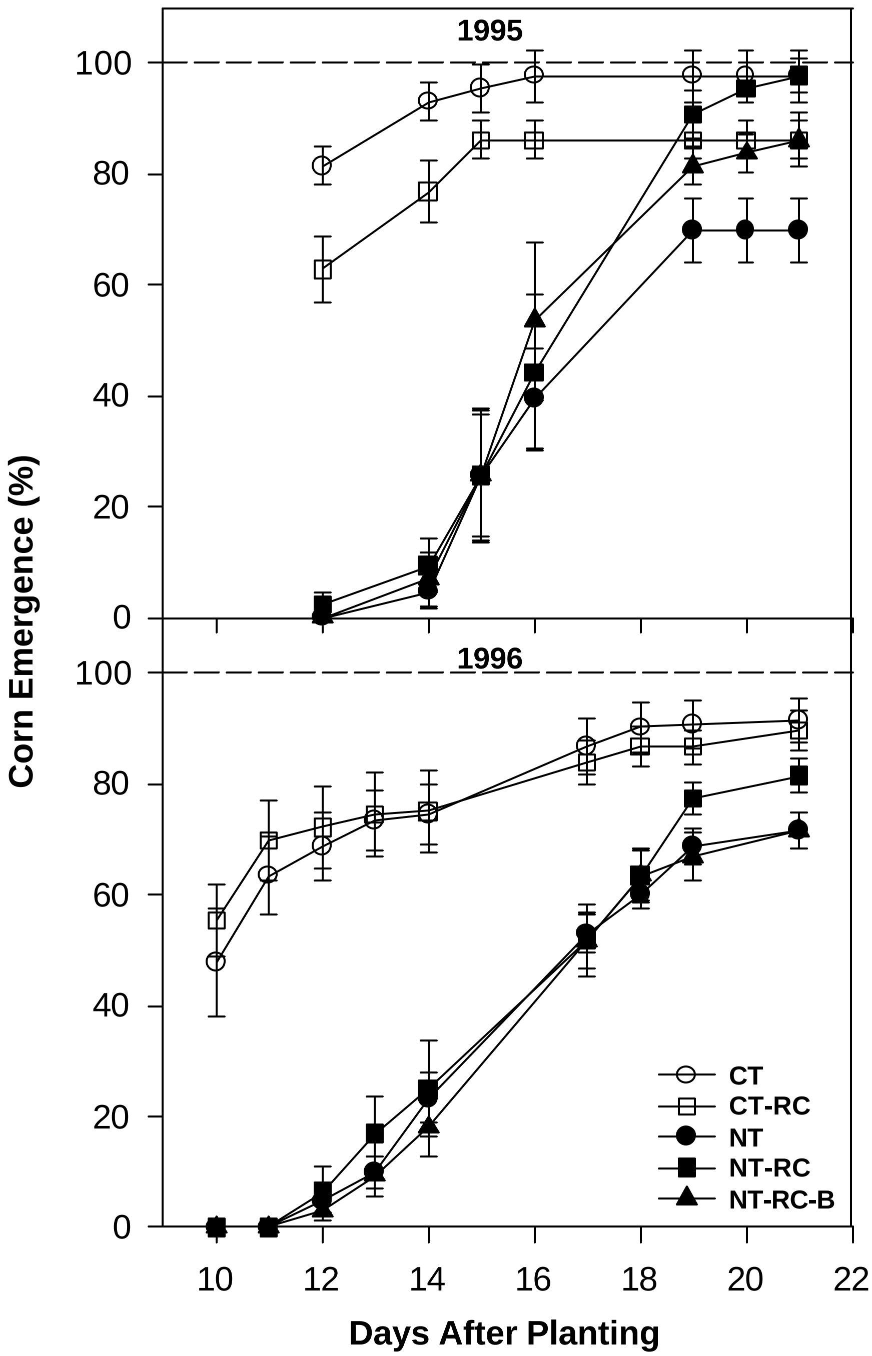

Figure 2. Corn emergence in 1995 for CT and NT treatments with/ without red clover and for NT-RC with the straw baled. Error bars are standard error (n=4).

The average daily soil temperatures during corn emergence in the 1995 growing season at both the 5 cm and 10 cm depths were about 1.6-2 EC warmer in the CT treatments than the NT treatments (Figs. 3 and 4). The temperature curves during this time period were parallel to each other and generally were rising as the season progressed. Red clover treatment had comparatively little effect on soil temperature as it did not affect the CT treatments and resulted in about 0.4 EC cooler temperatures in the NT treatments for both depths.

In 1996, the soil temperatures in both the 5 cm and 10 cm depths were about 1-1.5 EC greater in the CT compared to the NT treatments (Figs. 5 & 6). The red clover only influenced the soil temperature with the CT treatment as it resulted in about 0.5 EC warmer temperatures than the corresponding no-red clover treatment. Generally the soil temperature was increasing as the growing season progressed. Hence in both 1995 and 1996, the most dramatic effect was the higher temperatures in the CT versus the NT treatments during the early part of the growing season.

In 1995, the volumetric water content during early corn emergence in the 0-10 cm and 0-30 cm depths was about 1.5% wetter in the NT treatment than the CT treatment (Figs. 7 & 8). When red clover was included, the NT treatment was 3% wetter than the CT treatment at the 0-10 cm depth but only 0.4% wetter at the 0-30 cm depth. During this initial growth stage, the water content was dramatically decreasing due to the lack of precipitation. The first measurable rainfall occurred over 1 month after planting on June 27 with 30 mm rain.

From May 29, 1996 to June 21, 1996, the volumetric water content was about 4.5% wetter with NT than CT treatments in the 0-10 cm depth (Fig. 9). Red clover did not affect the soil water content during this time period. In the 0-30 cm depth, the NT treatment was about 4.7 % wetter than the CT treatment and the NT-RC treatment was about 3% wetter than the CT-RC

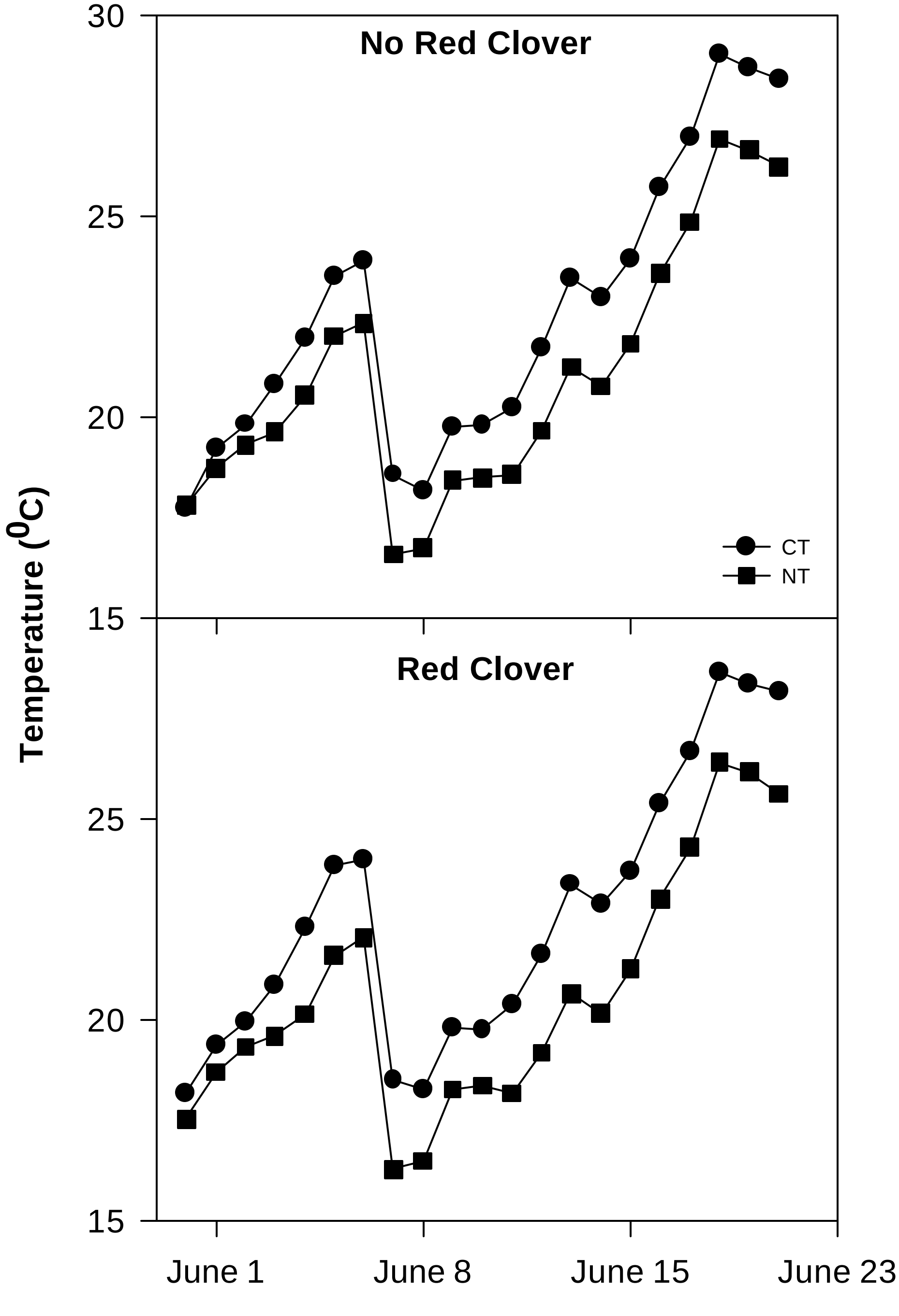

Figure 3. Soil temperature at 5 cm depth from the CT and NT plots with/without red clover in June, 1995.

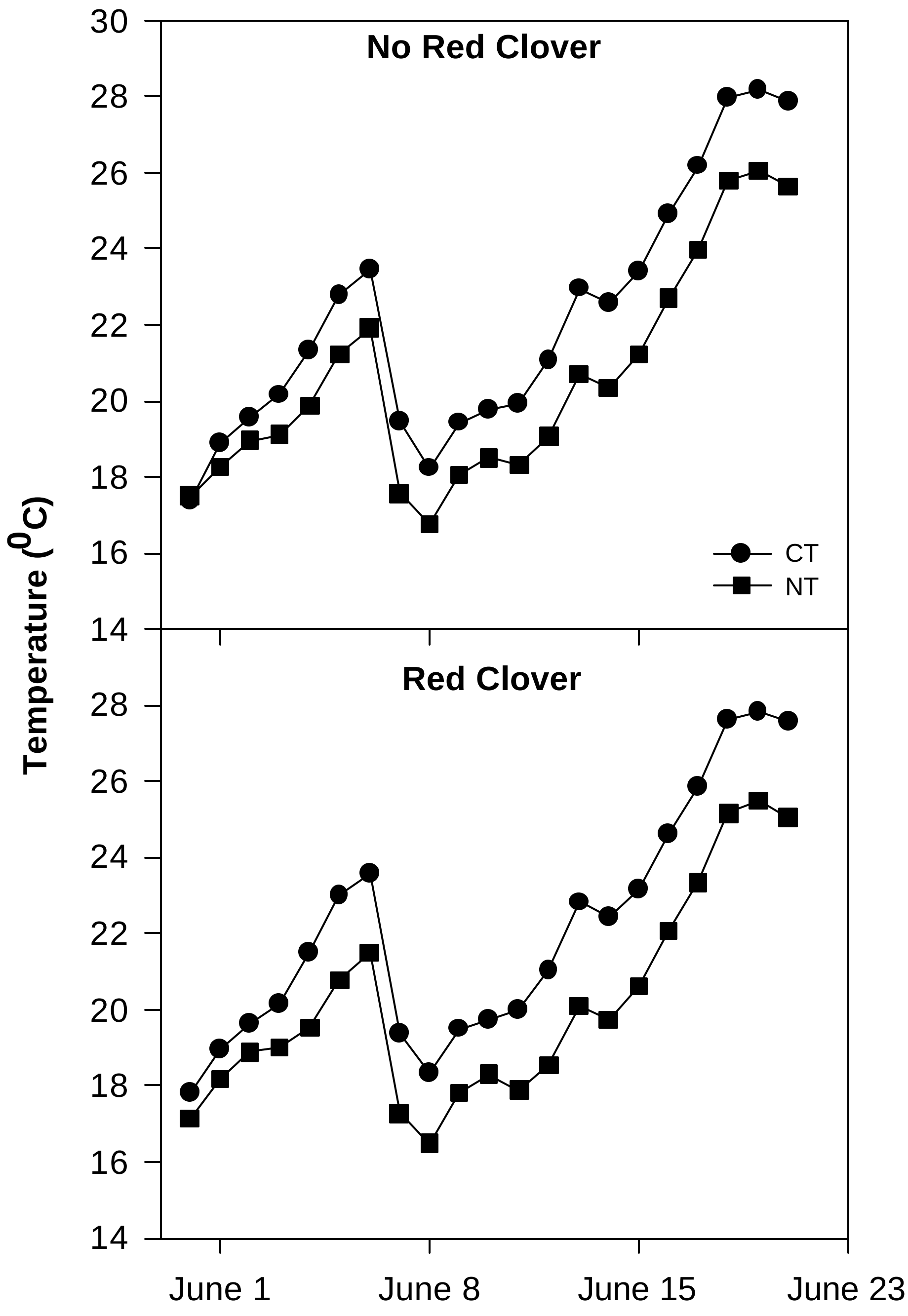

Figure 4. Soil temperature at 10 cm depth from the CT and NT plots with/without red clover in June, 1995.

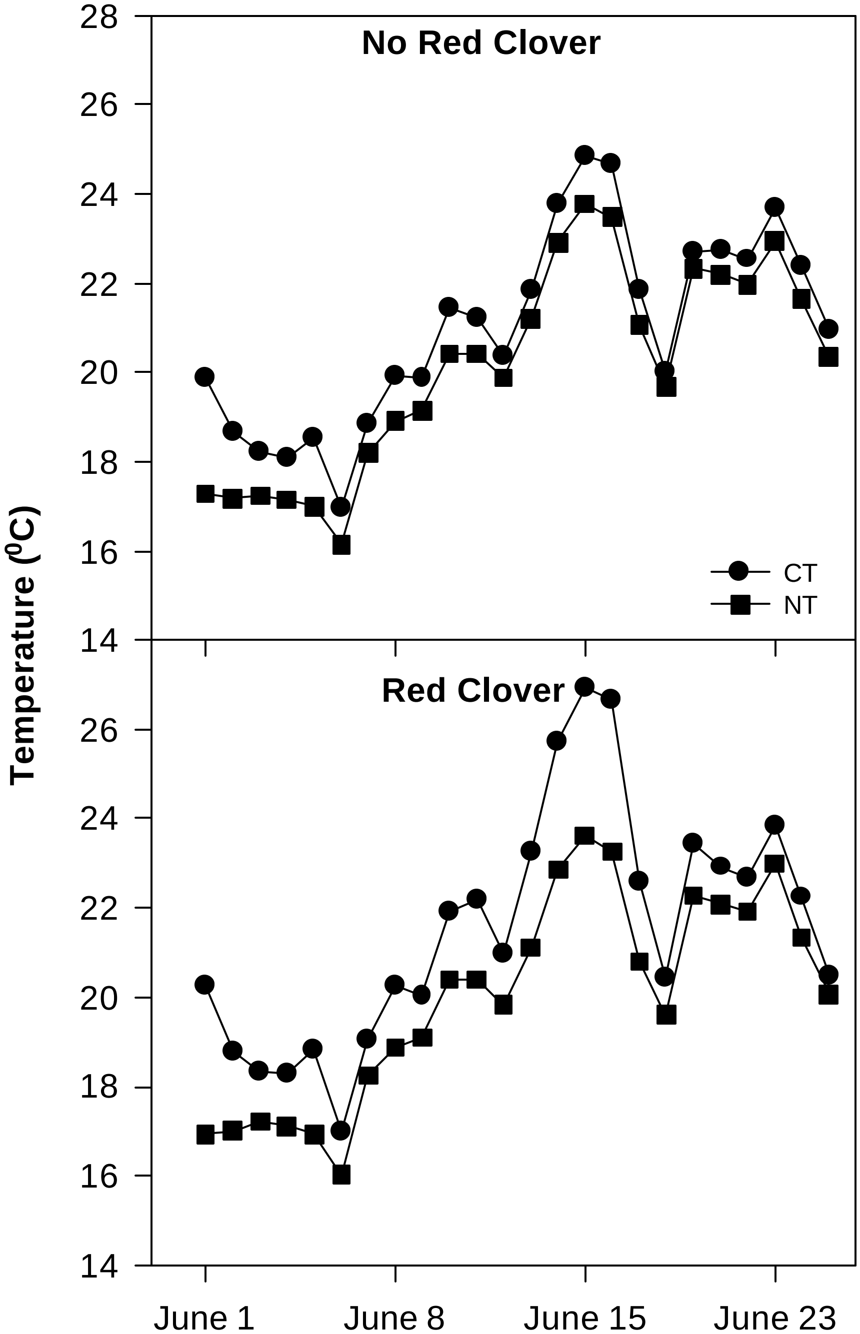

Figure 5. Soil temperature at 5 cm depth from the CT and NT plots with/without red clover in June, 1996.

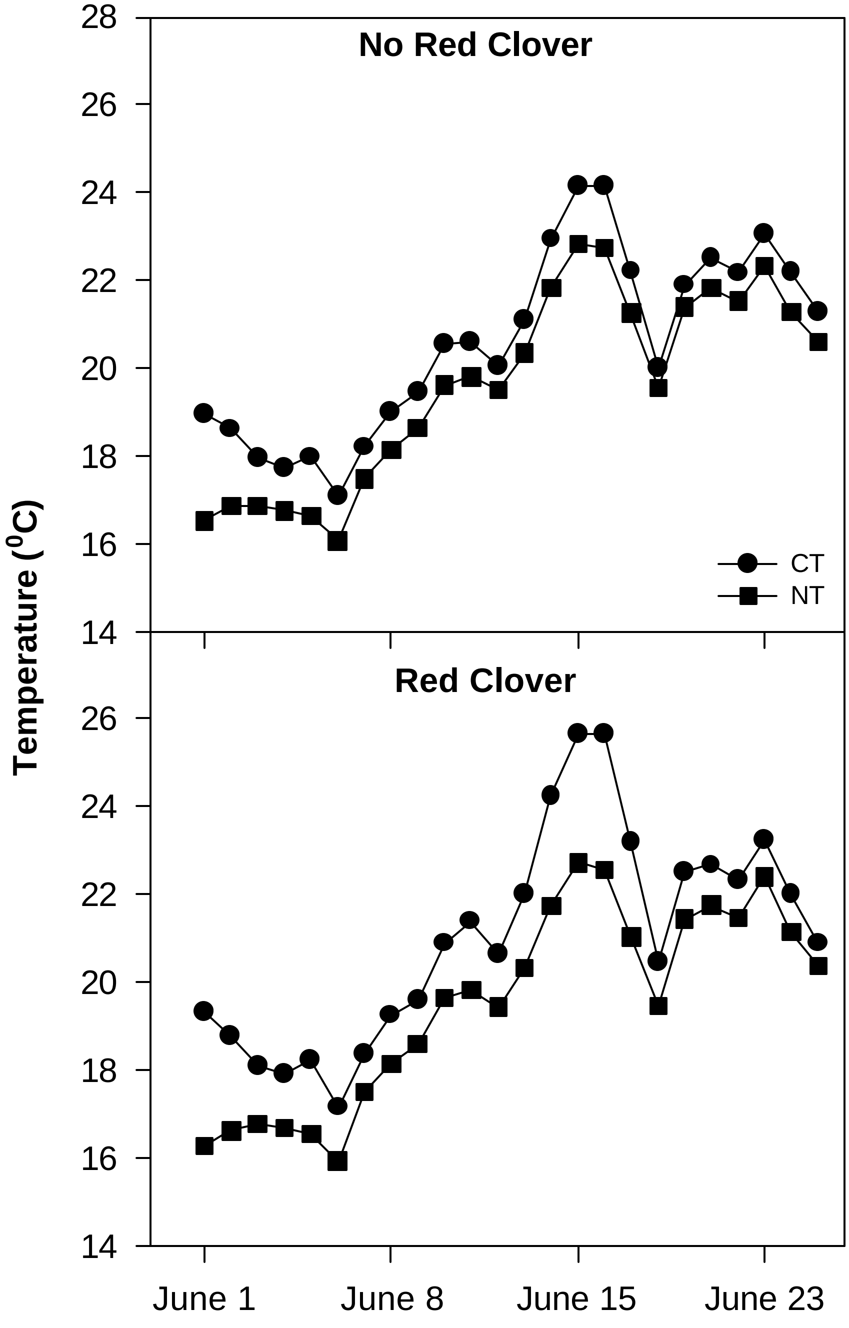

Figure 6. Soil temperature at 10 cm depth from the CT and NT plots with/without red clover in June, 1996.

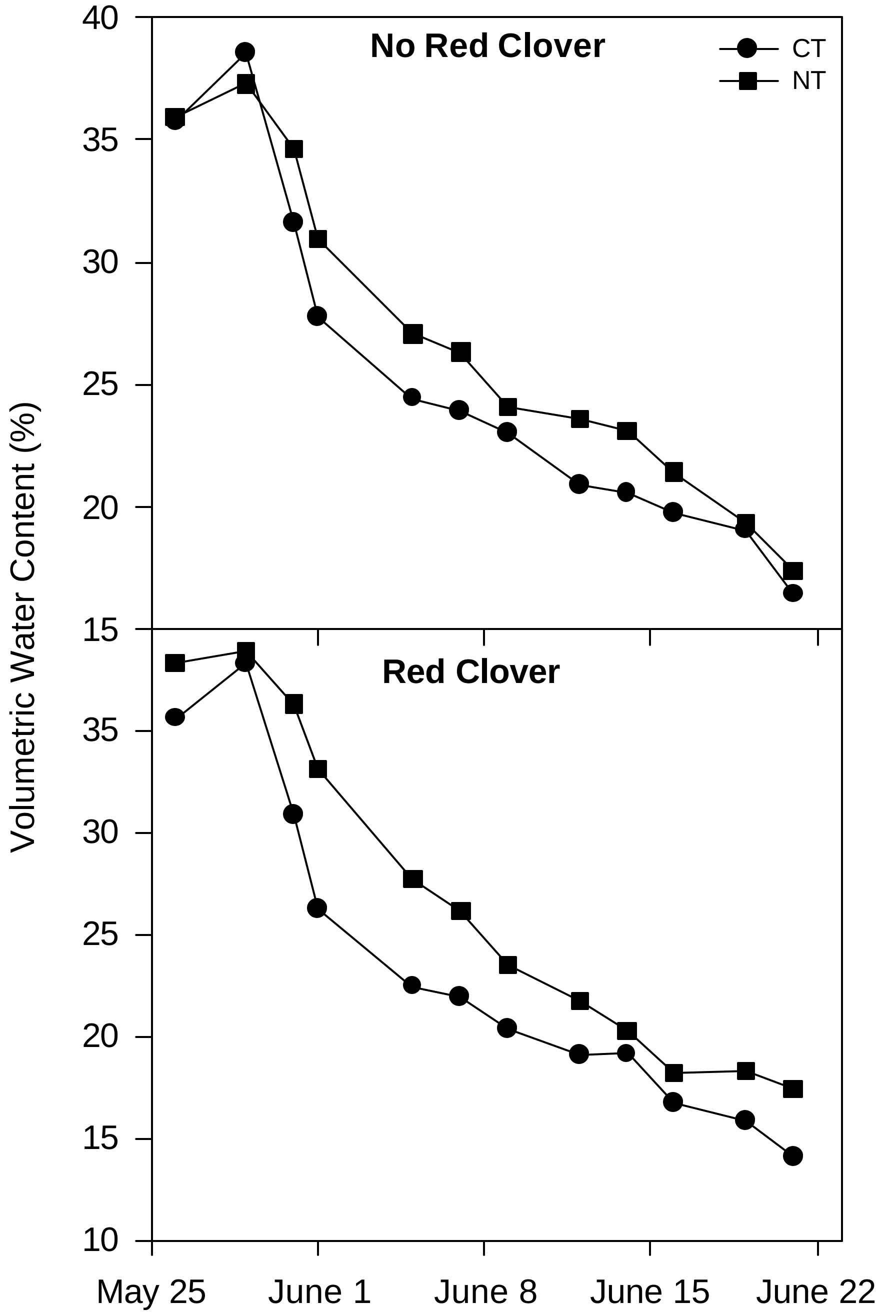

Figure 7. Soil volumetric water content in the 0-10 cm depth of the CT and NT plots with/without red clover from May 26 to June 21, 1995.

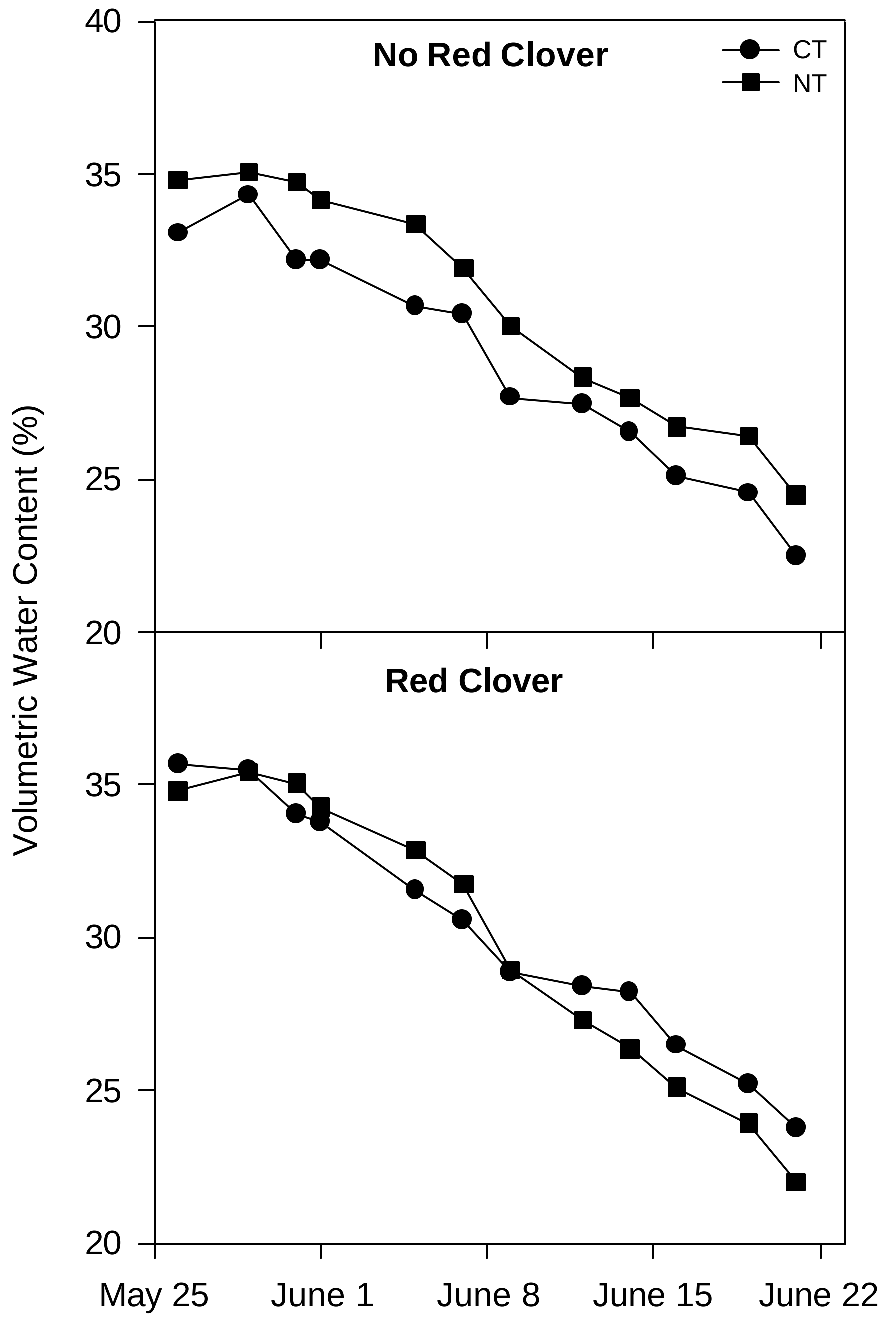

Figure 8. Soil volumetric water content in the 0-30 cm depth of the CT and NT plots with/without red clover from May 26 - June 21, 1995.

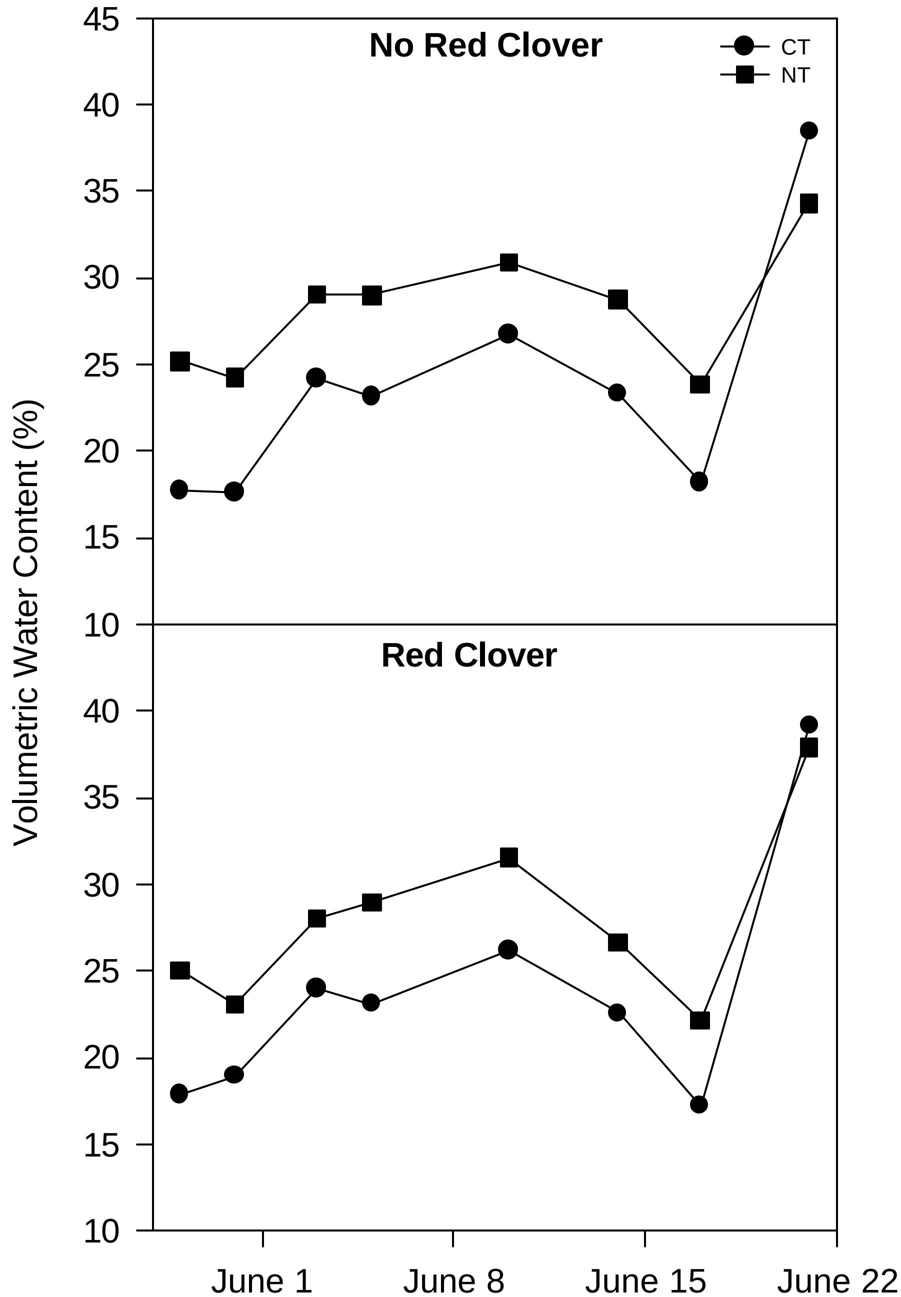

Figure 9. Soil volumetric water content in the 0-10 cm depth of the CT and NT plots with/without red clover from May 29 to June 21, 1996.

treatment (Fig. 10). The two NT treatments were not significantly different from each other but were significantly greater than both the CT treatments. Red clover increased the water content by 2.4% in the CT treatment but had no effect on the NT treatments. In 1996, it was also fairly dry for several weeks after planting with the first major rainfall (37 mm) occurring on June 18, 1996 which was 25 days after planting. The effect of this rainfall was apparent in the water content curves as it was the maximum water content for each treatment.

The early stages of corn growth require optimal temperatures and water contents to ensure rapid growth and complete emergence. In this study, the NT treatments were cooler and wetter which delayed emergence. The combination of NT and red clover was beneficial as the total number of plants that emerged and survived were considerably greater than NT and were similar to that of CT treatments. No-till treatments had a further problem of having the planting slot reopen even though the soil water content was greater which indicates that the early seedbed conditions for planting were also critical.

5.2 Residue decomposition during the growing season.

In both 1995 and 1996, there was very little surface residue during the growing seasons in the CT treatments, as expected, with less than 0.2 t ha^{-1} residue on the soil surface (Fig. 11). The maximum amount of residue with the NT treatment was 5.6 and 5.5 t ha^{-1} in 1995 and 1996, respectively. The NT-RC treatment had less residue with a maximum of 4.2 and 4.6 t ha^{-1} measured in the growing season. The average amount of residue on the NT treatment was 5.2 and 4.4 t ha^{-1} in 1995 and 1996, respectively for the NT treatment and 4.36 and 3.07 t ha^{-1} in 1995 and 1996, respectively for the NT-RC treatment. Hence, on average, when RC was included in the rotation, residue decomposition was increased by 16% in 1995 and by 31% in 1996. Surface residue decreased during the 1995 growing season but remained fairly steady

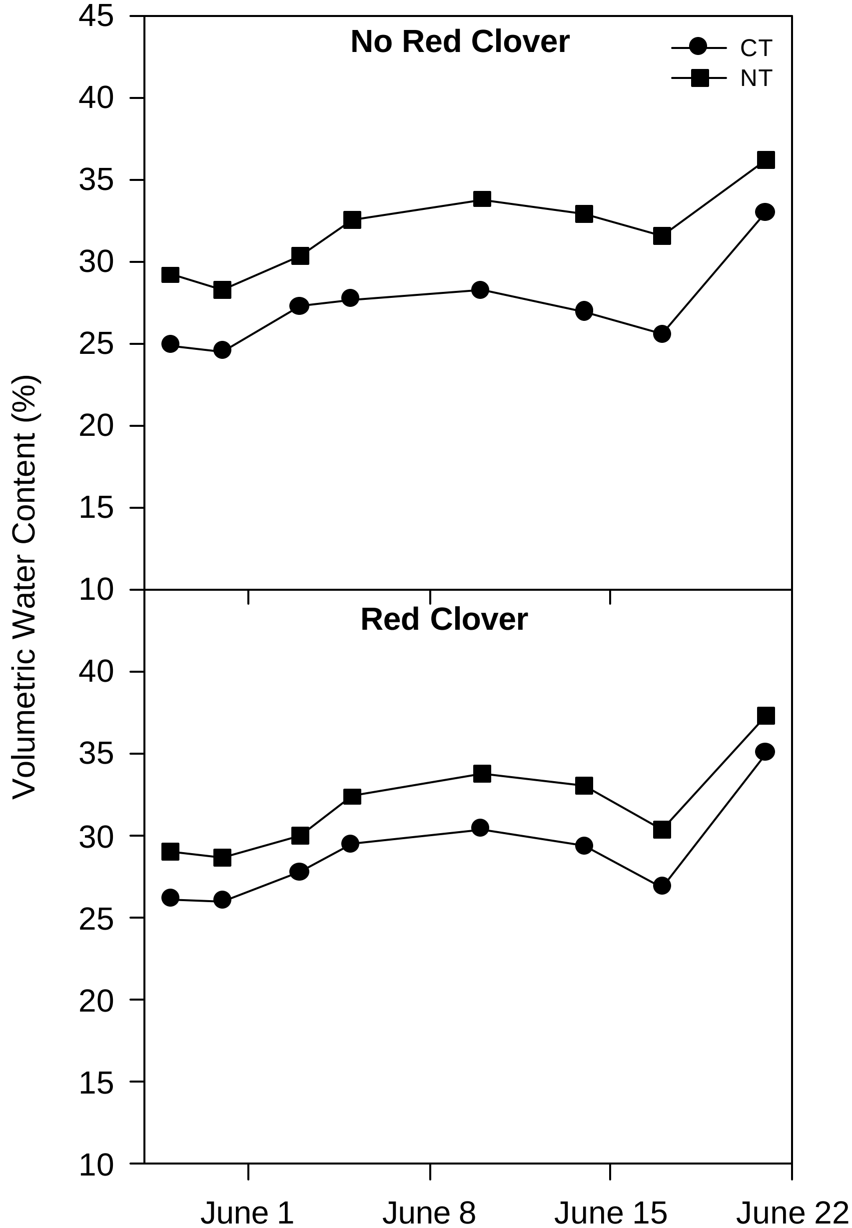

Figure 10. Soil volumetric water content in the 0-30 cm depth of the CT and NT plots with/without red clover from May 29 to June 21, 1996.

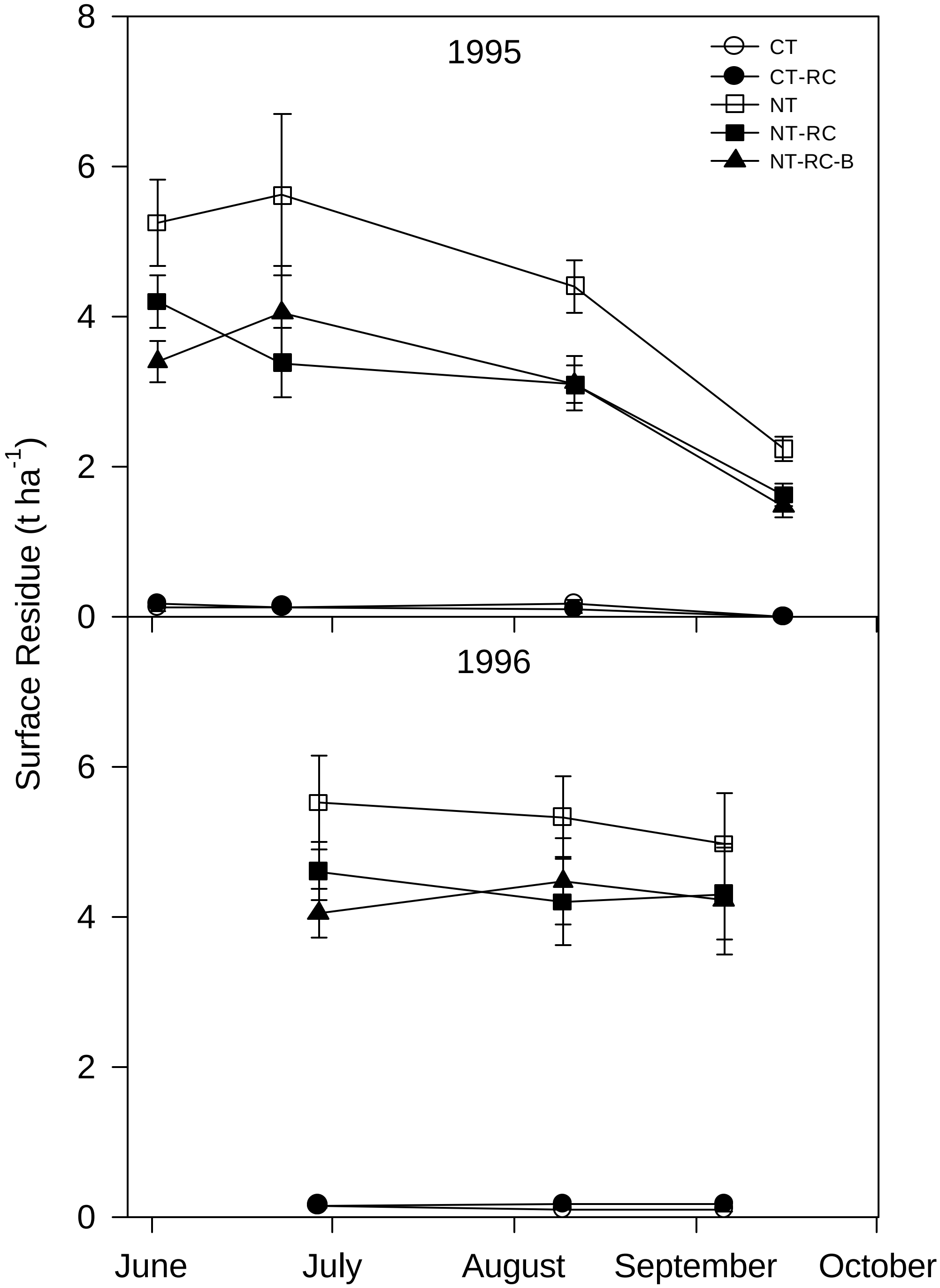

Figure 11. Surface Residue on the CT and NT plots with/without red clover in 1995 and 1996. Error bars are standard error (n=8).

during 1996. Both July and August were considerably drier in 1996 than 1995 (Fig. 1) which could partially explain the yearly differences in residue decomposition rates.

The NT treatment had lower soil respiration rates in 1994 than the corresponding CT treatments (Fig. 12). Soil respiration was greatest at the beginning of the growing season and decreased over time. On average, the CT treatment had a net production of CO_2 from the bare soil of 432 µg CO_2 m^{-2} s^{-1} compared to 341 µg CO_2 m^{-2} s^{-1} for the NT treatment. The CT-RC resulted in 452 µg CO_2 m^{-2} s^{-1} evolved compared to 347 µg CO_2 m^{-2} s^{-1} for the NT-RC treatment. On average, the NT treatments reduced CO_2 production by 22% compared to the CT treatments. Red clover increased the CO_2 production rate over the no red clover treatment with CT but did not affect the production from the NT system .

In 1995, the CT treatments resulted in about 309 µg CO_2 m^{-2} s^{-1} versus 213 µg CO_2 m^{-2} s^{-1} for the NT treatments which was a 31% reduction (Fig. 13). Red clover did not have a large effect on CO_2 production as there was only a 2.7% and 2.4% increase in production for the CT and NT treatments, respectively. The soil respiration rate also declined during the growing season similar to that in 1994 (Fig. 12).

The soil respiration rate was considerably lower in 1996 than in the previous two years with an average of 153 µg CO_2 m^{-2} s^{-1} for the CT treatments and 126 µg CO_2 m^{-2} s^{-1} for the NT treatments (Fig. 14). No-tillage decreased soil respiration by 18% in 1996. The effect of red clover on soil respiration was more dramatic as respiration was increased by 11% and 15% for the CT and NT treatments, respectively.

In 1995, the soil temperature values varied considerably over the growing season with peak temperatures in mid June and mid July for both the 5 and 10 cm depths (Figs. 15 and 16). The greatest differences in soil temperatures between treatments occurred in the early part of

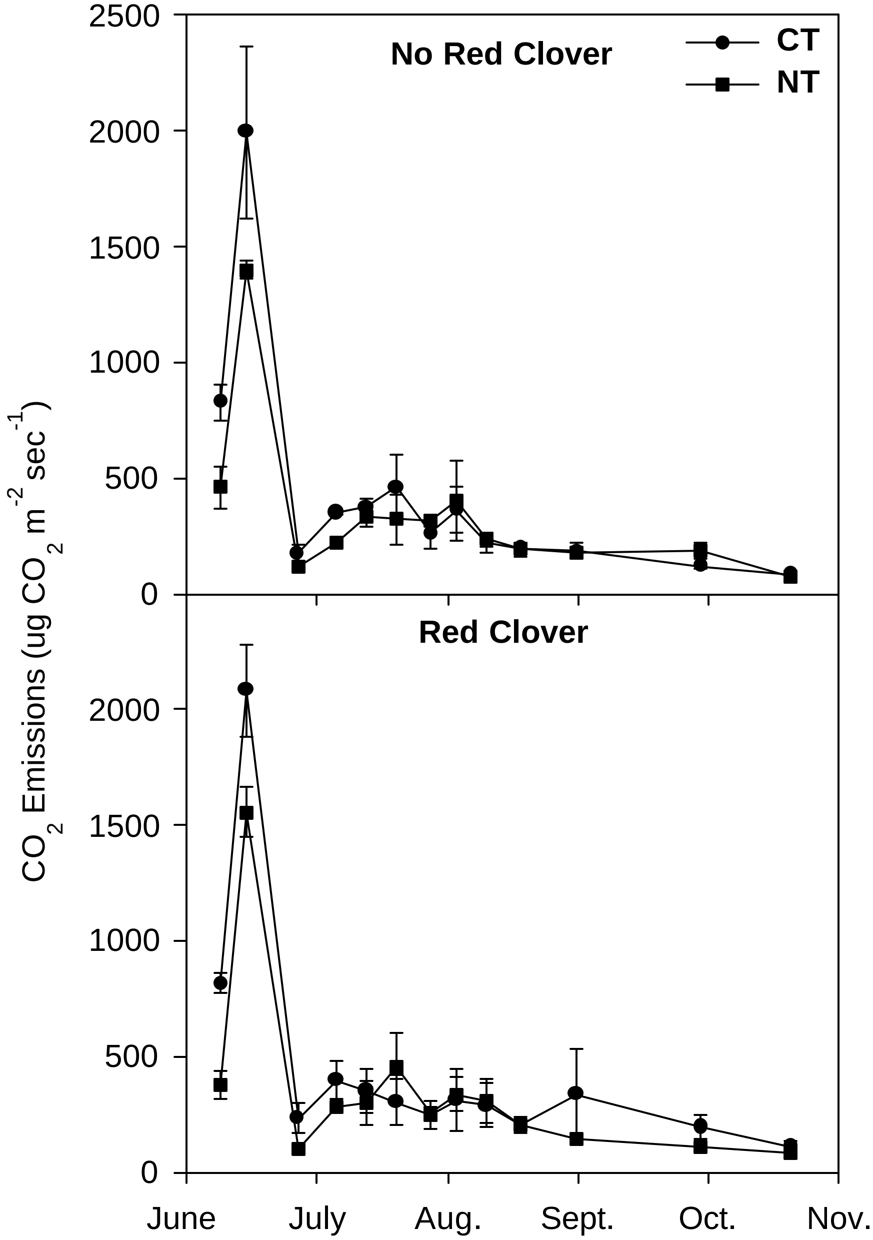

Figure 12. Soil respiration from the CT and NT plots with/without red clover in 1994. Error bars are standard error (n=6).

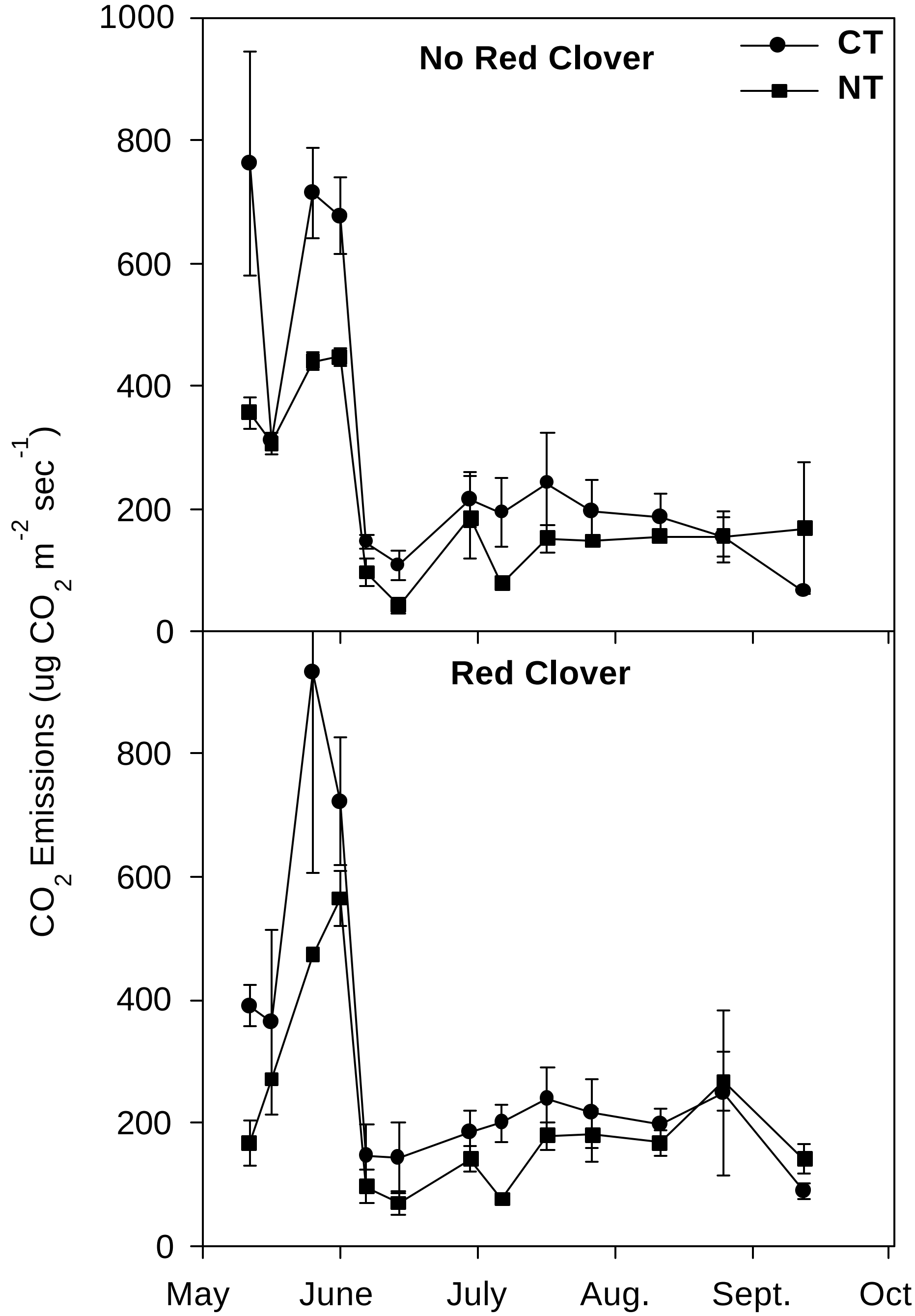

Figure 13. Soil respiration from the CT and NT plots with/without red clover in 1995. Error bars are standard error (n=6).

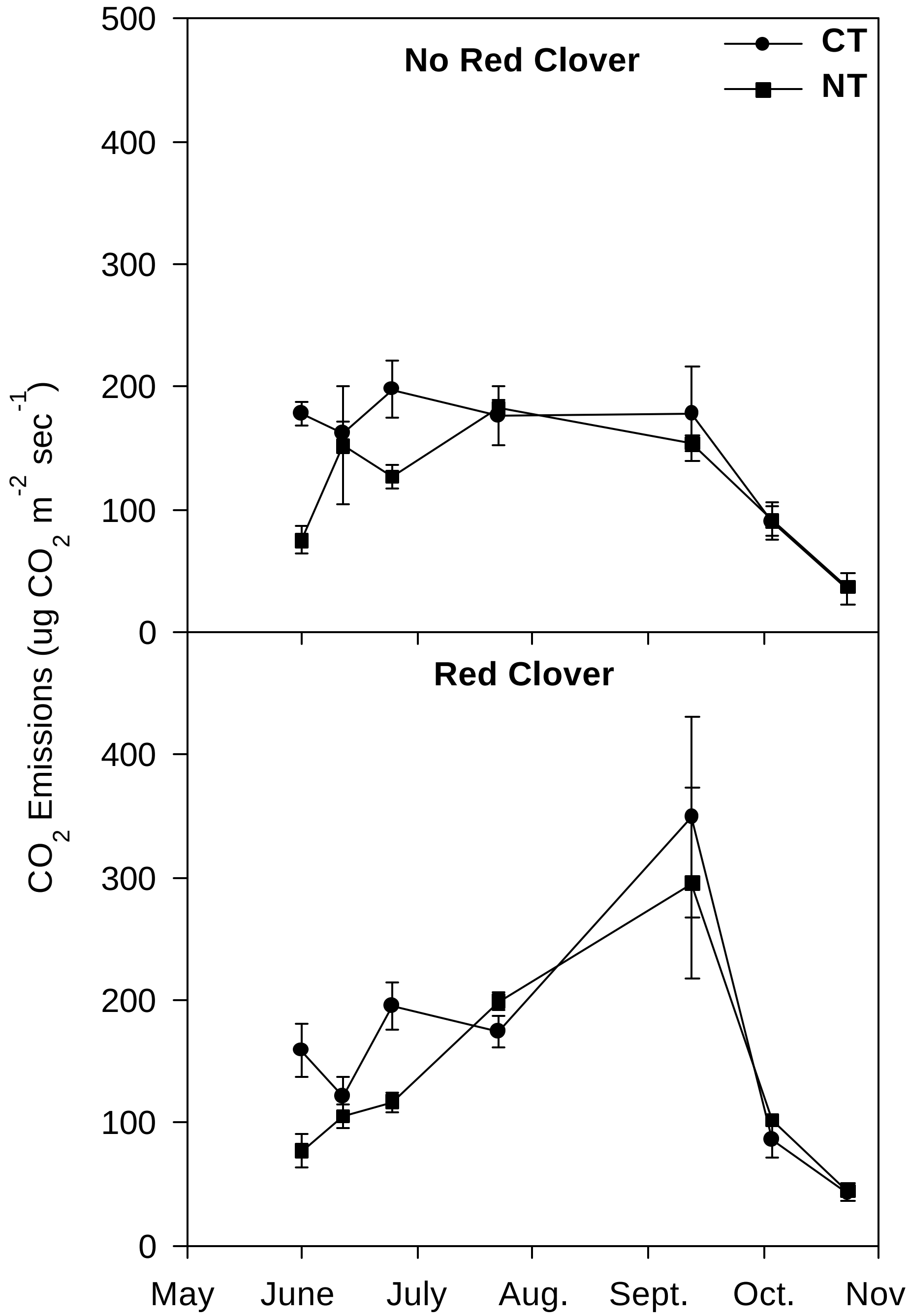

Figure 14. Soil respiration from the CT and NT plots with/without red clover in 1996. Error bars are standard error (n=6).

the growing season as shown previously (Figs. 3 and 4). The differences in soil temperature decreased as the season progressed which is consistent with the decrease in residue cover and water content as well as the shading from the corn canopy. The seasonal average soil temperatures were 21.1 EC for the CT and CT-RC treatments at both the 5 and 10 cm depths. The NT treatment reduced the average soil temperature by 0.35 EC and by 0.37 EC in the 5 and 10 cm depths. The NT-RC treatments were 0.12 and 0.19 EC lower than the CT-RC treatment at the 5 and 10 cm depths, respectively. Hence the seasonal differences in soil temperature were very small.

In 1996, the soil temperature peaked from mid June until mid July with higher temperatures in the CT and CT-RC treatments than the corresponding NT temperatures (Figs. 17 and 18). The greatest differences in temperature were at the early part of the growing season as shown previously (Figs. 5 and 6) with the differences diminishing during the growing season. The seasonal average temperature were 20.7EC and 20.6 EC for the CT treatments in the 5 and 10 cm depths, respectively with no differences between the CT and CT-RC treatments. The NT and NT-RC treatments had seasonal averages that were between 0.23 EC and 0.26 EC lower at 5 cm than the corresponding CT treatments and were between 0.36EC and 0.40 EC lower than the corresponding CT treatments at the 10 cm depth.

The microbial biomass C (MBC) content is an indicator of microbial activity, residue degradation and soil quality. In 1994, the MBC content was measured at the 0-10 cm depth four times during the growing season (Fig. 19). September and October had the greatest MBC contents. No-tillage treatments resulted in greater MBC contents than the CT treatments both with and without red clover. On average, the MBC level was 344 mg C kg^{-1} for the CT treatments, 378 mg C kg^{-1} for the NT treatments and 433 mg C kg^{-1} for the NT-RC treatment

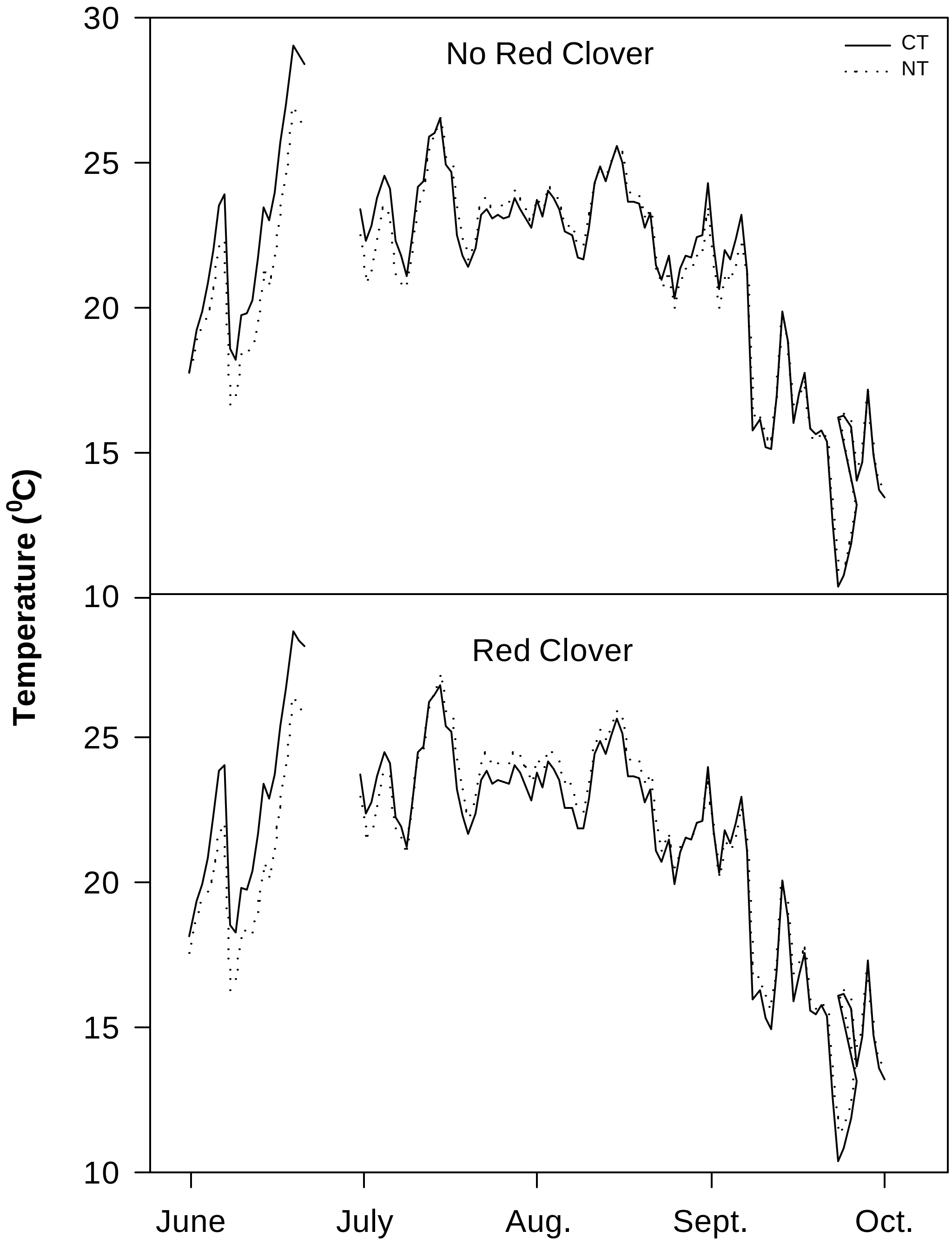

Figure 15. Soil temperature at 5 cm depth from the CT and NT plots with/without red clover in 1995.

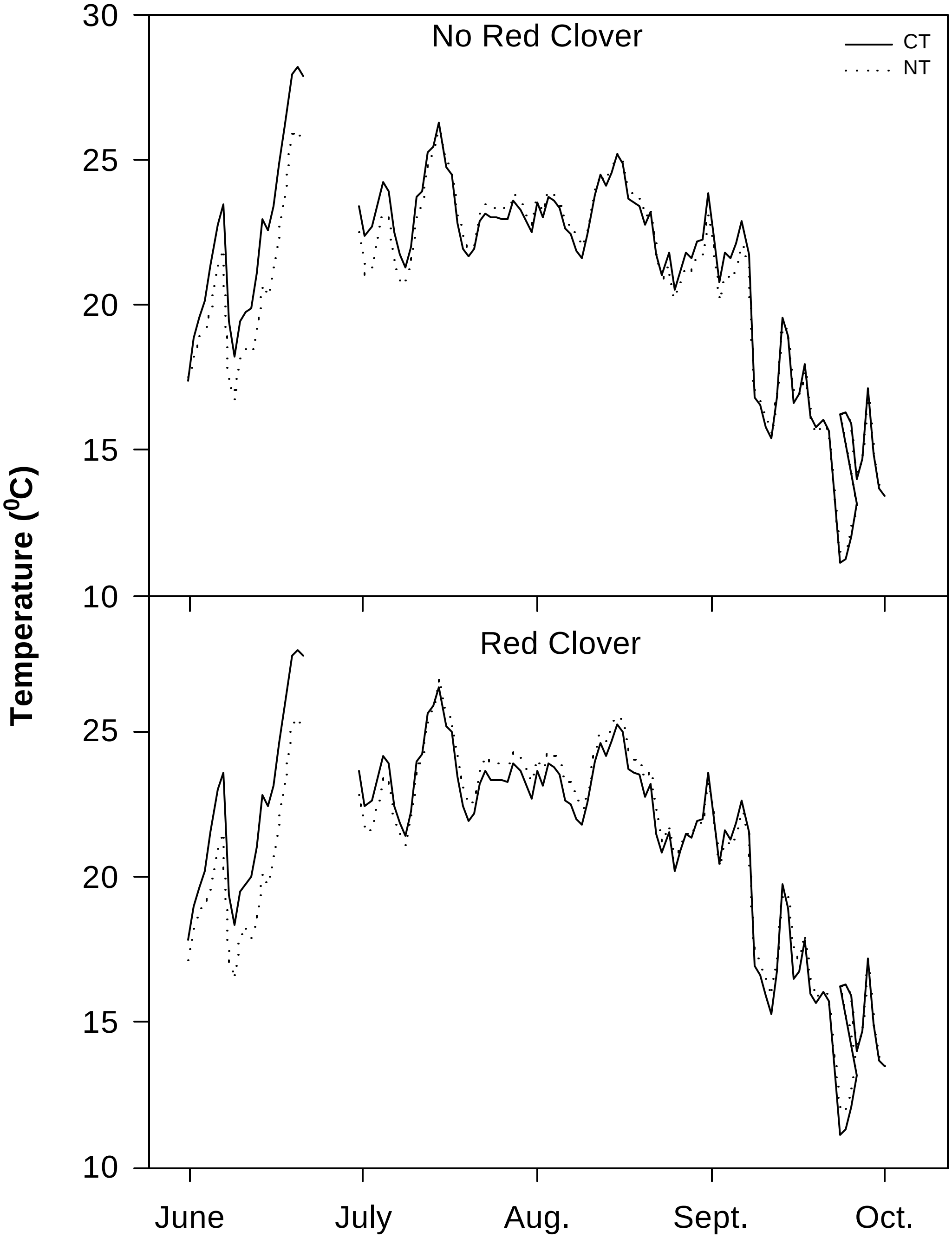

Figure 16. Soil temperature at 10 cm depth from the CT and NT plots with/without red clover in 1995.

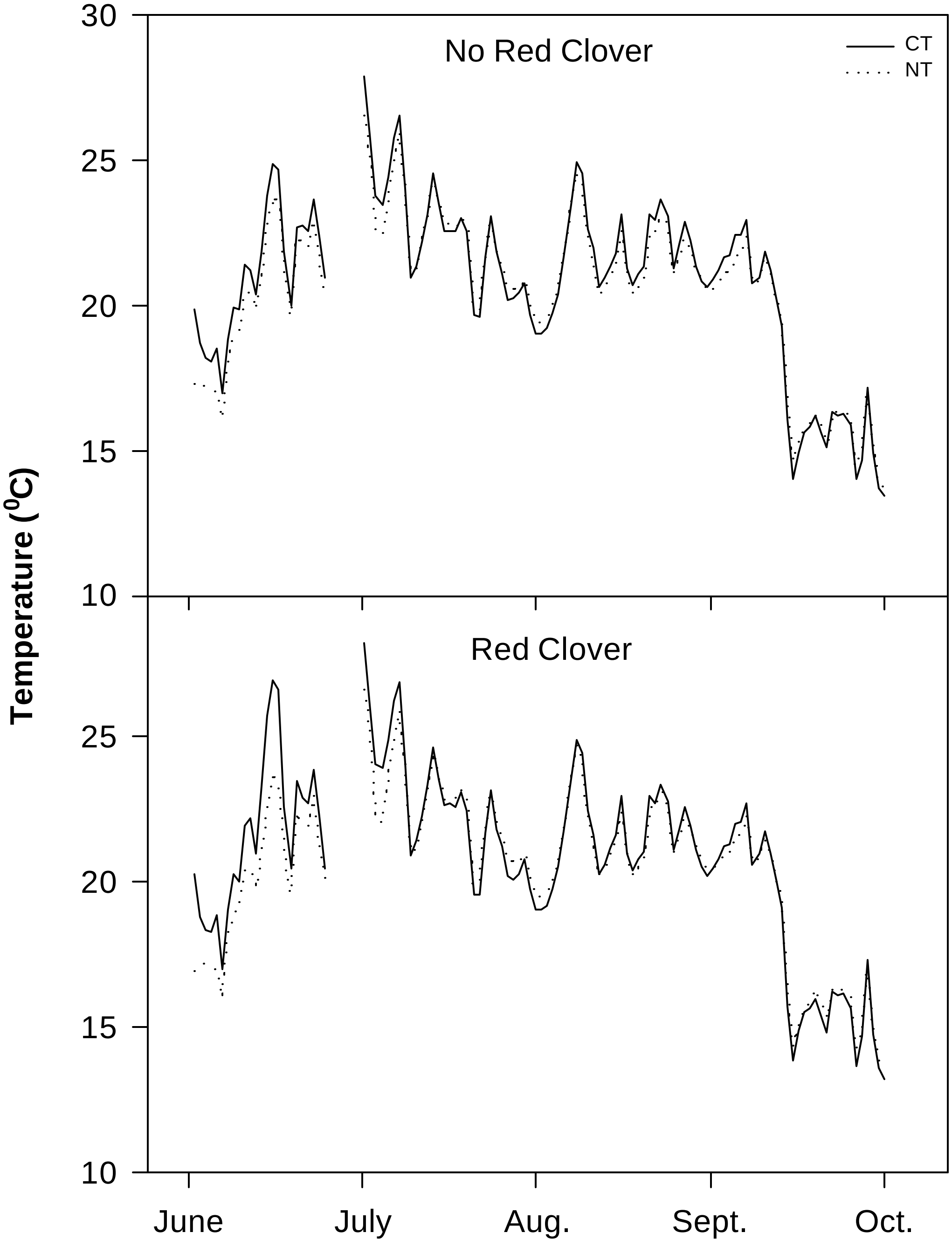

Figure 17. Soil temperature at 5 cm depth from the CT and NT plots with/without red clover in 1996.

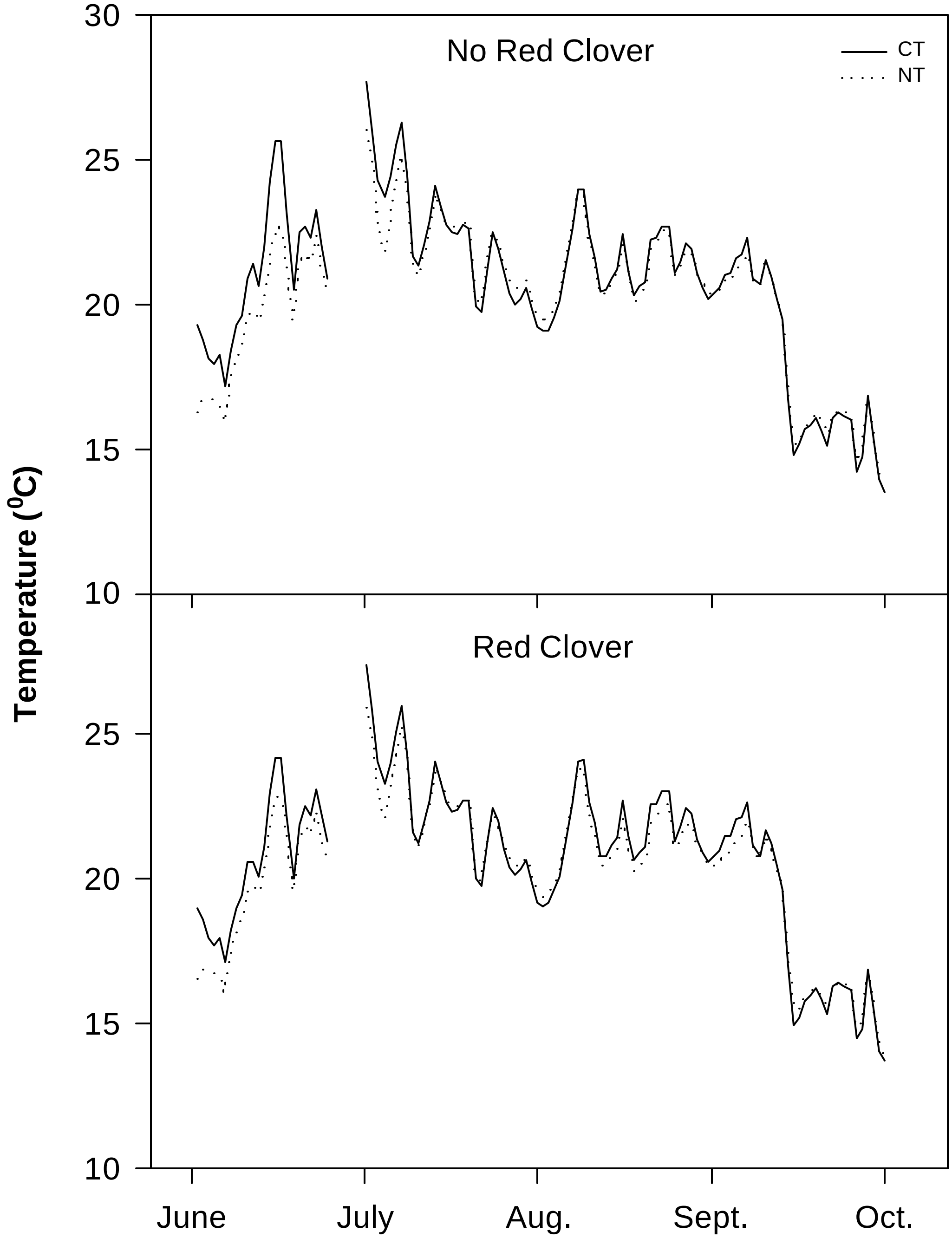

Figure 18. Soil temperature at 10 cm depth from the CT and NT plots with/without red clover in 1996.

which were 10% and 26% increases over the CT treatment. Hence the combination of NT-RC was particularly favorable for enhanced microbial activity.

In 1995, the MBC content of the soil at 0-10 cm averaged 176 mg C kg^{-1} in the CT treatment versus 192 mg C kg^{-1} in the NT treatment which was about a 10 % increase (Fig. 20). The greatest MBC content occurred with the NT-RC treatment at 199 mg C kg^{-1} which was a 13% increase over the CT treatment. Red clover also increased the MBC level of the CT treatment by ~ 10%. The differences in MBC were not as dramatic in 1996 and in several sampling period the levels were similar or greater with CT-RC compared to NT-RC.

In 1995, the MBC levels in the 10-20 cm depth were greater with the CT treatments than the NT treatments. In particular, the average MBC level was 283 mg C kg^{-1} for the CT versus 209 mg C kg^{-1} for the NT treatment (Fig. 21). Red clover increased the MBC level for the CT by 17% and for the NT treatments by 32% in the 10-20 cm depth. The MBC decreased during the 1995 growing season with the lowest levels in August. These declines reflect the decreasing amount of residue on the soil surface (Fig. 11) and in the soil.

In 1996, the NT treatment (257 mg C kg^{-1}) had consistently greater MBC contents than the CT treatments (222 mg C kg^{-1}) in the absence of red clover in the 0-10 cm depth (Fig. 22). When red clover was included, both the NT (249 mg C kg-1) and CT (245 mg C kg^{-1}) treatments had similar MBC levels. The MBC levels were greatest in September, which coincided with the large amount of precipitation (Fig. 1). In the 10-20 cm depth, NT resulted in greater MBC contents in May, July and August, but the pattern reversed for September and October (Fig. 23). Hence the average MBC contents of the NT and CT treatments were similar. Red clover increased the MBC levels by ~8% in the CT treatments, but had no effect in the NT treatments. The highest MBC contents were also in September and October after the high rainfall.

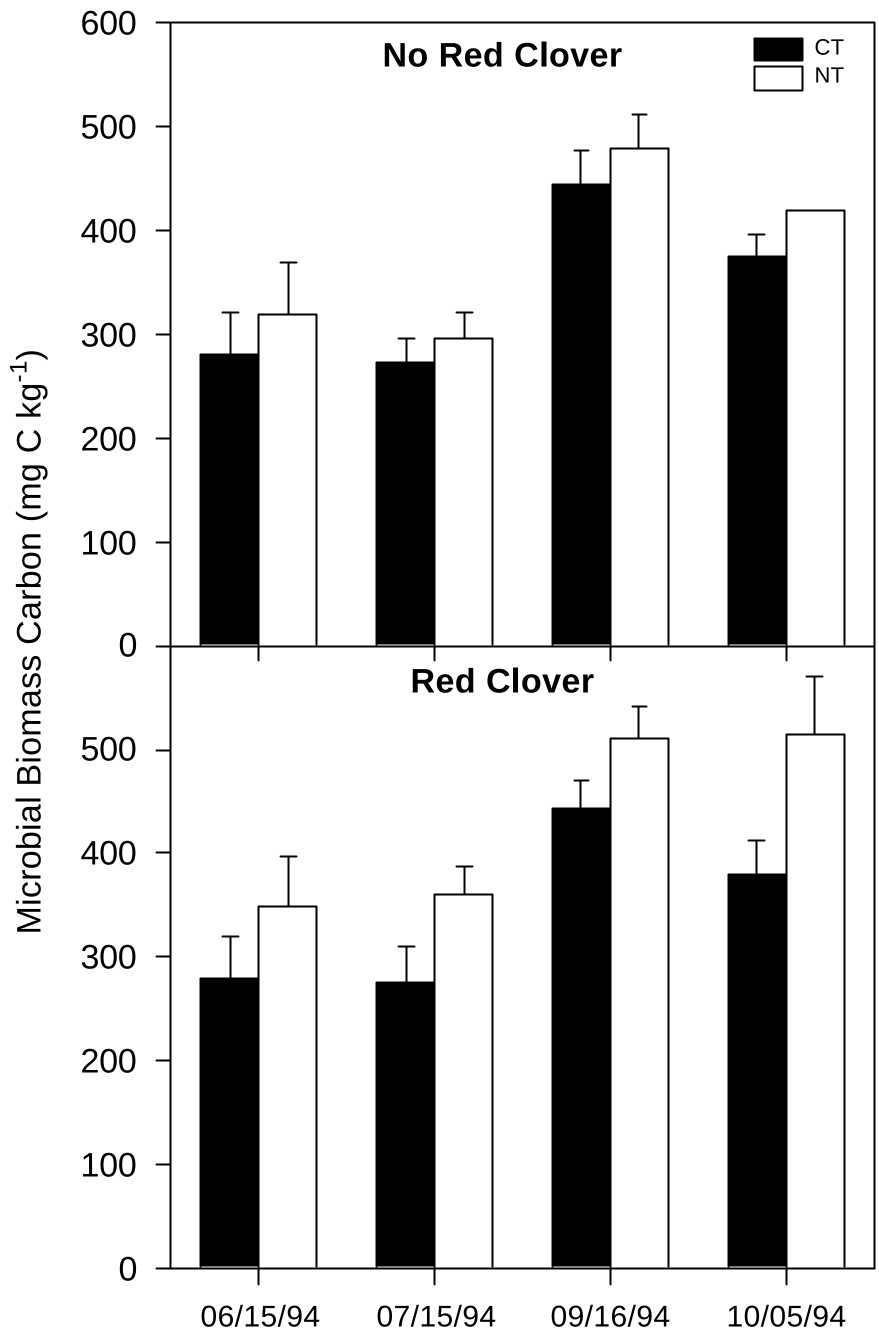

Figure 19. Soil microbial biomass C in the 0-10 cm depth of soil from the CT and NT plots with/without red clover in 1994. Error bars are standard error (n=8).

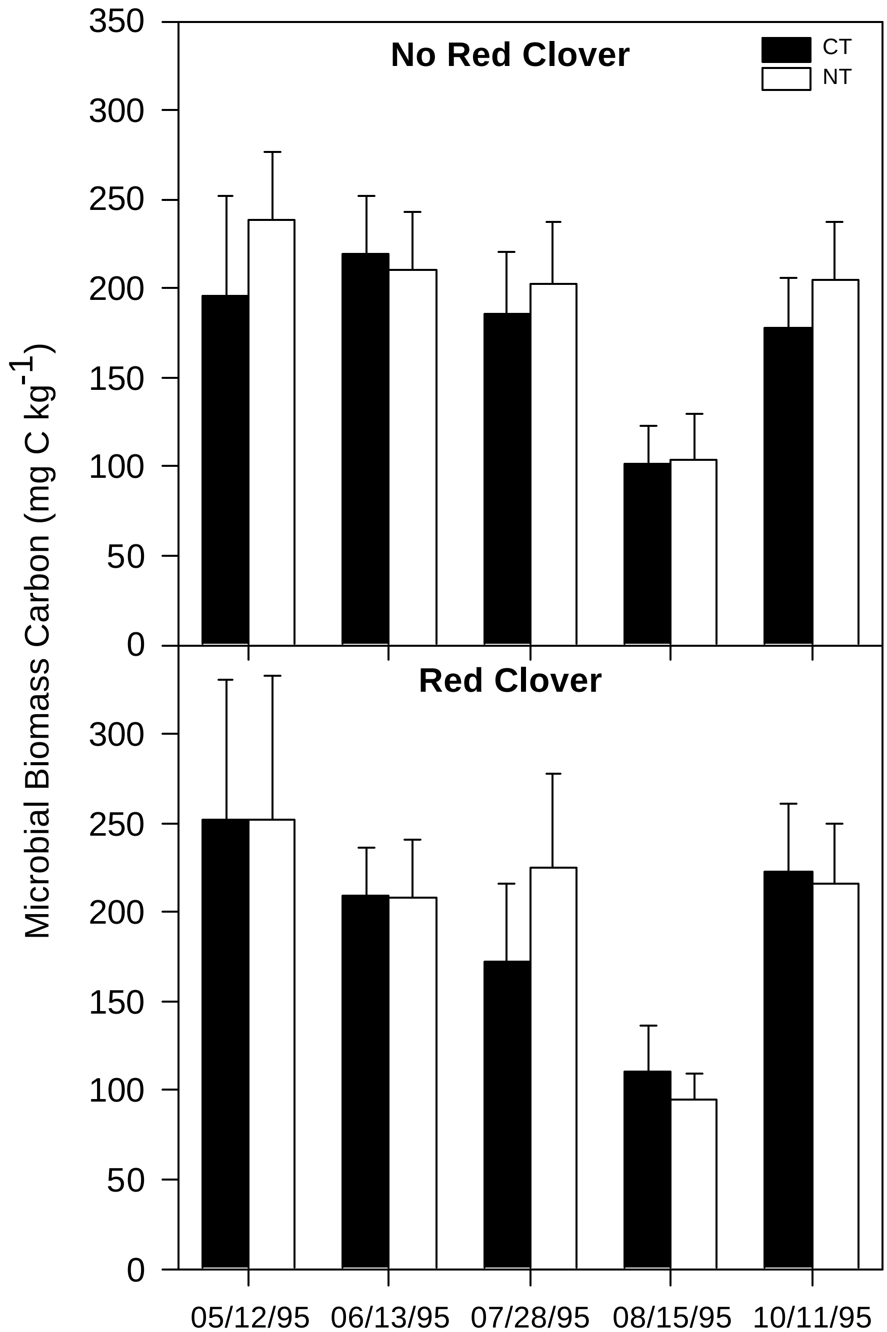

Figure 20. Soil microbial biomass C in the 0-10 cm depth of soil from the CT and NT plots with/without red clover in 1995. Error bars are standard error (n=8).

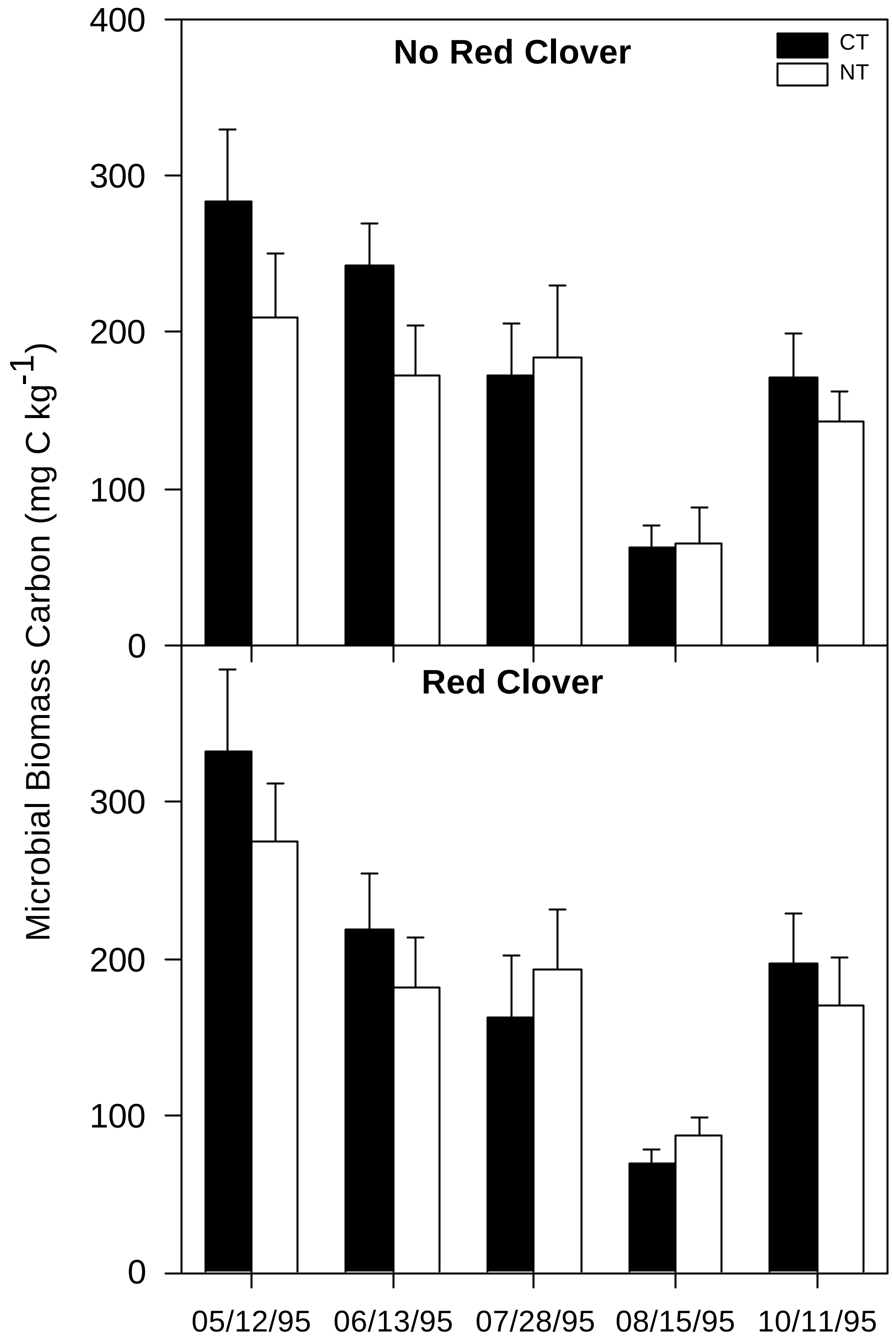

Figure 21. Soil microbial biomass C in the 10-20 cm depth of soil from the CT and NT plots with/without red clover in 1995. Error bars are standard error (n=8).

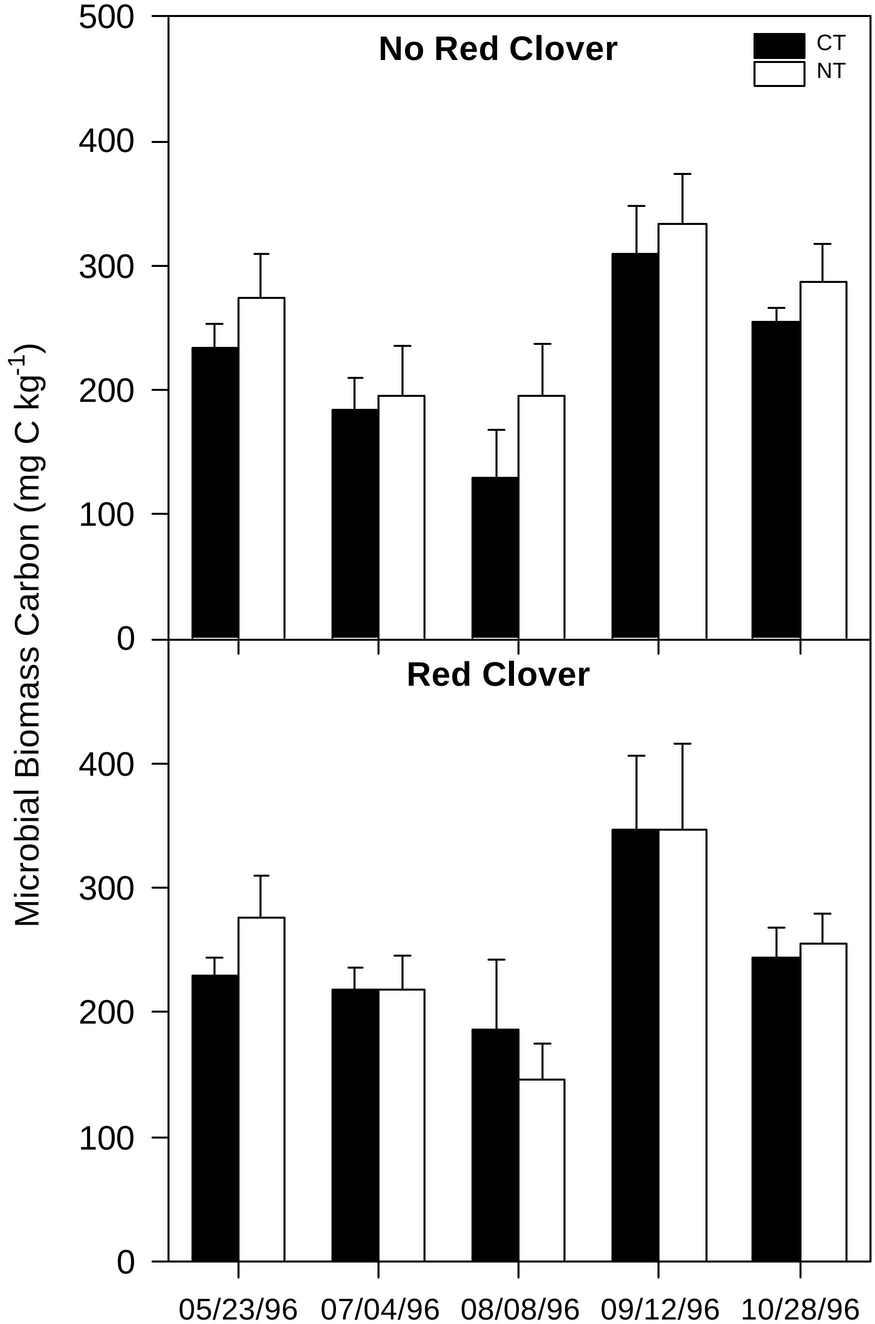

Figure 22. Soil microbial biomass C in the 0-10 cm depth of soil from the CT and NT plots with/without red clover in 1996. Error bars are standard error (n=8).

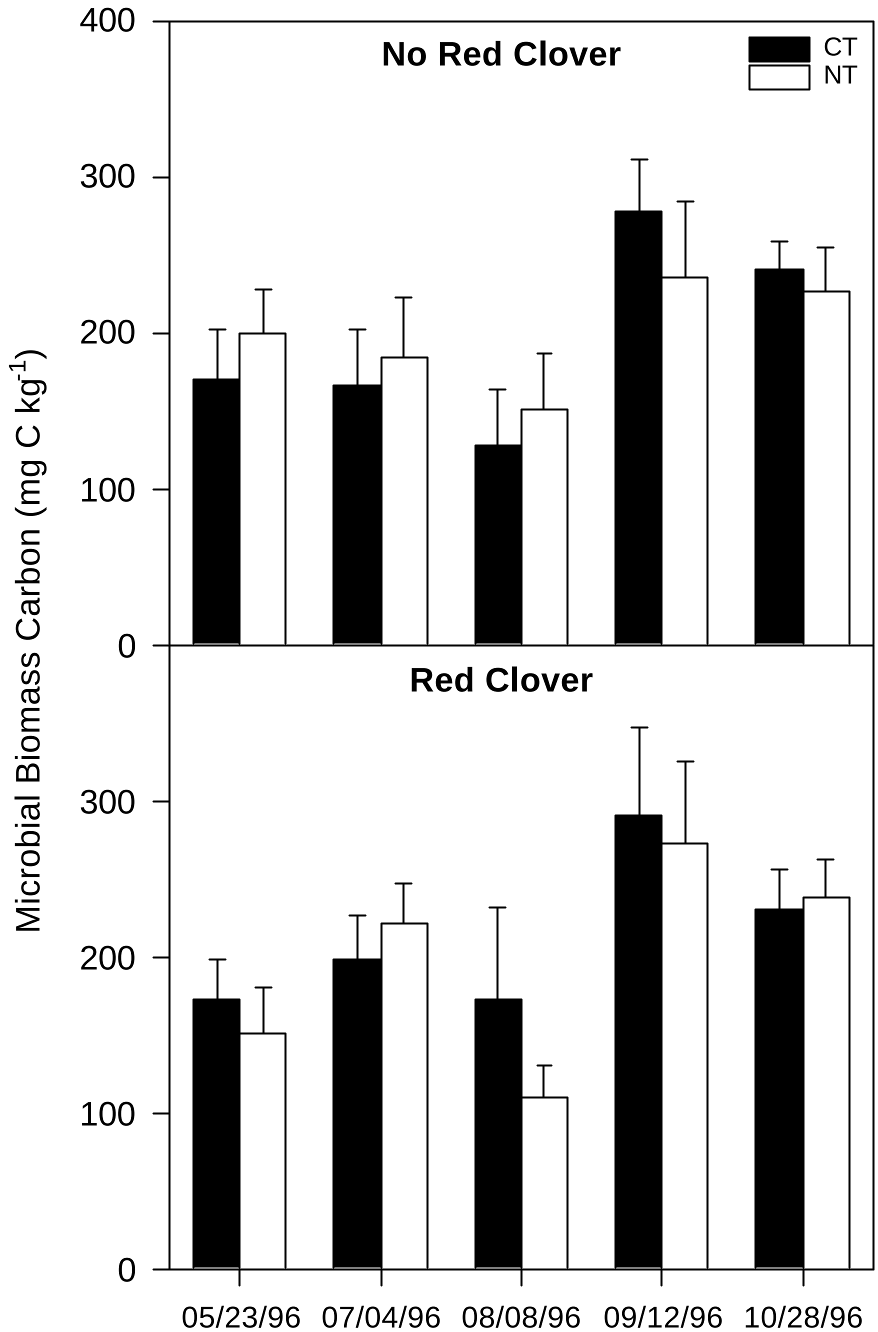

Figure 23. Soil microbial biomass C in the 10-20 cm depth of soil from the CT and NT plots with/without red clover in 1996. Error bars are standard error (n=8).

The volumetric water contents over the growing season varied considerably with rainfall events in 1995 (Figs. 24 and 25). In the early part of the growing season, the NT treatments were much wetter than the corresponding CT treatments and the pattern reversed in the beginning of September (Figs. 7,8,24 and 25). Averaged over the entire season, the NT was about 0.78% wetter than the CT treatment at the 0-10 cm depth and about 2% wetter than the CT treatment at the 0-30 cm depth when no red clover was present (Figs. 24 and 25). In the 0-10 cm depth, the combination of CT-RC was 0.26% drier than the CT treatment and the NT-RC treatment was about 1% drier than the NT treatment. In the 0-30 cm depth, the CT treatment was the driest at 25.2 % and the NT treatment was the wettest at 27.2% with intermediate water contents for the two red clover treatments.

In 1996, the growing season was very dry and water contents in the 0-10 cm and 0-30 cm depths decreased from early June until early September (Figs. 26 and 27). The NT treatment was consistently wetter than the CT treatment throughout the growing season at the 0-30 cm depth but only until early September in the 0-10 cm depth. When the average water content for the growing season was calculated, the CT and CT-RC treatments resulted in 21.3% and 21.9% water contents respectively , versus 23.4% and 24.5% water contents for the NT and NT-RC treatments, respectively in the 0-10 cm depth. In the 0-30 cm depth, NT was 4% wetter than CT whereas NT-RC was 3% wetter than the CT treatment. Furthermore, red clover increased the water content by 1.65% in the CT treatments and by 0.7% in the NT treatments. Hence in the 0-30 cm depths, the tillage effect on water content was quite remarkable throughout the growing season.

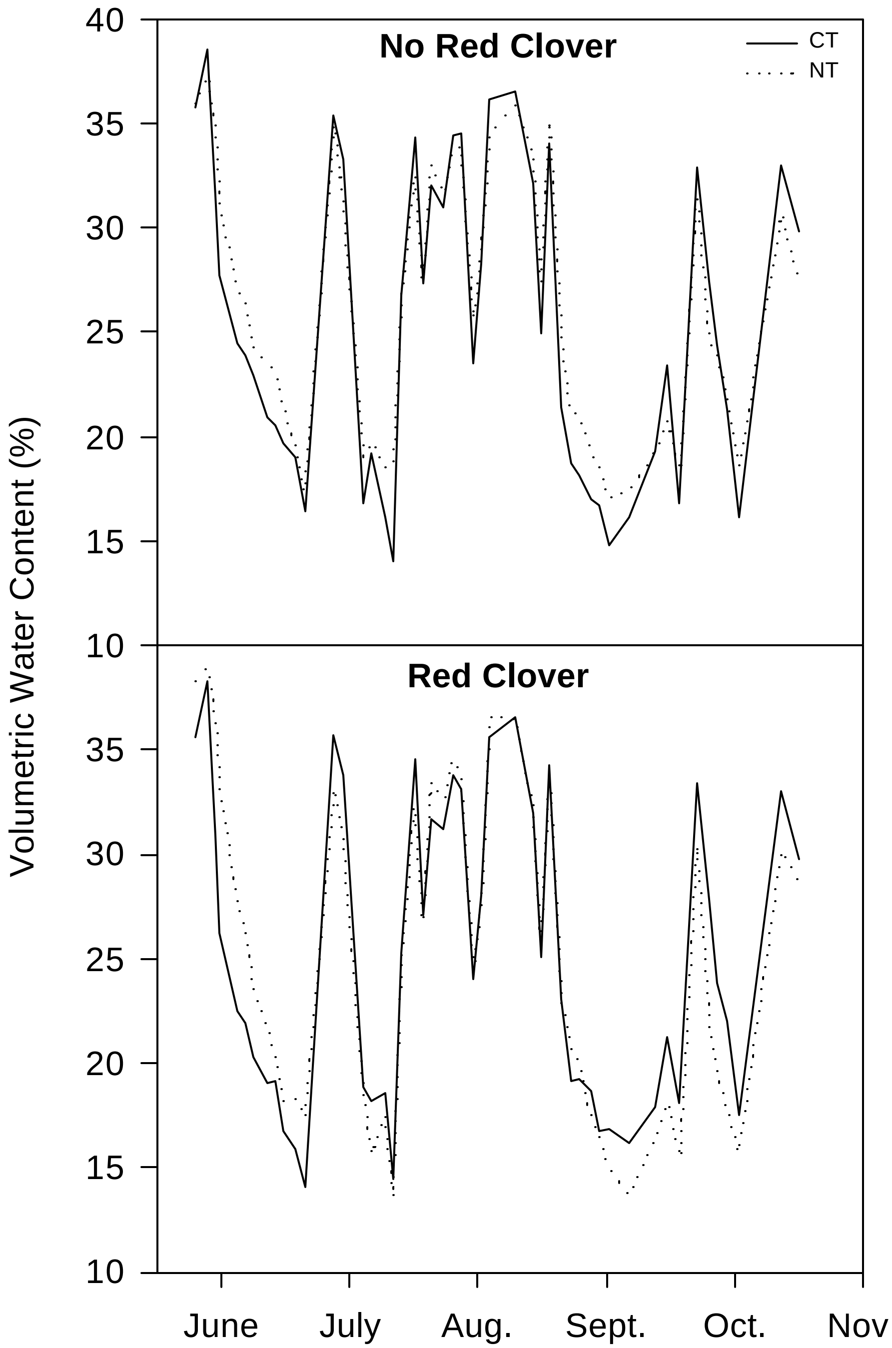

Figure 24. Soil volumetric water content in the 0-10 cm depth of the CT and NT plots with/without red clover in 1995.

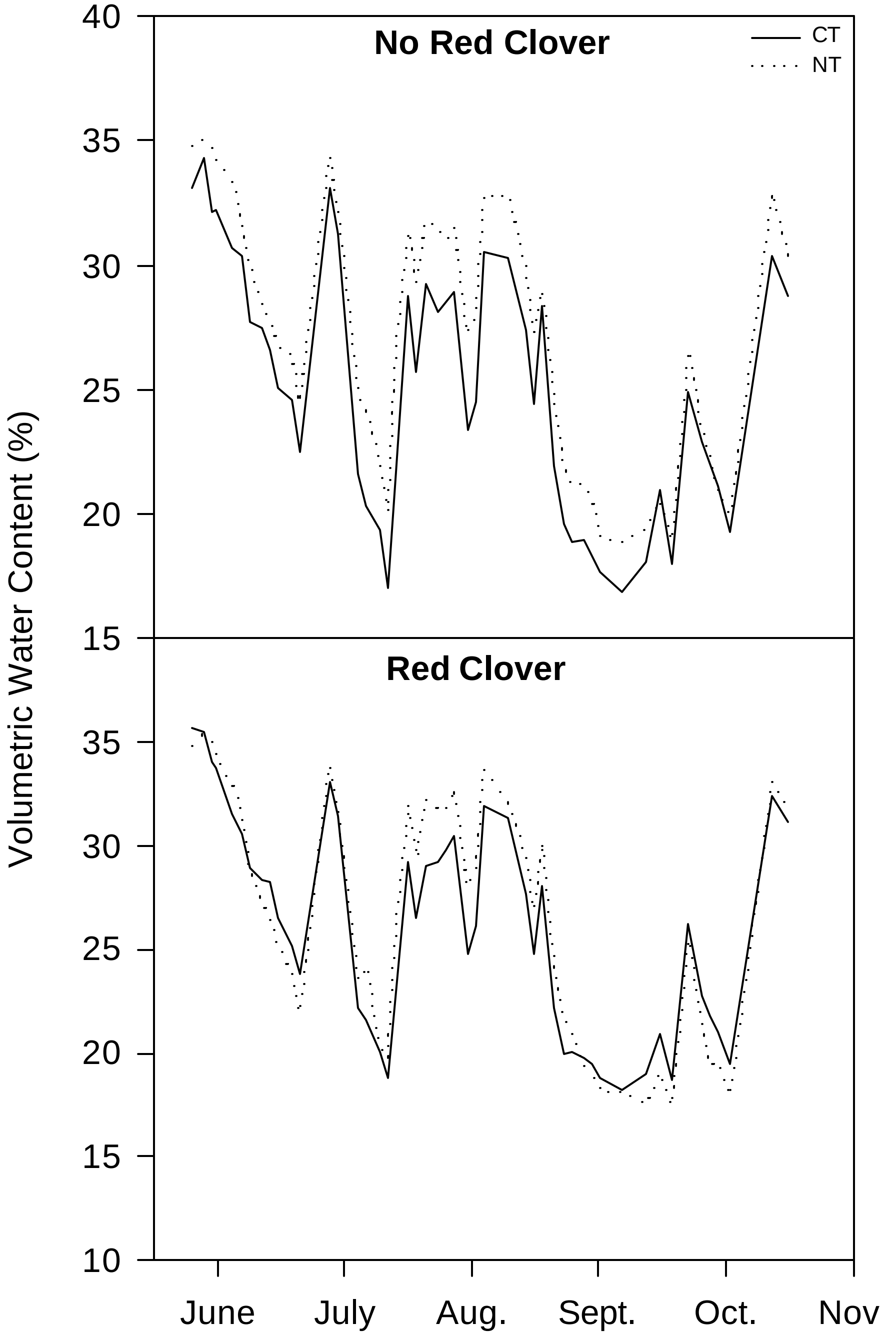

Figure 25. Soil volumetric water content in the 0-30 cm depth of the CT and NT plots with/without red clover in 1995.

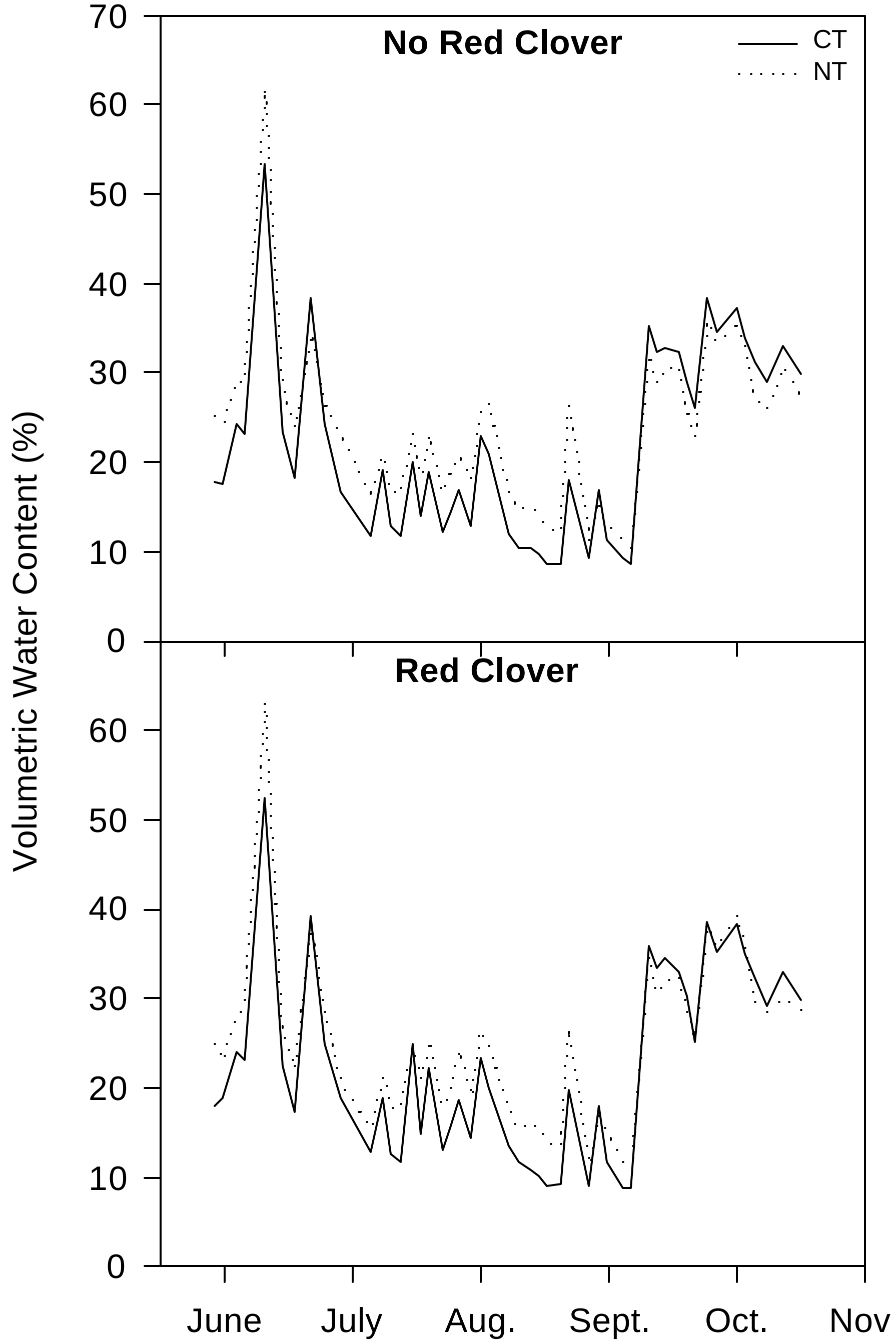

Figure 26. Soil volumetric water content in the 0-10 cm depth of the CT and NT plots with/without red clover in 1996.

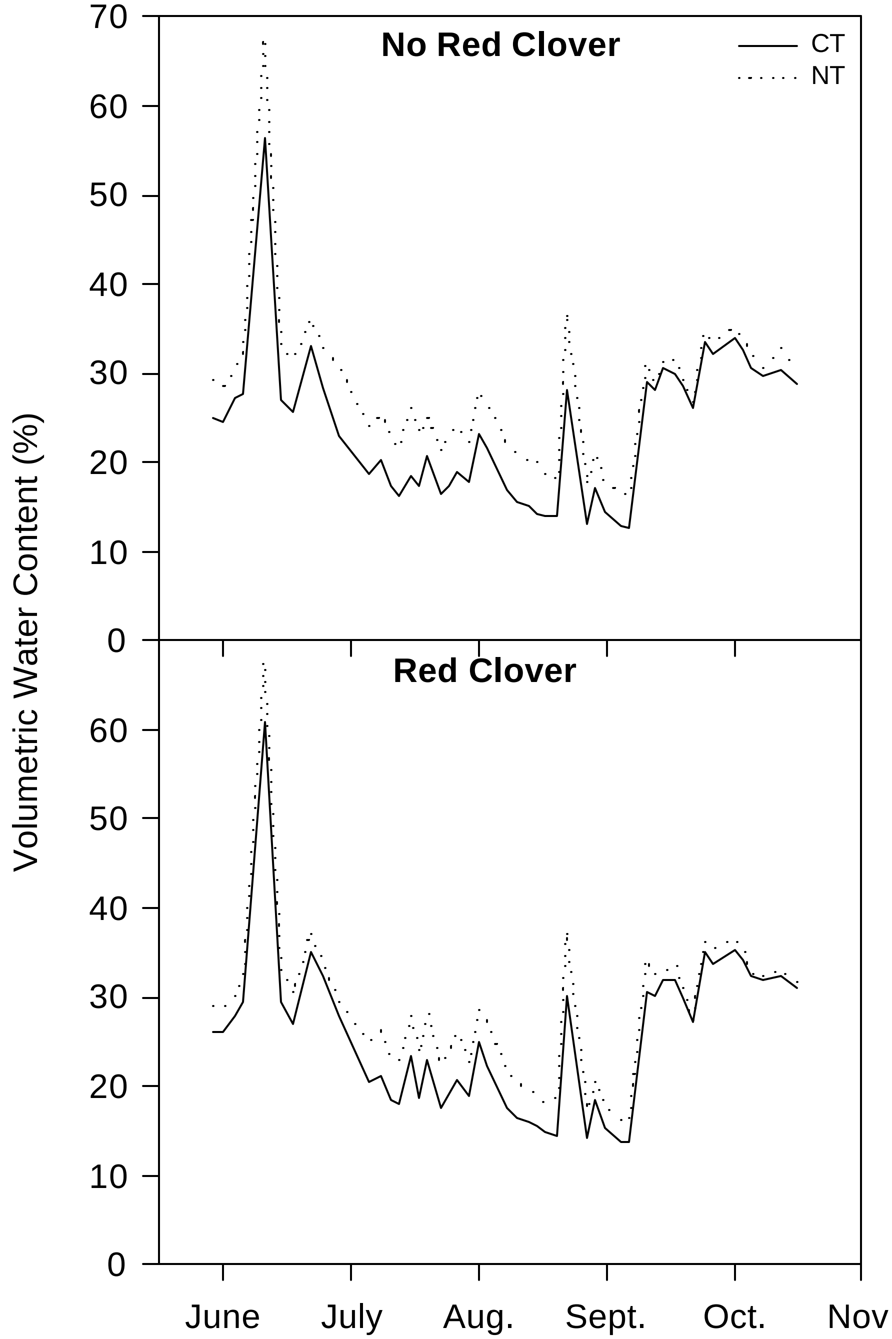

Figure 27. Soil volumetric water content in the 0-30 cm depth of the CT and NT plots with/without red clover in 1996.

5.3. Soil structure and crop productivity

The soil inorganic N levels were very low in the beginning of the growing season in both 1995 and 1996 for all treatments (Figs. 28 & 29). After side dress N was applied (June 24-25) the inorganic N levels peaked and then decreased to fairly low levels in the fall. There was very little effect of tillage or red clover on soil inorganic N levels.

Soil structural changes were estimated after harvest each year using WAS and MWD measurements (Figs. 30 and 31). In all years at the 0-5 cm depth, the NT treatments had greater WAS values than the CT treatments. However, these treatment differences were only significant ($P<0.0001$) in the third year of the study whereupon all NT treatments had significantly greater WAS values than the CT treatments. This time effect was not surprising as soil structural buildup does require sufficient time to show improvements. In the third year of the study, the NT treatments resulted in 50% greater WAS values than the CT treatments. Averaged over the three site-years, WAS for the NT treatment was 45.1% versus 34.7% for the CT treatment which is a 30% increase. The NT-RC treatment had an even greater increase with an average WAS value of 49.6% which was a 43% increase over the CT treatment. Hence the combination of NT and red clover was beneficial. Red clover did not influence the WAS values of CT treatment. There were no significant treatment differences for WAS in the 10-15 cm depth in any year.

The MWD values followed the same pattern at the 0-5 cm depth as WAS (Figs. 30 and 31). However, MWD diameter was a more sensitive indicator of soil structural improvements as significant differences were found in all three years. In both 1994 and 1995, the NT-RC treatment had significantly higher MWD values than the two CT treatments. In 1996, all three NT treatments had, on average 43% greater MWD values than the two CT treatments. The

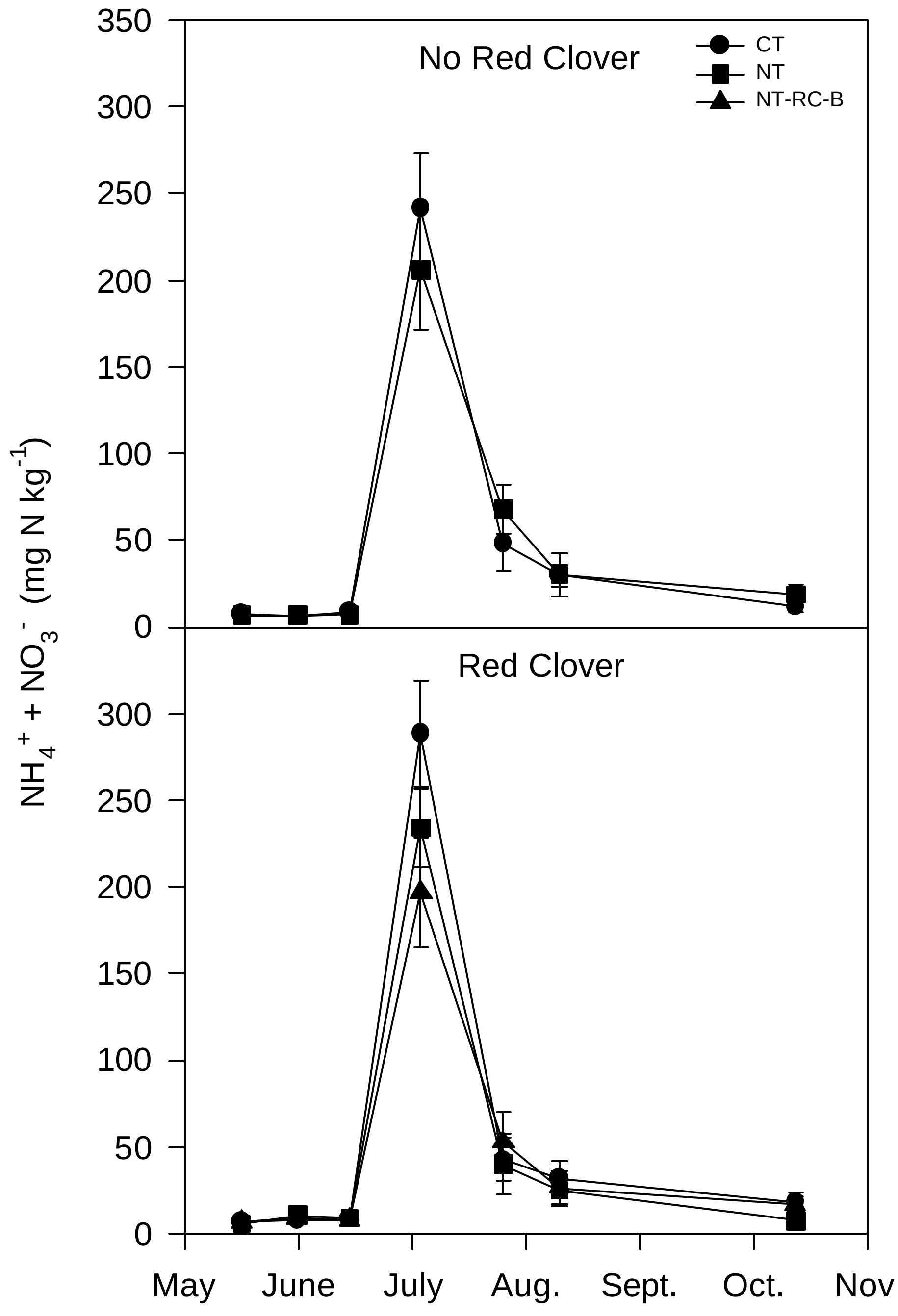

Figure 28. Soil ammonium + nitrate levels in the 0-30 cm depth of the CT and NT plots with/without red clover in 1995. Error bars are standard error (n=8).

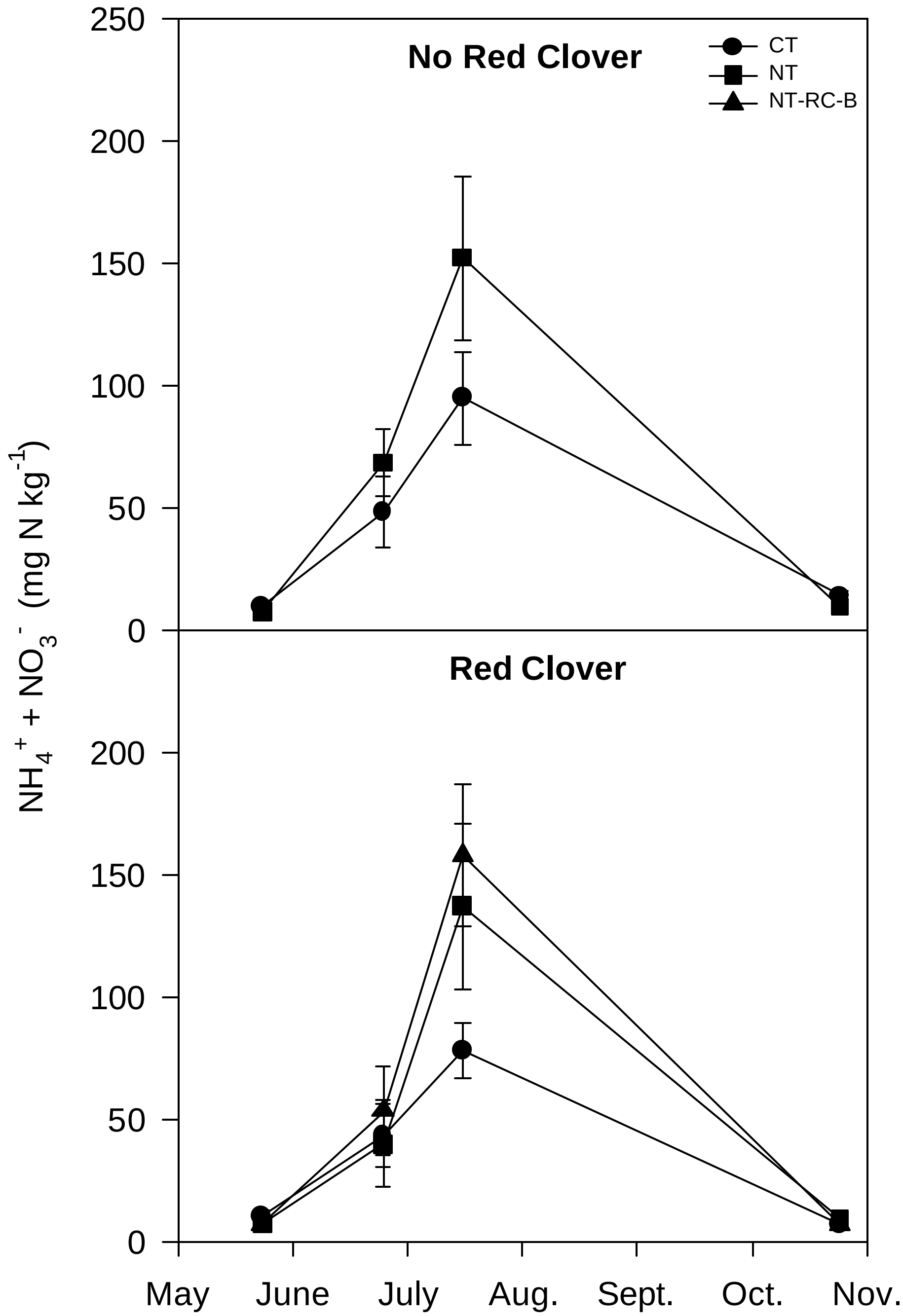

Figure 29. Soil ammonium + nitrate levels in the 0-30 cm depth of the CT and NT plots with/without red clover in 1996. Error bars are standard error (n=8).

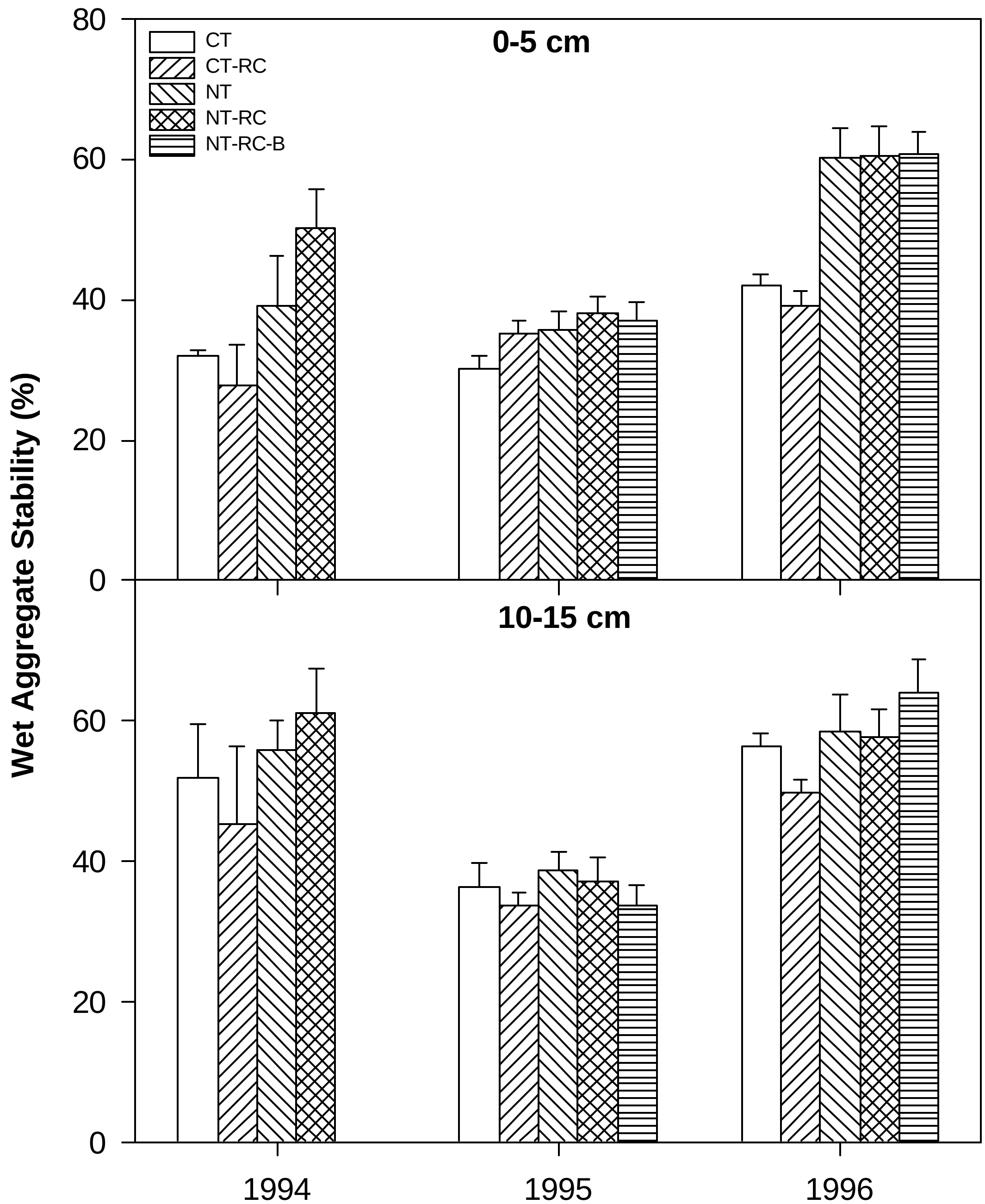

Figure 30. Soil wet aggregate stability of soil from the CT and NT plots with/without red clover in 1994, 1995 and 1996 at 0-5 cm and 10-15 cm depths. Error bars are standard error (n=8).

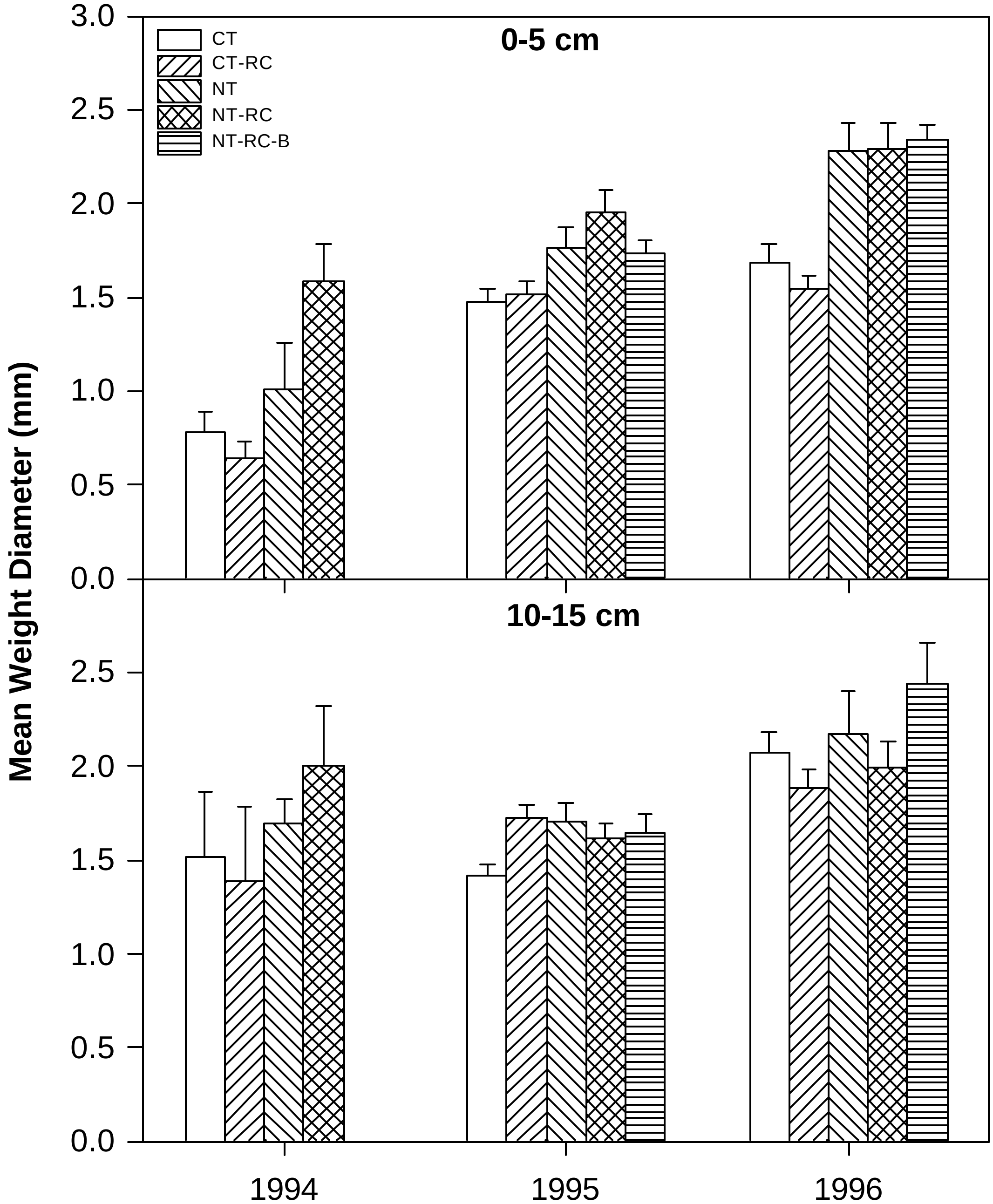

Figure 31. Mean weight diameter of soil from the CT and NT plots with/without red clover in 1994, 1995 and 1996 at 0-5 cm and 10-15 cm depths. Error bars are standard error (n=8).

three site-year average MWD value was 1.31 mm for the CT treatment, versus 1.68 mm for the NT treatment and 1.94 mm for the NT-RC treatment. The MWD was increased by 28% with the NT treatment and by 48% with the NT-RC treatment compared to the CT treatment. Hence the best structure occurred when no-tillage and cover crops were used. Similar to the WAS values, no significant differences occurred in the 10-15 cm depths.

Corn grain yields were greatest with the CT treatments in all three years whereas the NT and NT-RC-B treatments resulted in the lowest yields (Fig. 32). On average, the CT treatments (with/without red clover) had 13% greater yields than the NT treatment (without red clover) . In both 1994 and 1996, when red clover was included with NT, the yields were not significantly different from the CT and CT-RC treatment. The N uptake in the corn grain also followed the same pattern as the corn yields. Averaged over three years, the highest N uptake values were for the CT treatment at 113 kg N ha^{-1} and the lowest was with the NT (90 kg N ha^{-1}) and NT-RC-B (87 kg N ha^{-1}) treatments (Fig. 33). In no-tillage systems, red clover accelerated residue decomposition, increased corn emergence, improved soil structure and thereby enhanced corn growth and N uptake which ultimately increased yield and N fertilizer efficiency. Hence red clover may be one tool that can be used to enhance adoption of no-tillage systems for corn production especially for rotational systems where corn follows winter wheat.

5.4. Weed Ecology

As many as 14 different weed species occurred on the plots in each year, with two or three being particularly abundant. The species differed between years because the plots were located in different fields. In 1994 and 1996 the most common weed species were velvetleaf, ragweed, dandelion (1994) and chickweed (1996) (Fig. 34). In 1995 the most common weeds were flower-of-an-hour, shepherd's purse and crab grass. Dandelion, a perennial, and the

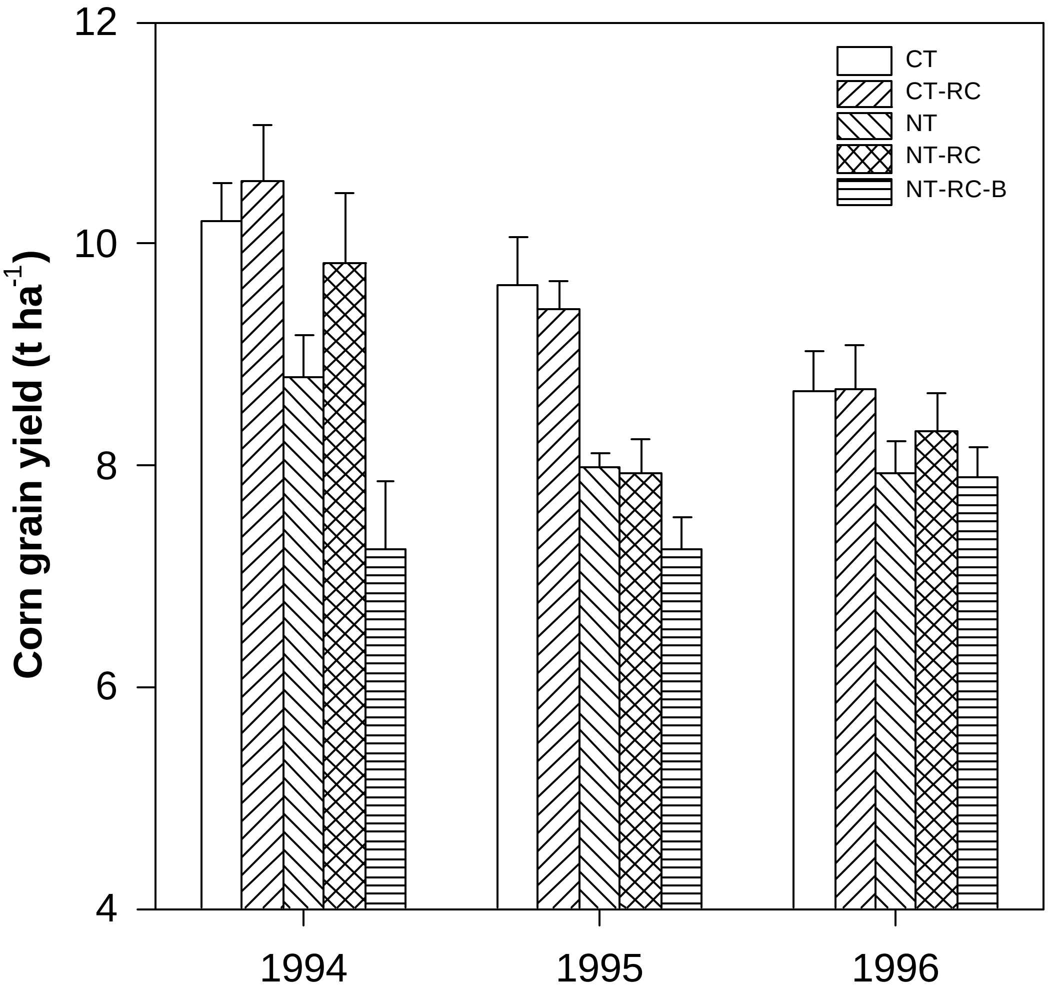

Figure 32. Corn grain yield from the CT and NT plots with/without red clover in 1994, 1995 and 1996. Error bars are standard error (n=8).

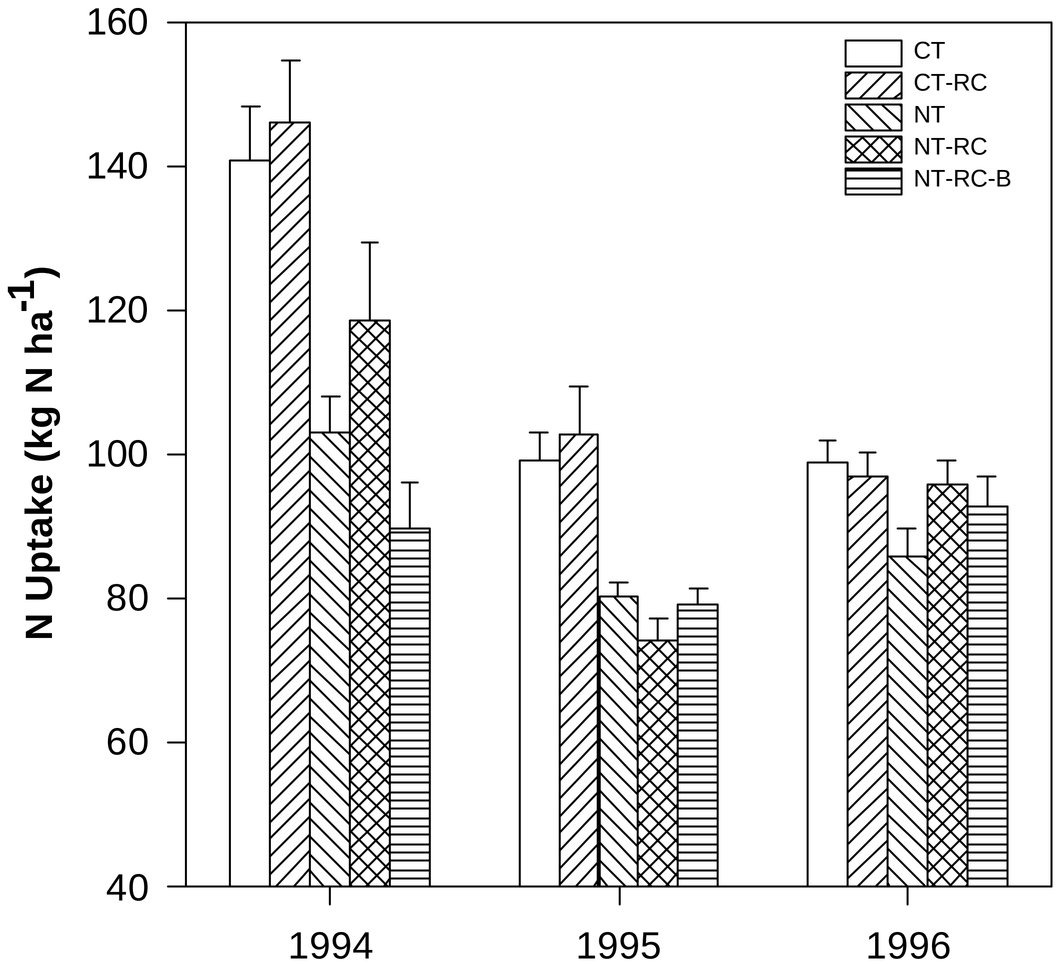

Figure 33. Nitrogen uptake in corn grain from the CT and NT plots with/ without red clover in 1994, 1995 and 1996. Error bars are standard error (n=8).

winter annuals chickweed and shepherd's purse, occurred in greater numbers under no tillage than under conventional tillage. The summer annuals velvetleaf, ragweed, flower of an hour and crab grass tended to be associated with conventional tillage plots, although ragweed numbers were very high on all plots in 1996. Weed species shifts from predominantly summer annuals in conventional tillage to winter annuals, biennials and perennials in no tillage have been noted in many studies. In our study the presence of red clover did not significantly affect weed species distribution or abundance. The effect of residue on weed emergence, as measured by comparisons of weed counts in the row versus between the row, was generally not significant. Most weeds occurred in higher numbers on the unsprayed compared to the sprayed plots, but velvetleaf occurred in higher numbers on the sprayed portions of no tillage plots in 1996, suggesting that removal of competing vegetation may be helping its emergence or survival under no tillage. Canonical discriminant analysis, using all the weed species data each year, showed a clear separation between the weed flora found on conventional tillage as compared to no tillage plots (Fig. 35). In one year of the study (1995), the weed flora present on the no tillage with red clover and wheat straw baled (NT-RCB) plots was also distinct from the rest.

In summary, no-till plots had a different weed assemblage than conventional plots, but within no-till plots, the presence or absence of red clover and residue levels had little impact on weed populations. Differences in weed species found in NT and CT are likely attributable to the direct effects of tillage on weed population dynamics, particularly with respect to weed seed burial and root disturbance. The practical implications are that growers must learn how to control a different and possibly broader spectrum of weeds in no-till systems.

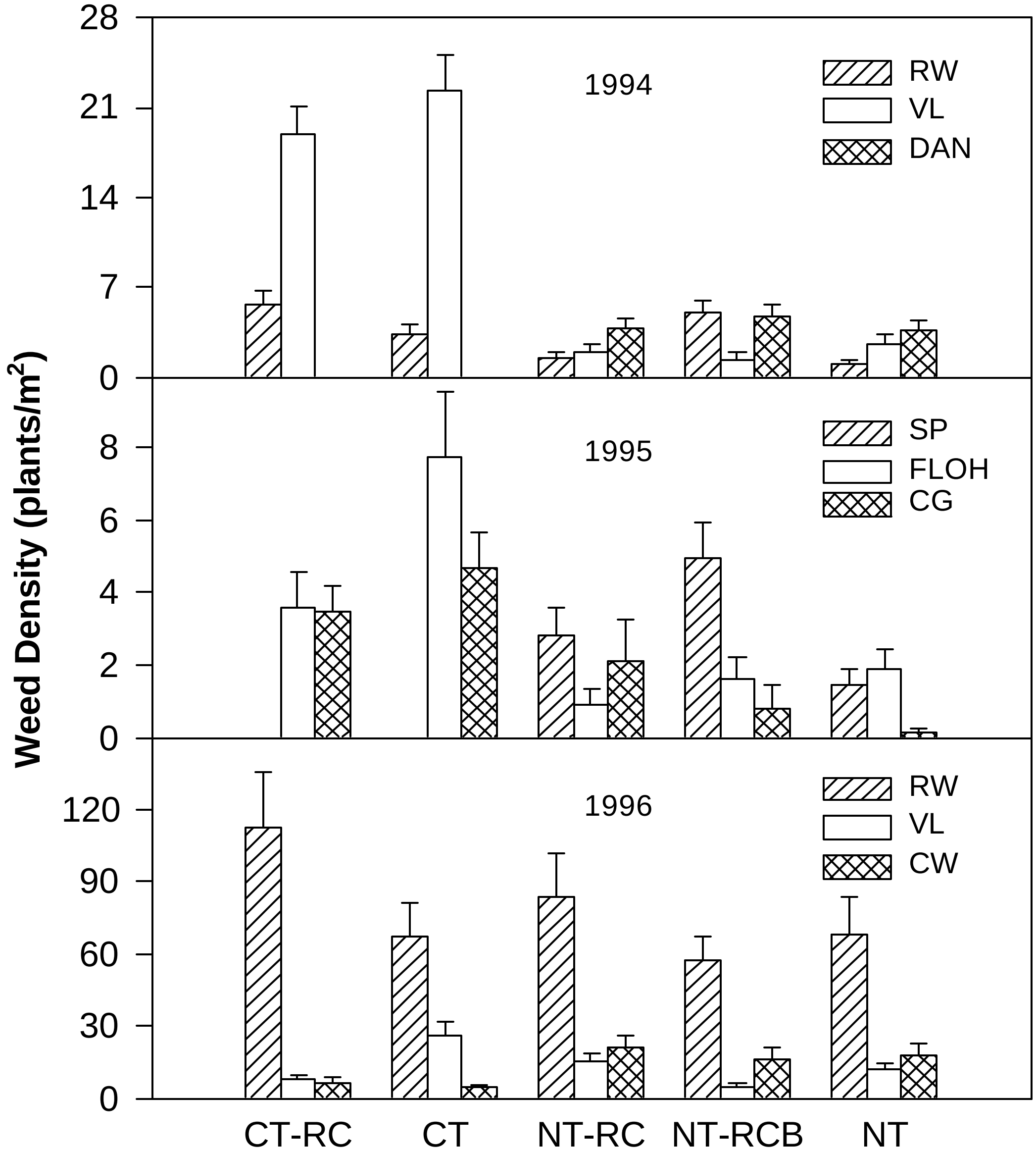

Figure 34. Density of most common weed species from CT and NT plots with and without red clover in 1994, 1995 and 1996. Error bars are standard error (N=64).

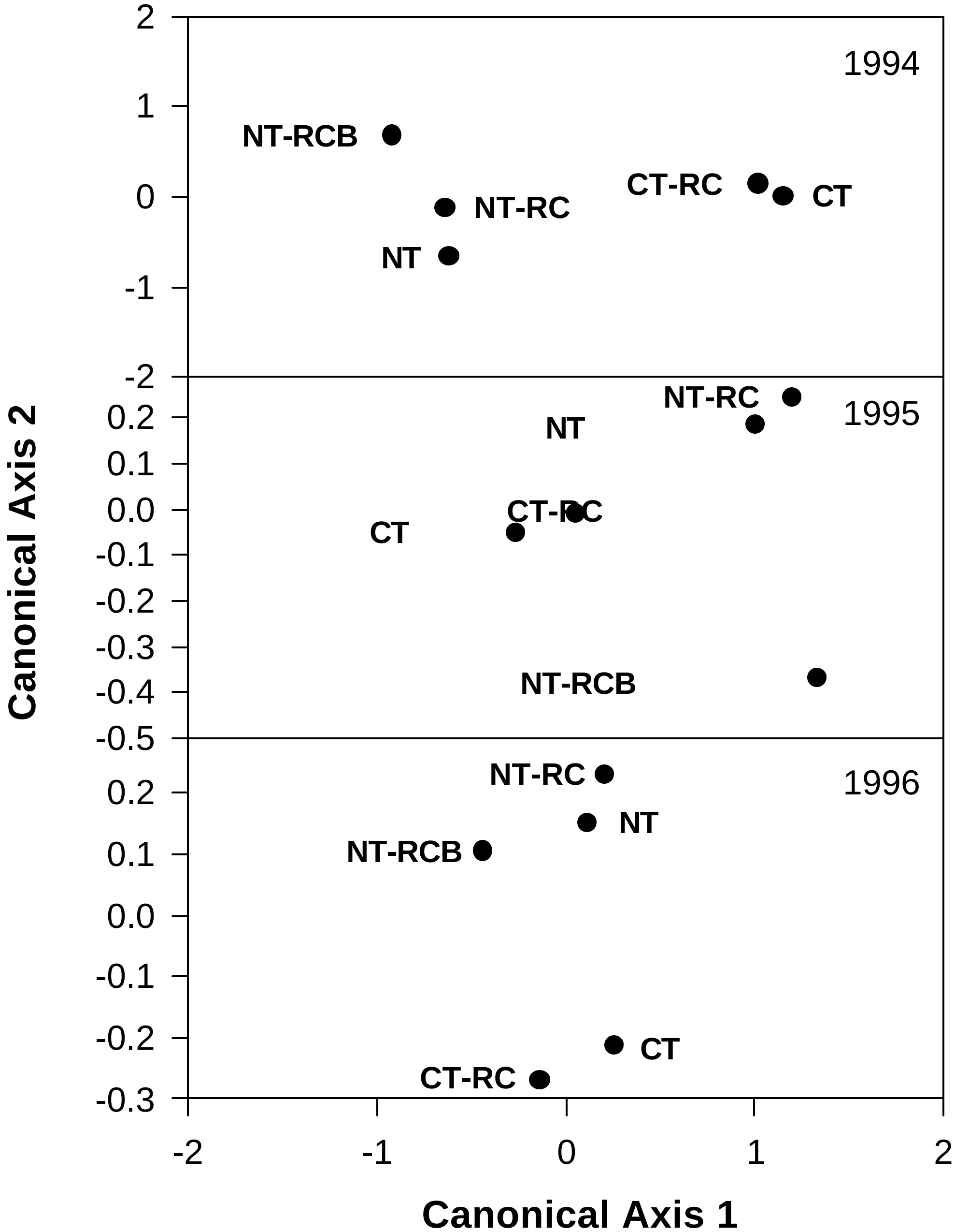

Figure 35. Canonical means for all weed species from CT and NT plots in 1994, 1995 and 1996, on the first and second canonical axes.

6. Acknowledgements

We greatly acknowledge the contribution from the Canada-Ontario Agriculture Green Plan. We would also like to express our appreciation to Mr. Vic Bernyk, Ms. Jacqueline St. Denis, Mr. George Stasko, and the farm crew for their expert technical assistance. We are also grateful to Dr. Philippe Rochette for providing advice and the soil respiration chambers.

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