TILLAGE-PLANTING SYSTEMS AND COVER CROPPING FOR SWEET CORN PRODUCTION IN THE WESTERN FRASER VALLEY

by

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Abstract

A combination of conservation tillage and winter cover crops might reduce soil degradation problems in the western Fraser Valley. This study was conducted to determine the effects of conventional spring tillage (ST) and conservation no-spring tillage (NST) following winter wheat (*Triticum aestivum* L.) and spring barley (*Hordeum vulgare* L.) cover crops on soil physical characteristics, slug and earthworm populations, soil available N, and sweet corn (*Zea mays* L. *saccharata* Sturt.) performance. The study was carried out in 1993, 1994, and 1995 on a silty clay loam Humic Gleysol in Delta, BC.

In the three years, bulk density, aeration porosity and aggregate stability were not affected by type of tillage, nor by type of cover crop. Before spring tillage there was no difference in soil penetration resistance between the two tillage systems. After spring tillage soil penetration resistance was higher in NST than in ST in the upper 15 to 20 cm of the soil profile and it ranged from 1500 to 2250 kPa. Spring barley cover crop resulted in higher soil penetration resistance than winter wheat in two out of three years. Lower soil water contents were observed at 20 cm depth with NST than with ST, while at other depths of measurement soil water contents were similar with both tillage treatments. Type of cover crop did not affect soil water content. Soil temperatures were lower by 0.4 to 1.0°C at 3 cm depth in NST than in ST during three weeks following corn planting, but NST soil temperatures were above the minimum temperature required for corn emergence and early corn growth.

In the fall of 1995, earthworm population was higher in NST than in ST. At the same time, spring barley cover crop resulted in higher earthworm numbers than winter wheat. Mild winter conditions in 1993/94 and 1994/95 led to high slug populations in NST during the following spring. Slug infestation in NST plots caused serious damage to young corn plants and was one of the main reasons for the crop failure in the 1994 and 1995 seasons. Sweet corn yields were greater with ST than with NST in two out of three years, while type of cover crop did not affect sweet corn yield. Greater sweet corn response to N application was observed under winter wheat than under spring barley cover crop in 1993, and the opposite was true in 1994 and 1995. Soil NO_3 concentrations were higher in NST than in ST during latter parts of 1993 and 1995 growing seasons, while in 1994 ST had higher soil NO_3 than NST at corn planting. Throughout the whole 1993 growing season higher concentration of soil NO_3 was observed with spring barley than with winter wheat cover crop, while in 1994 and 1995 this was true only at corn planting.

Elimination of spring tillage is not the best management option for sweet corn production in this region, since it resulted in a crop failure in two out of three years of this study that was carried out on the same site. Modifications of NST practice may hold promise for successful establishment of annual crops in the western Fraser Valley.

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List of Frequently Used Symbols and Abbreviations

ε_a	aeration porosity (m^3 m^{-3})
θ	soil water content (kg kg^{-1})
ρ_b	bulk density (Mg m^{-3})
B	blocking effect in analysis of variance
C	effect of cover crop species in analysis of variance
D	sampling date effect in analysis of variance
df	degrees of freedom
Exp. 1	experiment 1, established in 1993
Exp. 2	experiment 2, established in 1994
MWD	mean weight diameter, index of aggregate stability (mm)
n	number of observations
N	nitrogen effect in analysis of variance
NST	no-spring tillage (i.e. conservation tillage system)
PR	penetration resistance (kPa)
r^2	coefficient of simple determination
SB	spring barley cover crop
ST	spring tillage (i.e. conventional tillage system)
T	tillage effect in analysis of variance
WW	winter wheat cover crop

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1. INTRODUCTION

British Columbia has a very small agricultural land base since only 4% of the total land is suitable for agricultural production. The lower Fraser Valley, situated between Vancouver and Hope, BC, is the major agricultural region within the province, containing almost half of the farms and generating approximately 50% of the total provincial gross farm income. The western part of the lower Fraser Valley is suitable for a wide range of crops due to its favourable climate conditions, fertile soils, and flat topography. The annual value of the agricultural production of the western Fraser Valley farms is estimated to be in the order of $180 million (B.C. Annual Statistics, 1991).

The farmland of the western Fraser Valley fulfils a dual role as an agricultural resource and as wildlife habitat. These habitats are a vital link on the Pacific Flyway for approximately 1.5 million migratory shorebirds and waterfowl that over the year feed, rest, and roost in this area (Butler and Campbell, 1987).

As BC's population grows, agriculture and wildlife are being forced onto an ever shrinking land base. There is a constant pressure on land for industrial and airport expansions, ports, highways, residential sub-divisions, and golf courses. Expectations that land-use will change within the Agricultural Land Reserve jeopardise the stability of the agricultural industry. For example, about 65% of agricultural land in the Municipality of Delta is farmed on a rented or leased basis (Klohn Leonoff Ltd. et al., 1992,). Of the total leased land, 44% is rented on a year to year basis, while only 31% is leased on terms which are ten years or longer.

In the past 20 to 30 years many of the region's farmers have shifted from mixed farming to cash cropping. Production of a small range of cash crops, such as potato (*Solanum* *tuberosum* L.), pea (*Pisum sativum* L.), bean (*Phaseolus vulgaris* L.), and sweet corn (*Zea mays* L. *saccharata* Sturt.), that leave little residue behind year after year reduces the amount of soil organic matter. In addition, these specialized farms in the western Fraser Valley are located about 75 km away from the intensive animal production farms of the central Fraser Valley and therefore do not have ready access to manure as a source of organic amendment.

The lack of direct long-term farm tenure and no incentive given to farmers to practice conservation farming has resulted in soil degradation and a loss of crop productivity. Inadequate subsurface drainage, high soil compaction, poor infiltrability, reduction of soil organic matter, and distruction of surface soil structure are the most common soil degradation problems on Gleysols in the western Fraser Valley (de Vries, 1983; Temple, 1992). All these problems increase the occurrence of ponding during the off-season and in spring, which delays spring field operations.

Recognition of serious soil degradation problems on the fertile lowland soils of the western Fraser River led in the spring of 1991 to the formation of the Delta Farmers' Soil Conservation Group and the UBC Soil and Water Conservation Research Group, both with funding from the federal-provincial governments under the Soil and Water Conservation Accord (Bomke et al., 1996). The objective of these two groups was to cooperate in finding workable solutions to local soil degradation problems, with a focus on (i) evaluation of various cover crops, (ii) reclamation of badly degraded soils, and (iii) development of appropriate conservation tillage systems.

Conventional tillage in the western Fraser Valley (Table 1.1) consists of the primary (moldboard plowing, discing, and subsoiling) and secondary tillage (chiseling and packing) operations, which are generally performed in the spring (Temple, 1992). At this time of the year the soil is still quite wet and therefore there is a substantial risk of soil compaction and distraction of soil structure by various spring tillage operations. If the soil already has a poor structure each additional tillage operation even further destroys it making the soil more prone to ponding. Hence, there is an obvious need for some form of conservation tillage system that will either reduce the number of primary and secondary tillage operations and/or shift the primary tillage operations to the late summer when soils are relatively dry.

Table 1.1. The average number of conventional tillage operations practiced by farmers in the western Fraser Valley.

Tillage operation	Time of tillage		Total number
	Spring	Late summer	of operations
Primary tillage			
Moldboard plowing	1	0	1
Subsoiling	0.5[1]	0.5	1
Discing	2	1	3
Secondary tillage			
Packing	6-8	0	6-8
Chiseling	3-4	0	3-4
Total	12.5-15.5	1.5	14-17

[1]0.5=once every two years.

This study represents the first attempt to introduce conservation tillage in the western Fraser Valley, an area that has a unique combination of soil and climate conditions. Since soil trafficability/workability is favorable in the late summer all primary tillage operations were shifted to that part of the year and no spring tillage was performed in the conservation tillage system (i.e., no-spring tillage - NST). On the other hand, conventional tillage (i.e., spring tillage - ST) had the same type and number of primary tillage operations performed in the late summer, as did NST, with a difference that spring tillage was also performed.

Spring barley (*Hordeum vulgare* L.) and winter wheat (*Triticum aestivum* L.) cover crops have been included in both NST and ST treatments to provide the soil surface protection from heavy rainfall during the winter. These two cereals were chosen due to different frost tolerance. The spring barley usually mats down after the first killing frost providing soil surface protection as a dead mulch. The winter wheat, on the other hand, survives the winter providing living mulch until sweet corn planting time when it is chemically or mechanically killed.

Since soil and climate interactions are an important factor in the success of conservation tillage the general objective of this study was to assess the feasibility of NST, as a form of conservation tillage, combined with winter cover crops for sweet corn production in the western Fraser Valley. Combining cover crops with NST may reduce local soil degradation problems through soil protection from heavy winter rainfall, addition of organic matter to the soil, less soil disturbance, and performance of tillage operations at the optimal soil workability.

2. REVIEW OF CONSERVATION TILLAGE SYSTEMS AND THEIR EFFECTS ON SOIL CHARACTERISTICS AND CORN PERFORMANCE

2.1. Conservation Tillage

Conservation tillage is generally defined as "any tillage system that reduces loss of soil or water relative to conventional tillage, often a form of non-inversion tillage that retains protective amounts of residue mulch on the surface" (Soil Conserv. Soc. Am., 1982). Conventional tillage, on the other hand, has been defined as "the combined primary and secondary tillage operations performed in preparing seedbed for a given crop grown in a given geographical area" (Mannering and Fenster, 1983). Since the success of conservation tillage can be characterized by its ability to conserve soil water content and reduce soil erosion, it can also be defined as any tillage system that leaves at least 30% of the soil surface covered with residues after a crop is planted (Conservation Technology Information Center, 1991).

The Conservation Technology Information Center (1991) definition makes distinction between conservation and nonconservation tillage-planting systems. Three types of conservation tillage-planting systems, i.e. no-till, mulch till, and ridge till, all have >30% residue cover at planting. On the other hand, nonconservation tillage-planting systems leave either 15-30% residue cover at planting, when repeated secondary tillage follows a primary tillage other than moldboard plowing, or 0-15% residue cover, when moldboard plowing is practiced as a primary tillage.

The term conservation tillage was used for the first time in 1967 in Illinois by the Soil Conservation Service, the Cooperative Extension Service, and the Agricultural Stabilization and Conservation Service, through the Illinois Conservation Practices Committee during the campaign organized to encourage governmental support for various forms of reduced tillage. Although conservation tillage research started in the early 1940s (Van Doren and Stauffer, 1943) conservation tillage was not extensively used in North America until the 1970s (Allmaras and Dowdy, 1985).

In the past two to three decades many North American farmers have shifted from almost complete reliance on the moldboard plow to conservation tillage systems that disturb the soil less and leave more residue on the soil surface. The main reason for the adoption of conservation tillage was the increase of fossil fuel prices. Increased awareness of soil degradation problems and limiting nonrenewable resources also contributed to adoption of the conservation tillage systems by North American farmers.

Successful adoption of conservation tillage is both soil and crop specific and time dependent. Various land classifications have been developed to characterize soil tillage requirements (Cannell et al., 1978; Ross and Wilson, 1982; Ball and O'Sullivan, 1987; Allmaras et al., 1991). Some land classifications take into consideration the soil characteristics such as texture, subsoil permeability, and organic matter content (Ross and Wilson, 1982; Ball, 1986). However, additional information on soil behavioral characteristics (compactability, aggregate stability, macroporosity, and strength) is required since these characteristics influence the soil condition produced by tillage operations (Schafer and Johnson, 1982). Beside soil characteristics, adaptation of conservation tillage practices also depends on site and climate factors.

Soils in which the surface layers have a tendency to pack tightly through slaking are less suitable for conservation tillage, especially for zero-tillage. When crops are zero-till seeded into a compacted surface there is a possibility of inadequate seed coverage, smearing the soil by zero-till drill coulters, and formation of excessive soil strength in the vicinity of seeds. Under such conditions there is a higher probability of seedling damage by slugs and from allelopathic effects (Cannell et al., 1978; Putnam and Weston, 1986). The risk of unsatisfactory crop establishment and growth may be reduced by some form of cultivation. In the absence of cultivation a soil reaches an equilibrium level of consolidation dependent on the soil characteristics and amount of traffic over the soil, interacting with the soil moisture content (Pidgeon and Soane, 1977).

Resistance to compaction in soils is usually associated with drainage, texture, and organic matter content. Soils with good internal drainage are less at risk from both wheeling and slaking damage than soils with poor drainage, since soil strength is greater at lower water content (Smedema, 1979). Soils with low organic matter content and sand content above 65% (w/w) or silt content above 50% (w/w) compact readily (Stengel et al., 1984). The ability of the soil to restore its structure by shrinkage and swelling cycles is limited when expanding clay minerals are present in low amounts (Carter, 1987). Addition of organic matter to the soil tends to reduce the effect of compacting forces and to enhance recovery of degraded soil structure in compacted soils (Soane, 1990).

It is also important to consider climatic factors before adopting conservation tillage, especially in humid, temperate regions such as the western Fraser Valley. Climate can influence soil workability and the soil response to compaction. Owing to a unique combination of soil, climate, and management practices, the western Fraser Valley has clearly defined compaction problems. Soils in this region may be low in organic matter, are subjected to high precipitation, do not go through regular cycles of freezing and thawing, and often support crops that require numerous tillage operations for seedbed preparation and weed control in addition to the normal planting and harvest operations. As a result, tillage pans develop that persist over the growing season and often significantly reduce yields. Excess precipitation in combination with poor soil internal drainage and shallow water table is the biggest climatic constraint to soil workability (Carter, 1994). Ball and O'Sullivan (1987) developed a soil suitability classification for tillage based on date of return to field capacity moisture in the fall and the duration of field capacity moisture over the main growing season. Smedema (1979) used a relationship between field capacity and plastic limit as a measure of soil workability.

High amounts of crop residues, usually present in humid regions, can cause problems for adoption of conservation tillage due to: (i) mechanical interference with planting operations (Vyn et al., 1994), (ii) slow drying and warming of the soil in the spring (Pidgeon and Soane, 1977), (iii) increase of crop diseases and pests (Hughes and Gaynor, 1984), (iv) reduction of crop productivity due to allelopathy (Raimbault et al., 1991), and (v) reduction in the efficiency of fertilizers and pesticides (Groffman, 1985).

Various residue management strategies were developed in order to deal with excessive crop residues. Generally, some form of tillage is required for the successful adoption of conservation tillage in humid regions with high residue levels. Ehlers and Claupein (1994) described mulch tillage systems during which the harvester cuts and evenly distributes the residues at the surface. Residues are mixed into the soil by rotovation implements. By choice of machine and working depth the farmer can decide how much residue will be left at the surface. Vyn et al. (1994) assessed partial width tillage in row crops to remove residues from the planting row, which improved emergence. A winged opener for zero-till developed in New Zealand (Cross Slot^{TM}) has been shown to successfully plant through both flat, detached residues and standing stubble, providing the seed with an ideal microenvironment for emergence (Choudhary and Baker, 1994).

Residues maintained at or near the soil surface may be a source of phytotoxin release during rainfall or microbial decomposition of the residue. Also, crop residues on the soil surface can increase incidence of plant diseases and presence of pests. Use of some soil disturbance, that allows mixing of beneficial and detrimental microorganisms in the rhizosphere, together with crop rotation provides a successful control of plant pathogens (Rovira et al., 1990). Higher population of certain pests, such as mollusks (i.e. slugs), which can affect the early growth of crops, may happen in humid regions (Hammond and Stinner, 1987; Martin, 1991). At the same time, crop residues maintained near the soil surface may have beneficial effects on earthworm activity (Ehlers, 1975; Barnes and Ellis, 1979; House and Parmelee, 1985; Logsdon and Linden, 1992).

2.1.1. Cover Crops in Conservation Tillage Systems

Cover crops are crops which are not grown generally for harvest, but which serve multiple functions in crop rotation systems. Usually cereals, legumes or their mixtures are grown as cover crops in order to protect the soil against erosion, ameliorate soil structure, enhance soil fertility, and suppress weeds, insect pests, and plant pathogens (Hardwick, 1981). Cover crop residues facilitate the use of conservation tillage.

Erosion control by cover crops is based on the principle of improving soil structure, providing a continuous ground cover to protect soil against raindrop impact, and reducing the velocity and carrying capacity of over land flow. The effect of cover crops on soil structure is a function of root density, coverage of the soil surface, and the intensity of cultivation and traffic. The success of cover crops in improving the structure of a given soil is related to the type of cover crops grown. In a study by Hermawan (1995) on a silty clay loam soil on Westham Island, B.C. the greatest soil structural improvement was observed with annual ryegrass (*Lolium multiflorum* L.), followed by fall rye (*Secale cereale* L.) and spring barley.

Cover crops may provide additional benefits through serving as means of managing soil N levels. Decomposition of a legume cover crop usually releases inorganic N into the soil, due to the relatively narrow C/N ratios of legume residues. Recently there has been much interest in leguminous cover crops that can add biologically fixed N to the soil and reduce N fertilizer rates (Power, 1987; Wagger, 1989b; Blevins et al., 1990). Cereals provide no biologically fixed N, as do legumes, and they pose the potential risk of immobilizing applied fertilizer N because of their wide C/N ratios.

Huntington et al. (1985) reported that hairy vetch (*Vicia villosa* Roth.) was more effective than rye in meeting corn N requirements, but there was a poor synchronization between N mineralization from hairy vetch residues and corn N uptake. Only 29% of the N in hairy vetch was recovered by the corn, and most of this N became available after the period of corn silking. In a study conducted on fine sandy loam in North Carolina Wagger (1989b) estimated corn N recovery of hairy vetch and crimson clover(*Trifolium incarnatum* L.) at 40-45 kg N ha^{-1}. This represented 30% of the total N content of hairy vetch and 36% of total N in crimson clover. In an additional experiment, Wagger (1989a) observed a net immobilization of N after the incorporation or rye residues, which had C/N ratios above threshold value of 25/1.

Soil organic N status is also an important factor in potential recovery of cover crop N. Ladd et al. (1983) reported that medic (*Medicago littoralis* L.) residue-N recovery by wheat in a high-N soil (0.17%) averaged 28%, whereas in a low-N soil (0.09%) recovery was 20%. They attributed this to differences in the quality and turnover of the active organic matter pools in soil through which the medic residue N cycled.

Cover crops can control weeds through competition, allelopathy, and physical effects. A potential disadvantage of using cover crops for weed control is that they may compete with the main crop for light, water, and nutrients. Unfortunately, cover crops that suppress weeds the best also tend to be effective in suppressing the main crop, so additional management by herbicides, tillage or mowing is required (Vrable et al., 1983). Space competition resulting in negative effects for the main crop is usually associated with dry conditions. Weed control can also be provided by killed winter cover crops. Winter cereals such as rye and hairy vetch, that are killed at the time of main crop planting, can provide weed control through physical and/or allelopathic effects of their residues. There is evidence that part of the suppressive effect of rye may involve production of allelopathic chemicals (Barnes and Putnam, 1983). Residues from killed cover crops usually provide good weed control for a short period of time, but additional weed control measures may be necessary in the long-term (Weston, 1990).

Conservation tillage can affect many factors of the crop environment. In a fairly direct way, it can affect soil structure, macroporosity, compaction, and may influence soil water content and soil temperature. By making an impact on all of these factors conservation tillage can affect seed emergence, root growth, and overall crop performance. Therefore, the effect of conservation tillage on the soil characteristics mentioned above and its implications for sweet corn production will be the main emphasis of this review.

2.2. Soil Bulk Density and Aeration Porosity

Soil bulk density is defined as a ratio of dry mass to the total volume of soil (solids plus pore space occupied by air and water). Soil porosity represents the ratio of the volume of pores to the total volume of soil. Aeration porosity, on the other hand, is the pore space filled with air at soil water suction equivalent to 0.6 m. Both bulk density and aeration porosity indirectly control plant growth through their effects on soil water, temperature, aeration, and compaction (Letey, 1985). Soil bulk density and aeration porosity are inversely related. Hence, any practice that affects the one also affects the other. Concerns exist that continuous conservation tillage may increase soil bulk density and reduce aeration porosity and thereby inhibit/restrict plant root growth.

The pore space exists because of gaps in the packing of particles and because of disturbances due to root growth, activity of soil fauna, swelling, cracking and shrinking, and tillage that alter the spacing of aggregates and particles. Soil porosity consists of an interconnected system of pores of various sizes and shapes and as such it allows soil to act as a medium for the movement of water and air. Many systems have been devised for describing soil pores. Generally, the main types of soil pores are the micropores, macropores, and fissures, such as planar voids due to cracking and biopores from dead root channels and earthworm channels. The larger pores, i.e. macropores, planar voids, and biopores allow the ready movement of air and percolating water. In contrast, micropores are mostly filled with water and do not permit much air movement. Although there is no clear demarcation, pores with diameter larger than 30 μm (Francis et al., 1988), 50 μm (Greenland, 1981; Carter, 1988a; Dickson and Campbell, 1990) or 60 μm (Kohnke, 1968; McKeague et al., 1986) have been termed 'macropores'. Pores with diameters larger than 500 μm (Greenland, 1981) are fissures.

It is very hard to establish a critical value at which soil aeration is likely to become limiting to root respiration and growth. There are many factors affecting root growth, such as soil water content and temperature, oxygen supply, level of toxins and pathogens in the soil, nutrient supply, the system of pores into which roots can grow, and the soil compressibility. Many of these factors interact with each other, complicating even more the determination of the critical value of aeration porosity for root growth. According to the literature review done by Wesseling (1974) there is a range from 0.05 to 0.2 $m^3\ m^{-3}$ over which aeration porosity has been found to become limiting. Soils with aeration porosity above 0.1 $m^3\ m^{-3}$ are most likely to be adequately aerated (Greenwood, 1975; Greenland, 1981). However, this depends on crop type, soil texture (Bowen, 1981), the degree of pore continuity (Douglas, 1986; Carter, 1988b), and orientation of the pores relative to the preferred geotropic growth direction (Whiteley and Dexter, 1983).

Results from continuous long-term tillage studies on soil bulk density are quite variable. Previous research has shown that soil bulk density is greater in no-tillage than conventional tillage systems (Pidgeon and Soane, 1977; Gantzer and Blake, 1978; Ehlers et al., 1983; Kladivko et al., 1986; Roth et al., 1988; Hammel, 1989; Rhoton et al., 1993). However, several studies have indicated little or no difference in soil bulk density due to tillage (Shear and Moschler, 1969; Lal, 1976; Blevins et al., 1983; Tollner et al., 1984; McFarland et al., 1990). Cropping sequence may also affect soil bulk density owing to differential soil water usage and variations in quantities of residues produced. Gerard et al. (1988) reported higher soil bulk densities under both conventional and conservation tillage systems with wheat than with sorghum (S*orghum bicolor* L.).

Changes in soil physical characteristics that occur as a result of changing from moldboard plow to conservation tillage might be expected to develop slowly after the initiation of conservation tillage. Voorhees and Lindstrom (1984) found that, initially, the introduction of conservation tillage resulted in soil that was less porous at 0-15 cm depth than found under moldboard plowing in silty clay loam in Minnesota. This difference gradually changed with time and after three to four years, conservation tillage produced a higher porosity than did plowing. About seven years of conservation tillage were needed to produce soil with a porosity equal to that of plowing at a depth of 15 to 30 cm.

Another important aspect of tillage with respect to soil porosity and bulk density is its effect on soil fauna activity, especially earthworms. Increased earthworm activity has been observed under no-till compared to tilled treatments (Boone et al., 1976; Lal, 1976; MacKay and Kladivko, 1985). Stable earthworm channels, which increase soil porosity, also provide good infiltration (Ehlers, 1975). In a study on Westham Island, B.C. Hermawan (1995) found a large number of continuous and stable channels produced by the shallow burrowing earthworms on the winter cover cropping site, which significantly improved water infiltration in comparison to the bare soil. In addition to the improved activity of soil fauna with no-tillage, formation of shrinkage cracks in some soils may facilitate root development, water movement, and gas diffusion necessary for plant growth (Ehlers et al., 1983). All this might offset the increased soil bulk density under no-tillage.

2.3. Soil Compaction

Soil compaction may be defined as the compression of a mass of soil into a smaller volume (Raghavan et al., 1990). The resistance of a soil to compaction is determined by its cohesive and frictional strength. The values of these two strength components depend on soil water content, texture, particle shape, type of clay minerals, aggregate size, ionic composition and concentration of the soil solution, and organic matter. When soil is subjected to a load that is sufficient to cause compaction the soil response consists of particle rearrangement and pore space reduction, which in turn causes changes in aeration, water, and nutrient relations of the soil mass. The degree of soil compaction is usually expressed in terms of bulk density or penetration resistance.

Concerns exist that continuous conservation tillage may increase bulk density and soil strength within surface soil layers. Densification of the soil surface might be adverse to root growth, shoot emergence, and eventually crop yield (Voorhees and Lindstrom, 1983; Ehlers et al., 1983). As Bowen (1981) pointed out it is much easier to establish the relationship between the presence of compacted layers and root growth or shoot emergence than to show the relationship between soil compaction and crop yield.

There have been some disagreements in the literature regarding the critical value for penetration resistance that limits root growth. Penetration resistance above 1500 kPa is associated with reductions in root density and penetration (Threadgill, 1982). Penetration resistance above 2000-2500 kPa (Taylor et al., 1966; Gerard et al., 1982; Ehlers et al., 1983) or above 3000 kPa (Hamblin et al., 1982; Busscher and Sojka, 1987) are all indicated in the literature as a critical value above which root growth is limited. Critical penetration resistance depends on other soil physical characteristics at the time of measurement, type of penetrometer used, and type of crop grown. Ehlers et al. (1983) reported that the limiting penetration resistance for root growth of oat (*Avena sativa* L.) was 3600 kPa in the tilled A_p horizon and 4600-5100 kPa in the untilled A_p horizon. Higher limiting penetration resistance for root growth in the untilled soil was attributed to the presence of a continuous pore system created by earthworms and roots from the preceding crops.

Numerous studies have been conducted on root growth and distribution as affected by conservation tillage compared to conventional tillage. In moldboard plowed loess in Germany the root quantity of oat in the 10-20 cm layer was higher than in untilled soil (Ehlers et al., 1983). The main reason for higher root concentration in that layer was the presence of a traffic pan at the 25-30 cm depth. This traffic pan had higher bulk density and penetration resistance than any layer of untilled soil in this study. In deeper layers, root quantity of oats, was consistently greater under no-tillage than under moldboard plowed soil. Accordingly, water uptake from deeper parts of the soil profile was better from untilled soil compared to plowed soil.

Several methods have been used to reduce the effects of soil compaction on crop production. The most obvious approach to the prevention of soil compaction is the reduction of the number of primary and secondary tillage operations and using the most efficient implement at the most appropriate time. An extremely important factor is the timing of field operations in relation to soil water content (Taylor and Gardner, 1963). Especially damaging is the practice of cultivating soil high in clay and silt content with heavy equipment when the soil is wet and its strength is low. At water contents above the optimum for compaction, wheel slip can contribute to soil structure degradation and subsequent compaction as much as loading (Davies et al., 1973; Raghavan et al., 1978). Shifting the tillage to fall, to coincide with drier soil conditions, reduced soil compaction in Prince Edward Island (Carter, 1992b).

Since random traffic over the field by heavy machinery is one of the major causes of soil compaction, controlled traffic has been proposed to avoid compaction. A controlled-traffic system restricts wheel traffic to specific, narrow lines, so that a larger area remains uncompacted (Gerik et al., 1987; Kaspar et al., 1991). In management systems with controlled traffic the soil conditions in rows, trafficked interrows, and untrafficked interrows can be drastically different and may alter corn root distribution (Taylor, 1983). Choudhary and Prihar (1974) reported that interrow compaction inhibited lateral spread of corn roots in the surface soil layers and caused greater downward growth of roots. Other researchers (Bauder et al., 1985; Kaspar et al., 1995) also reported greater corn root length density in untrafficked interrows than in the adjacent trafficked interrows. Fausey and Dylla (1984) observed no corn yield difference between rows with trafficked interrows on one side and rows without trafficked interrows on either side, when adequate fertilizer was applied. But, when no N fertilizer was applied corn yields were significantly lower from rows with trafficked interrows on one side.

It has been hypothesized that soil compaction can be alleviated by roots of certain plants. Root penetration by *Leucaena sp.* (Heinonen, 1986) and bahiagrass (*Paspalum notatum* Flugge) (Elkins et al., 1977) can perforate compact layers and create easily accessible pathways for the roots of succeeding crops.

Several studies showed the importance of the action of soil organisms in reducing soil compaction (Bowen, 1981; Dexter, 1986; Logsdon and Allmaras, 1991). Earthworm burrows increase water infiltration and allow root growth through soil layers that might otherwise reduce or prevent root penetration (Ehlers et al., 1983). Materials cast by earthworms may have a role in influencing soil compaction through their action in stabilizing aggregates (Oades, 1984).

2.4. Aggregate Stability

A good soil structure is important for maintaining favorable soil physical conditions for plant growth. Soil structure has been defined as the arrangement of soil primary particles into stable aggregates (peds) and the associated pore spaces (Oades, 1984). Soil structure is created when physical forces, such as: drying, shrink/swell, freeze/thaw, root growth, animal movement, or compaction mold the soil into aggregates (Paul and Clark, 1988).

A soil may be classified as having good structure if it is aggregated and stable. Aggregate stability is a relative term that has been used to describe the resistance of soil structure to some destructive forces, such as raindrop impact and dispersion by water. As aggregates become larger, the stability of the aggregates becomes more important because their arrangement dictates pore-size distribution, water infiltration rates, and soil erosion. If the soil aggregates are unstable, water infiltration will decrease due to the destructive rainfall impact that causes blocking of the pores with broken aggregates (Lynch and Bragg, 1985). Disaggregation by rain falling on unstable aggregates on the soil surface of a Gleysol (Ladner series) in the western Fraser Valley led to a surface seal and ponding, which reduced soil trafficability early in spring (Abbaspour, 1988).

Crop management practices, such as tillage, crop rotation, N fertilization, and residue application influence the amount and quality of organic matter and the state of aggregation in soils (Parton et al., 1987). Long-term experiments have shown that cultivation of native or meadow soils results in reduction of soil organic matter content and aggregate stability (Tiessen et al., 1982; Elliott, 1986; Benito and Diaz-Fierros, 1992). Reinert et al. (1991) suggested that introduction of zero-tillage on previously cultivated soils would increase aggregate stability and decrease its temporal variation over the long term. Conversely, zero-till crop production of a never-tilled soil would result in a decrease of aggregate stability and increase its variance over time.

Soil tillage affects soil structural stability through its influence on soil water content and redistribution of organic matter, which in turn changes soil microbial activity (Carter, 1986; Kay, 1990; Perfect et al., 1990). Although organic matter is an important binding agent of soil aggregates, changes in water-stable aggregates under different management systems have not always been associated with changes in total soil organic matter (Tisdall and Oades, 1982; Baldock et al., 1987). Tisdall and Oades (1982) pointed out that water stability of macroaggregates depends on roots and hyphae and as such is controlled by tillage, which influences the growth of plant roots and the oxidation of organic carbon. The microaggregates are stabilized against disruption by the persistent organic binding agents, i.e. resistant aromatic components associated with polyvalent metal cations and strongly sorbed polymers.

Several studies have reported that the stability of macroaggregates increased slightly after several years of zero-tillage in comparison to conventional tillage (Hamblin, 1980; Douglas and Goss, 1982; Chan and Mead, 1988; Schonning and Rasmussen, 1989; Raimbault and Vyn, 1991).

Considerable fluctuation in aggregate stability over the growing season has been reported by Stefanson (1971), Bullock et al. (1988), and Reinert et al. (1991). Perfect et al. (1990) showed that soil water content variation during the season was the most significant factor associated with the observed seasonal fluctuation in aggregate stability.

Soil structure and its stability are also influenced by the types of crops grown. For example, the number of water-stable aggregates increases under well established grass pastures. This increase is related to the length of plant roots and mycorrhizal hyphae (Tisdall and Oades, 1980, Baldock and Kay, 1987). Roots may contribute to an increase in stability through physical enmeshment, release of organic stabilizing materials, and water extraction (Reid and Goss, 1982). Angers and Mehuys (1988) found that aggregate stability of clay soil was 40% higher under alfalfa (*Medicago sativa* L.) than under corn and fallow. Plant species that regenerate the structural stability can be incorporated into cropping systems by interseeding in the main crop or by being planted as cover crops between regular cropping seasons (Scott et al. 1987). Hermawan and Bomke (1996) reported a generally lower stability of soil aggregates under cash-winter cover cropping integration than under grass ley on both drained and poorly drained sites in the western Fraser Valley.

Conservation tillage can cause a relatively rapid organic matter accumulation near the soil surface (Carter et al., 1990; Angers et al., 1992). This increase in organic matter induced by conservation tillage provides a substrate for numerous soil micro and macro organisms, that increase the biological activity and subsequently aggregate stability (Weill et al., 1989; Carter, 1992a).

Both aggregate size and stability are affected by earthworms through their feeding and casting activity (Edwards and Lofty, 1977; MacKay and Kladivko, 1985). Earthworm burrowing, together with root penetration, brings soil particles closer to each other creating and stabilizing soil aggregates (Edwards and Lofty, 1977; Kladivko et al., 1986).

2.5. Soil Water Content

The influence of conservation tillage on soil water content and movement depends on the degree of reduction in tillage, the length of time that the conservation tillage system is practiced, and the amount of crop residues left on the soil surface. Numerous studies (Blevins et al., 1971; Pidgeon and Soane, 1977; Gantzer and Blake, 1978; Johnson et al., 1984; Lindstrom et al., 1984; Tollner et al., 1984) have reported greater soil water contents under conservation tillage compared with conventional tillage systems. Greater soil water contents with conservation tillage are attributed to greater infiltration, lower evaporative moisture losses, less runoff, and reduced soil crusting.

Conservation tillage systems increase soil water content by improving soil hydrological characteristics such as profile water recharge by increasing water infiltration and transmission. In a study by Johnson and Moldenhauer (1979) fall chisel plowing was found to double the infiltration rate over fall moldboard plowing.

A surface layer of crop residue, associated with the conservation tillage systems, is an effective way of reducing evaporation. Blevins et al. (1971) observed that mulch reduced evaporation during the early part of corn growing season, resulting in greater water reserve under no-tillage. Later during the growing season, as the canopy began to close, soil water evaporation became less important and plant transpiration became the main source of soil water reduction. The conclusion of this study was that the higher level of soil water stored under no-till may help corn to survive through short drought periods without severe water stress developing in the plants.

Long-term conservation tillage increases the soil organic matter content, which in turn may stabilize the structure and reduce the tendency of the soil to crust (West et al., 1991). Langdale et al. (1979) measured greater annual runoff amounts from conventional tillage (17.3% of total rainfall) than from no-tillage (7.0% of total rainfall).

A residue layer can increase infiltration indirectly by encouraging biological activity near the soil surface. Gantzer and Blake (1978) attributed the increased capability of conservation tillage soils to store water to a rearrangement of the pore size distribution. The macropores, which are created by plant roots and activity of soil fauna, and which are normally disrupted by conventional tillage, tend to persist and be better connected when conservation tillage is used (Barnes and Ellis, 1979). As documented by several studies (Ehlers, 1975; Beven and Germann, 1982) macropores, when open at the soil surface, are highly conductive pathways for water to flow deep into the profile. The increase in macropore continuity under conservation tillage may compensate for the reduction in total porosity sometimes observed with conservation tillage.

Some studies have shown that the better pore continuity to lower soil depths under no-tillage can result in rapid capillary rise and higher water losses by evaporation (Phillips, 1980; Darwent and Bailey, 1981). Some form of shallow tillage may be required for conservation of soil water by disrupting pore continuity and reducing upward movement and evaporative losses of soil water (Hammel et al., 1981; Tanaka, 1985; Carefoot et al., 1990).

The influence of conservation tillage on soil water content and subsequent plant growth depends on tillage method, climate, and soil characteristics. The increase of soil water content by conservation tillage practices might be beneficial in well-drained, crust-prone soils on slopes (Triplett et al., 1968), but may have little effect on the hydrology of noncrusting, poorly drained soils, or soils on flat landscapes (Lal et al., 1989).

2.6. Soil Temperature

Soil temperature is a function of the net amount of heat that enters or leaves the soil (i.e. net radiation) and thermal characteristics of the soil. Part of net radiation is transformed into heat, which warms the soil, plants, and atmosphere. Another part is taken up by plants in their metabolic processes, such as photosynthesis and respiration. A major portion of net radiation is absorbed as latent heat through evaporation and transpiration. The partitioning of the energy arriving at the soil surface is dependent on the thermal characteristics of the soil. The soil color, structure, texture, exposure, water content, as well as the amount and type of plant residues left at or beneath the soil surface all have an effect on the amount of heat entering the soil. Since conservation tillage directly influences many of these factors, it also influences soil temperature.

Loosening of the soil together with crop residue incorporation through tillage operations changes soil bulk density and water content of the plow layer. This in turn can influence soil thermal characteristics, i.e. thermal conductivity, volumetric heat capacity, and thermal diffusivity (Allmaras et al., 1977). Johnson and Lowery (1985) found that thermal diffusivity of silt loam soil was 20% lower under conventional tillage than under no-till in the 5-15 cm soil layer. Similarly, in a study conducted by Hay et al. (1978) lower soil temperatures at the surface, higher surface reflection coefficient, and greater thermal diffusivity were observed under zero-till compared to plowed soil. This combination resulted in overall lower daily soil heat sums for zero-till soil during the first 20 days after planting.

Tillage can also influence soil temperature by changing the shape of the soil surface. Ridge-tillage can increase soil temperature (Spoor and Giles, 1973; Radke, 1982), since the ridge drains more rapidly and can be oriented in such way that one side is more directly exposed to incoming solar radiation.

Residues maintained on the surface by conservation tillage have a complex influence on soil temperature because residues cause interactions among some of the factors that affect soil temperature. Consequently, soil temperature under crop residues will differ from that of bare soil. Surface crop residue has a high radiation reflectivity and low thermal conductivity compared to soil beneath it. Dry corn stalk mulch had 20% lower thermal conductivity than soil in the experiment conducted by van Wijk et al. (1959). The albedo (reflectivity coefficient) of this mulch was approximately 18% compared to the 8% for the soil. Reflection is normally greatest from bright residues, such as wheat straw, and decreases with residue aging (discoloration) and decomposition. Soil temperatures generally decrease as reflectance increases. In the experiment conducted by Gausman et al. (1975) reflectance was the greatest from surface-matted sugarcane (*Saccharum officinarum* L.), followed by bare soil and standing sugarcane.

Crop residues have an effect on soil temperature through both the higher radiation reflectance and by an insulating effect. If only radiation reflectance is responsible for soil thermal changes, 100% coverage of the soil surface would cause maximum reflectance regardless of the residue amount that is above that needed for 100% surface coverage. But higher residue amounts do affect soil temperature, as a result of insulation effect. With an increase of thickness of the residue layer the insulating effect increases (Moody et al., 1963; Mock and Erbach, 1977; Gupta and Gupta, 1983). In the study by Unger (1978) wheat straw at 8-12 t ha^{-1} resulted in lower soil temperatures during a hot period and higher soil temperatures during a cold period than did wheat straw at 4 t ha^{-1}, which provided almost 100% surface coverage.

Griffith et al. (1973) reported that tillage systems that had the highest amount of crop residues on the soil surface had the coolest soil temperatures. Other studies showed generally lower soil maximum temperatures with residues present than with bare soil (Willis et al., 1957; van Wijk et al., 1959; Burrows and Larson, 1962; Moody et al., 1963; Van Doren and

Allamaras, 1978; Unger, 1978; Aston and Fischer, 1986; Carter and Rennie, 1985; Fortin and Pierce, 1990). In some studies the removal of crop residues from the entire zero-till plots (Gauer et al., 1982; Wall and Stobbe, 1984) or clearing of residues out of the row area (Fortin, 1993; Azooz et al., 1995) resulted in increase of soil temperatures, which became similar to soil temperatures observed on tilled plots.

Surface residues associated with conservation tillage reduce soil temperature in the spring as compared with conventional tillage. Reduction of soil temperatures may delay or reduce corn emergence and eventually may reduce the yield of corn grown in regions with cool and wet springs. This delay of corn emergence shortens the growing season, increases the susceptibility of seedling to diseases, and thus reduces plant population (Eagles and Brooking, 1981).

Soil temperature at the planting depth, is one of the most important factors controlling early corn development. Shoot apical meristem remains in the soil for the first four to six weeks after emergence, i.e. until the full extension of the sixth leaf and initiation of the reproductive organs (Beauchamp and Torrence, 1969). During this time, the temperature of shoot meristem is closer to soil than to air temperature (Watts, 1973; Al-Darby and Lowery, 1987). Riley (1981) showed that soil temperatures of 26 to 30°C are optimum for both emergence and early seedling growth and that emergence is reduced below 13°C and fails below 10°C.

In warmer regions (e.g., southern U.S.) where soil temperatures in the corn root zone during the early growing season are not far from optimum, a reduction of approximately 1°C does not cause a large reduction in corn development in mulched treatments as compared to bare soil (van Wijk et al., 1959). In contrast, in colder, northern regions where soil temperatures are much below optimum and occasionally go below minimum soil temperatures for corn development, a reduction of 1°C markedly reduces corn development in mulched treatments as compared to bare soil.

2.7. Nitrogen Management in Conservation Tillage

With the acceptance of conservation tillage systems as alternatives to conventional tillage, different soil conditions are created that can influence soil N and plant growth. Conservation tillage systems leave a layer of crop residues on the soil surface that in the long-term increases soil organic matter content. This increase means a buildup of a labile pool of organic N in soil, which is mineralized during the subsequent growing season. This labile pool of organic N is located in the top few centimeters of soil under no-tillage, whereas in conventional tillage it is mixed throughout the plow layer (Stinner et al., 1983; El-Haris et al., 1983).

Stratification of crop residues and increase of soil organic matter near the soil surface with conservation tillage are accompanied by greater soil microbial biomass. Doran (1980) found higher populations of both nitrifying and denitrifying bacteria at the 0-7.5 cm depth of no-till soils in comparison to conventionally tilled soils. Even though the microbial activity is increased at the surface under no-tillage, less surface area of residues is exposed to bacterial action when the residues are undisturbed as compared with mixing them in the plow layer (Wells, 1984). Accordingly, greater soil N mineralization is usually observed under conventional tillage than under conservation tillage (Free, 1970; Dowdell and Cannell, 1975; Doran and Power, 1983; House et al., 1984; Groffman, 1985). Rice et al. (1986) concluded that lower N mineralization under conservation tillage has a transient effect (i.e. it may be observed initially, but it will not persist). After approximately ten years N mineralization became similar in no-till and conventionally tilled plots.

To compensate for lower mineralization of soil N associated with conservation tillage it has been suggested to grow corn in rotation with soybean or forage legumes. Another beneficial management practice is the introduction of winter annual legumes as cover crops into conservation tillage systems (Mitchell and Teel, 1977; Ebelhar et al., 1984; Utomo et al., 1990). Cover crops such as crimson clover and hairy vetch can provide substantial amounts of N to subsequent crops. As reported by Bomke et al. (1996) crimson clover seeded in August in the western Fraser Valley contained up to 92 kg N ha^{-1}, although the most impressive cover crop N content of 149 kg N ha^{-1} was observed in the winter wheat and hairy vetch mix.

Mineralization-immobilization of soil N is not the only part of the N cycle that is affected by reduced cultivation. Uncultivated soil with a layer of crop residues on its surface is usually cooler and wetter than plowed soil. This can lead to increased N losses through denitrification and leaching. In addition, significant N losses can occur through ammonia volatilization when ammonium containing, or ammonium forming fertilizers, particularly urea, are left on the soil-residue surface.

Denitrification losses tend to be greater under conservation tillage as compared to conventional tillage largely because of the increased soil moisture (Rice and Smith, 1982). Groffman (1985) concluded that under drier conditions no-till soil conserves more moisture and has higher denitrification rates than conventionally tilled soil. Aulakh et al.

(1984) reported that even a small increase in soil moisture content can be accompanied by a very large increase in the rate of denitrification. No-till systems tend to increase the supply of organic carbon to microorganisms near the soil surface, where higher soil water content and lower soil temperature may favor denitrification. The presence of more anaerobic conditions in no-till soils at 0-7.5 cm depth contributed to the greater denitrification potential and higher population of denitrifiers compared to conventionally tilled soils (Linn and Doran, 1984).

Denitrification losses of surface applied N fertilizers are the most severe in late spring and early summer on soils with slow water movement through the root zone, but they can also occur to some extent on well-drained soils. Delayed or split applications of fertilizer N (Wells, 1984), use of nitrification inhibitors (Frye et al., 1980), and subsurface application (Hilton et al., 1994) can reduce denitrification losses and improve fertilizer N efficiency under conservation tillage.

There is a concern that somewhat higher soil water contents and increased infiltration under conservation tillage may promote groundwater pollution by NO_3^- leaching from the root zone (Thomas et al., 1973; Tyler and Thomas, 1977). However, if the additional soil water content under conservation tillage increases corn yield and N recovery (Shanholtz and Lillard, 1969) then, the conservation tillage system would decrease the potential for NO_3 leaching below the root zone. Angle et al. (1993) observed that no-tillage may reduce leaching of nitrates in moderately well-drained loam soil especially at lower N rates. Similar reports were made by Muir et al. (1973), Keller and Mengel, (1986), and Roth and Fox (1990). Long-term study of no-tillage on poorly drained clay loam soil in Minnesota has indicated that lower corn yield and N uptake with no-till lowered evapotranspiration and, together with a higher amount of unused fertilizer N, increased NO_3 leaching losses in comparison with conventional tillage (Randall and Iragavarapu, 1995). As Gilliam and Hoyt (1987) have pointed out, conservation tillage systems may increase or decrease nitrate leaching in the short term depending upon soil type, fertilization method, and rainfall distribution.

Volatilization of N as ammonia is a much bigger problem with surface applied urea-based fertilizers in conservation tillage than in conventional tillage (Bandel et al., 1980; Mengel et al., 1982; Fenn and Hossner, 1985; Urban et al., 1987). Addition of urea or some other ammonium containing or forming fertilizer to the soil covered with residues will result in urea hydrolysis on the residue surfaces and subsequent NH_3 volatilization. Due to relatively low CEC of residues, a small number of NH_4^+ ions will be retained on exchange sites, which will increase ammonium concentrations on crop residues and consequently increase NH_3 volatilization. Additional explanation for the greater NH_3 volatilization under conservation tillage in comparison to conventional tillage, might be in higher soil water content in the former. Small NH_3 losses at low soil water contents are due to a lack of water necessary to dissolve added urea fertilizer, which is a prerequisite for urea hydrolysis. A quantitative estimate of the loss of ammonia by volatilization is very difficult to make (Bandel et al., 1980; Wells, 1984). Fox and Hoffman (1981) categorized ammonia volatilization losses in Pennsylvania based on rainfall amount and the length of time between surface application and rainfall occurrence. Losses were substantial when no rain fell within six days of N surface application. There were no losses with 10 mm of rain occurring within two days of N application. Injecting urea-containing fertilizers several centimeters under the soil surface significantly reduced ammonia volatilization (Fox et al., 1986; Howard and Tyler, 1989).

2.8. Corn Performance

Response of both sweet corn and grain corn to conservation tillage depends on several factors including soil type, topography, internal drainage, preceding crop, climatic conditions during the growing season, and management system used. Generalization of tillage effects on corn performance cannot be made without consideration of such factors as stand establishment, disease and pest incidence, weed control, and fertilizer management.

Much less attention has been focused on conservation tillage systems for sweet corn than for grain corn production. Sweet corn is a type of corn differing from other corn types only in a recessive gene that prevents or retards the normal conversion of sugar into starch as the endosperm develops (Aldrich et al., 1975). Since their sugary condition reduces the total amount of food they can store, the kernels of sweet corn have lower ability to germinate and emerge than those other corn types. At the same time, sweet corn kernels are more susceptible to mold. All these conditions make them more frail and less productive. Certain differences between grain and sweet corn may make conservation tillage less feasible for sweet corn. Grain corn is usually seeded in narrower rows and produces higher biomass than sweet corn. This in turn results in better and quicker canopy coverage by grain corn and subsequent better competition with weeds. In addition, sweet corn kernels are less vigorous and more susceptible to pests than kernels of grain corn.

Numerous studies showed similar or higher grain corn yields obtained with conservation tillage in comparison to the conventional tillage (Blevins et al., 1971; Griffith et al., 1973; Legg et al., 1979; Rice et al., 1986; Al-Darby and Lowery, 1987).

Reduction of corn yields with no-till compared with the conventional moldboard plowing systems is usually reported on fine-textured, imperfectly drained soils, especially those located where temperature reductions are likely to slow down corn development (Griffith et al., 1977; Unger, 1990). In colder, humid regions mulch layers associated with conservation tillage will not improve corn yield through soil water conservation, but on the contrary, corn yield may be suppressed due to the reduction of soil temperatures in the early spring (Unger and Stewart, 1976). Lower spring soil temperatures delay corn emergence and even further limit short growing season effects resulting in lower corn yields in cold humid regions. Similarly, Petersen et al. (1986) observed lower sweet corn yield from no-till treatment than from conventional tillage on silty clay loam in Oregon, due to lower soil temperatures in no-till plots. Additional problems in this study were created by weed competition and slug damage of sweet corn plants after emergence under no-tillage.

Conservation tillage has been less satisfactory than conventional tillage on poorly drained soils with continuous cropping. Vyn and Raimbault (1993) observed that the continuous no-till corn production on fine-textured soil in Ontario resulted in higher bulk density, lower macroporosity, higher soil compaction, and lower proportion of aggregates smaller than 5 mm in diameter. These poor soil conditions in the seedbed inhibited root growth and reduced plant health.

Corn yield differences between conservation and conventional tillage systems were smaller or nonexistent when corn was grown after some other crop. On very poorly drained clay soil in Ohio, Lal et al. (1994) observed that corn yields in a long-term rotation with soybean were somewhat higher under no-tillage than under moldboard plowing. The nature of the relationship among corn yield, crop rotation, and tillage is not completely understood.

In order to improve corn yields on poorly drained soils several practices were suggested. These include ridge planting (Mock and Erbach, 1977; Eckert, 1990), in-row surface residue removal (Allmaras and Nelson, 1971; Vyn et al., 1994), in-row soil loosening (Van Doren, 1973), chisel plowing (Fausey and Lal, 1989), and growing cover crops for improving soil structure (Lal et al., 1991).

On coarse-textured, well-drained soils no-tillage practices tend to produce equal or greater yields of sweet corn (Knavel et al., 1977; Mohler, 1991) and grain corn (Griffith et al., 1973; Van Doren et al., 1976) than moldboard plowing. The major reason for improved corn yields is increased water storage in the soil profile due to the presence of mulch cover (Lal et al., 1994). Gains in no-till corn production due to surface residues and subsequent better water storage usually occur in drier years (Van Doren and Allmaras, 1978; Eckert, 1984) and in warmer regions (Moody et al., 1963; Miller and Shrader, 1976).

Improvement of soil structure may also be a reason for better corn performance under no-tillage. Kladivko et al. (1986) reported that conservation tillage has greater positive effects on grain corn development and yield when practiced on soils characterized by low organic matter content and poor structure than on soils with high organic matter content and good structure.

2.9. Summary

Adoption of conservation tillage systems is strongly dependent on soil type and climate (Cannell et al., 1978; Carter 1994a). The development of conservation tillage originated in sub-humid to semi-arid climates of North America due to need to reduce soil and water losses relative to conventional tillage and, hence, the emphasis was placed on increasing crop residues at the soil surface.

High amounts of crop residue left at the soil surface by conservation tillage can create different conditions in humid climatic regions relative to sub-humid to semi-arid regions. For example, it can create wet soil conditions that lead to difficulties in soil workability, increased soil compaction, higher incidence of diseases, lower soil temperatures at the time of planting, and delayed planting with conservation tillage relative to conventional tillage. Therefore, different approaches are needed for the adoption of conservation tillage systems in humid climatic regions than in regions with moderate precipitation. Carter (1994b) indicated that major characteristics of conservation tillage in humid regions are a continuum of live cover (e.g., provided by cover crops), degree of residue incorporation, and efficiency of crop establishment. These characteristics can be achieved through minimum tillage, rotational tillage, and tillage timing.

The main soil constraints to introduction of conservation tillage, and especially no-tillage, in humid climates are excessive soil compaction, poor drainage, low soil strength, and poor soil structure (Cannell et al., 1978; Ball and O'Sullivan, 1987; Heinonen, 1991). Therefore the most suitable soils for reduction in tillage are well-drained, well-structured soils able to self structure due to a presence of expanding clay minerals.

Our study was conducted in a humid temperate region with mild, wet winters and dry summers. The uneven annual distribution of precipitation results in need to perform tillage and plant winter cover crops in the late summer/early fall before the beginning of the heavy rainfall. Field experiments in this study were established on a silty clay loam Humic Gleysol, which is poorly drained and has relatively shallow watertable. Since these soils might have drainage problems and poor structure they are not suitable for complete elimination of tillage operations and the most appropriate conservation tillage approach for the soil and climate combination in this region is to have minimal and appropriately timed tillage.

In addition to the unique interaction of soil and climatic conditions in this region, NST practice used in our study is different from practices used in other conservation tillage studies. No-spring tillage system did not involve a complete elimination of tillage, such as the case in no-till systems, but had the primary tillage performed in the late summer. In addition, the soil was protected from the rainfall impact during winter with cover crops, while in most conservation tillage studies overwinter protection of the soil is provided by residues of the preceding crop.

Conventional tillage (ST) in this study consisted of late summer and spring discing, while in the majority of conservation tillage studies conventional tillage was performed by moldboard plowing (Rounsevell and Jones, 1993; Cannell and Hawes, 1994; Tyler et al., 1994). Discing chops crop residues and incorporates about 45 to 55% of residues into the soil (Colvin et al. 1981), while moldboard plowing buries most of the crop residues with very little mixing and leaves the soil surface almost bare. Therefore these two tillage implements have a different impact on soil characteristics, such as aggregate stability, porosity, pore continuity, and infiltrability.

No-spring tillage system followed by winter cover crops in the western Fraser Valley was initiated to (i) shift tillage operations to the late summer, when the soil workability conditions are optimal, (ii) reduce the excessive number of tillage operations practiced by local farmers, (iii) provide the soil coverage during winter and early spring, and (iv) improve overall soil tilth through increase of organic matter near the soil surface, which in turn, can improve aggregate stability and reduce slaking, crust formation, and ponding.

Introduction of a new management practice, such as NST, affects many factors of the crop environment. In a fairly direct way it can affect soil structure, porosity, compaction, soil water content, and soil temperature. By making an impact on all these soil characteristics NST can indirectly affect crop emergence, root growth, availability of soil N, and overall sweet corn performance.

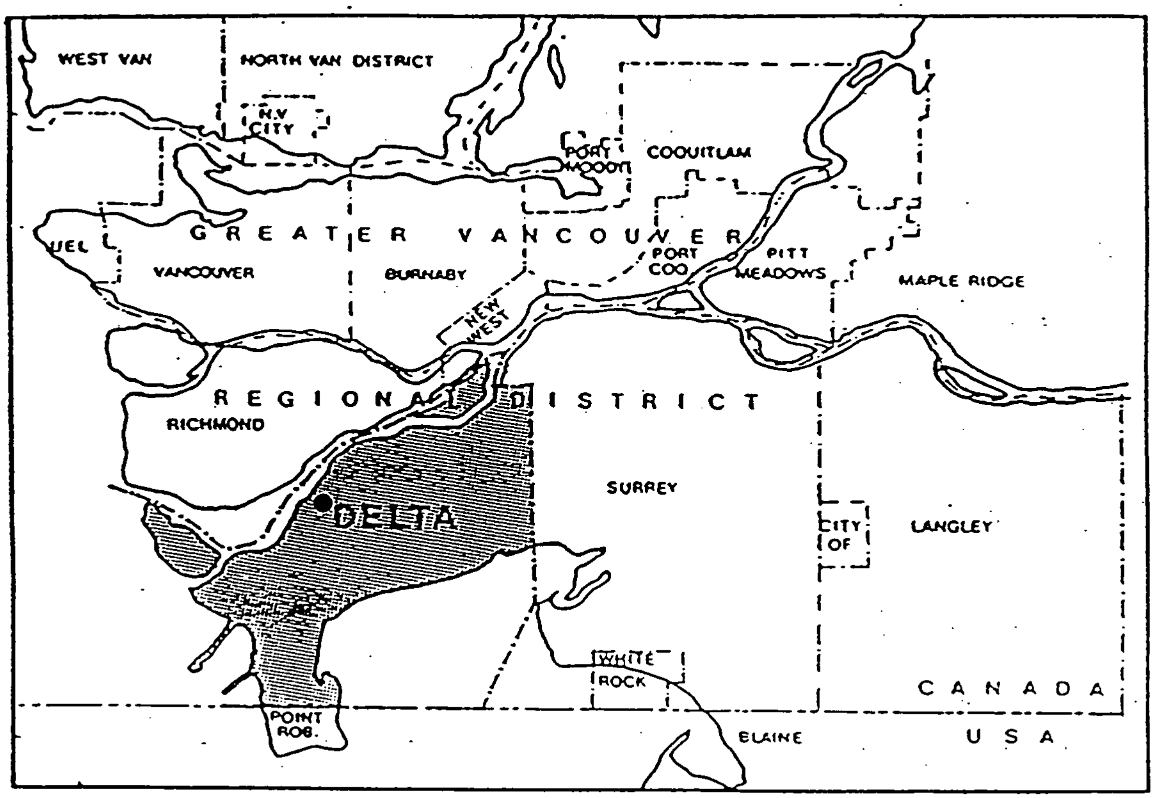
Hence, the objectives of this study were to determine the effects of NST and ST following winter wheat and spring barley cover crops in the western Fraser Valley on:

1. soil physical characteristics, such as: bulk density, aeration porosity, compaction, aggregate stability, water content, and temperature,
2. soil available N during sweet corn growing season, and
3. sweet corn performance.

An additional objective was to establish the optimal N rate for sweet corn production with NST in the western Fraser Valley.

3. MATERIALS AND METHODS

In order to meet the overall objectives of this study, two field experiments were conducted in the Municipality of Delta, about 35 km south of Vancouver (49° 15' N and 123° 00' W), on land farmed by Mr. Bert Nottingham (Figure 3.1). These experiments were conducted on a silty clay loam Humic Gleysol of the Westham series.



● Location of experiments

Figure 3.1. Map of the Fraser River delta and location of experiments.

3.1. Site Description

3.1.1. Experiment 1

In order to determine the effects of NST and ST following winter wheat and spring barley cover crops on soil physical characteristics, soil available N, and sweet corn performance experiment 1 (Exp. 1) was conducted in 1993, 1994, and 1995 on a field southwest of the intersection of 65thB Avenue and 64th Street in Delta, BC. This experiment was located on the same area throughout this study.

Exp. 1 was laid out as a split-block, randomized complete block design with four replications (Figure 3.2). Two tillage systems (NST and ST) were the main-plot treatments, two N rates (0 and 150 kg ha^{-1}) were subplot treatments, and two cover crops (spring barley and winter wheat) were treated as a sub-subplot treatments. The main plot size was 15 × 9 m and the subplot size was 7.5 × 9 m.

Tillage operations on both NST and ST treatments (Table 3.1) were carried out with field-scale equipment. Late summer tillage was performed after crop harvest on September 20, 21, and 12 in 1992, 1993, and 1994, respectively. Primary tillage was performed on May 13, 1993, April 30, 1994 and May 1, 1995. Secondary spring tillage in 1993 and 1994 was performed on the same dates as primary spring tillage, while in 1995 it was done on May 15.

The N rate of 150 kg ha^{-1} was chosen, since it is the amount of N frequently prescribed by processing companies for sweet corn production with conventional tillage.

Spring barley (Ladner common no. 1) and winter wheat (cv. Monopol) were seeded as cover crops on two adjacent parts of same field and Exp. 1 was replicated over these two cover crops.

Sweet corn (hybrid "Jubilee") was planted to a 3 cm depth, using a modified four-row "John Deere 752" no-till drill, on May 18, 7, and 15, in 1993, 1994, and 1995, respectively. The row spacing was 0.76 m in 1993 and 1995 growing seasons resulting in a plant population of 87,000 plants ha^{-1}, while in 1994 growing season the row spacing was 1 m and the plant population was 67,000 plants ha^{-1}.

Nitrogen fertilizer (urea, 46% N) was broadcast by hand, at the rates indicated in Figure 3.2, on the soil surface immediately after corn planting. Phosphorus fertilizer was placed at 7.5 cm depth in the soil by the no-till drill during corn planting according to soil testing recommendations (Neufeld, 1980). Potassium fertilizer was not applied since the soil was high in potassium (Table A. 2).

In order to kill winter wheat and the few surviving plants of spring barley glyphosate [N-(phosphonomethyl) glycine] and 2,4-D [2,4-Dichlorophenoxyacetic acid] were applied approximately one month before corn planting. Rates of glyphosate application were 3.1, 6.7, and 5.5 L ha^{-1} in 1993, 1994, and 1995, respectively. Rates of 2,4-D were 1.2, 1.0, and 0 L ha^{-1} in 1993, 1994, and 1995, respectively. As it turned out, herbicide rates applied in 1993 were low and the winter wheat continued to grow after the spraying. Hence mowing was required to completely eliminate winter wheat.

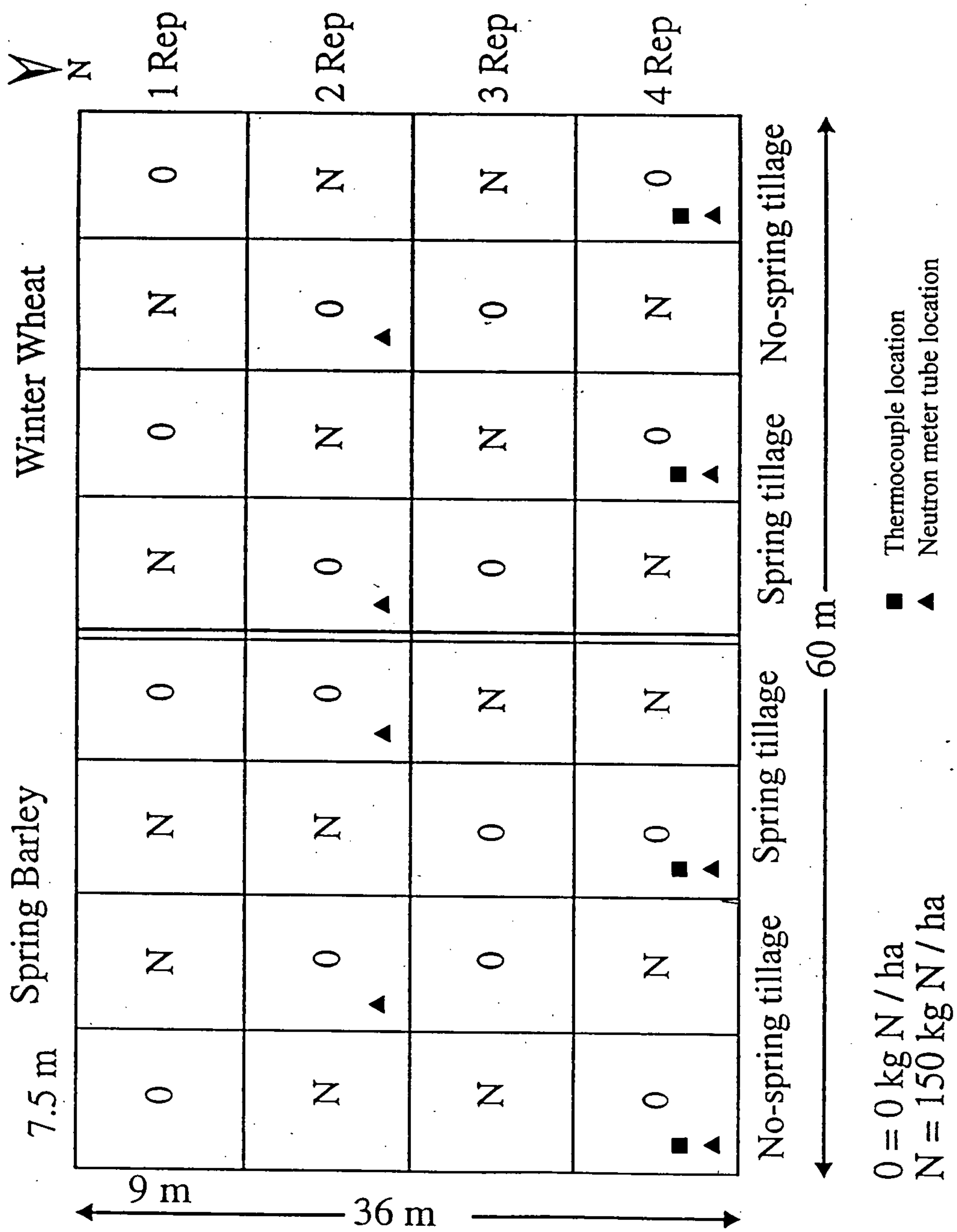


Figure 3.2. Layout of Exp. 1 established in the spring 1993.

Table 3.1. Tillage operations associated with two tillage-planting systems in Exp. 1.

Tillage-planting	Season	Late summer tillage		Spring tillage	
system		Pre-primary	Primary (depth, cm)	Primary (depth, cm)	Secondary (depth, cm)
NST	1992/93	None	Subsoiling (30), and 2×discing (7.5)	None	None
	1993/94	Chop corn residue by disc	2×Discing (25)	None	None
	1994/95	Chop corn residue by disc	Subsoiling (30), and 2×discing (7.5)	None	None
ST	1992/93	None	Subsoiling (30), and 2×discing (7.5)	2×Discing (15)	5×Discing (7.5)
	1993/94	Chop corn residue by disc	2×Discing (25)	2×Discing (15)	5×Discing (7.5)
	1994/95	Chop corn residue by disc	Subsoiling (30), and 2×discing (7.5)	2×Discing (15)	5×Discing (7.5)

Broadleaf and grass weeds were controlled by the application of 4 L ha^{-1} of atrazine-bentazon mixture, i.e. [6-chloro-N-ethyl-N'-(1-methylethyl)-1,3,5-trazine-2,4-diamine] and [(3-(1-methylethyl)-1H,-2,1,3-benzothiadiazin-4(3H)-one2,2-dioxide] applied postemergence on June 10, 1993. Weed control (both broadleaf and grass weeds) was achieved with eradicane [S-ethyl dipropylcarbamothioate] and atrazine [6-chloro-N-ethyl-N'-(1-methylethyl)-1,3,5-trazine-2,4-diamine] at rates of 4.9 L ha^{-1} and 1.2 L ha^{-1}, respectively, on May 4, 1994. A mixture containing 4 L ha^{-1} of atrazine and bentazon was applied postemergence on June 7, 1995, but in spite of the herbicide application, a heavy infestation of barnyard grass (*Echinochloa crusgalli* (L.) Beauv.) occurred on ST treatment. Hence, additional spraying with 3.0 L ha^{-1} of atrazine and 2.2 L ha^{-1} of glyphosate was done on July 7, 1995.

On August 19, 1994, food processing company workers topped the corn plants by mistake and consequently whole corn biomass measurements could not be obtained.

Sweet corn was harvested on September 16, 6, and 7, 1993, 1994, and 1995, respectively. Corn residues were left on the site after the harvests and were chopped and disced into the soil prior to seeding winter cover crops. Cover crops were seeded in rows 15 cm apart using the "John Deere 752" no-till drill. Seeding rate was 100 kg ha^{-1} for both spring barley and winter wheat and seedings were done on September 10, 21, and 12, 1992, 1993, and 1994, respectively.

3.1.2. Experiment 2

In order to establish the optimal N rate for sweet corn production with NST experiment 2 (Exp. 2) was conducted in 1994 and 1995 in the same field as Exp. 1. While Exp. 1 was located on the same site during three consecutive years, Exp. 2 was located on two different, but adjacent sites in 1994 and 1995.

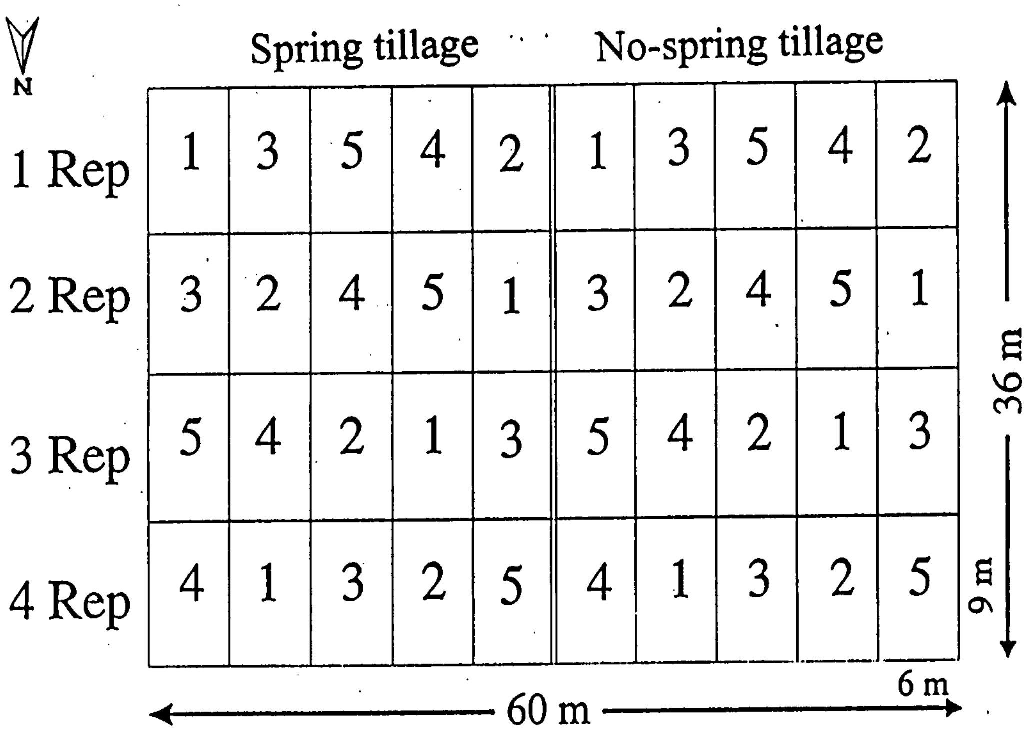
Exp. 2 was also laid out as a split-block, randomized complete block design with four replications. Tillage systems (NST and ST) were the main-plot treatments and five N rates (0, 50, 100, 150 and 200 kg ha^{-1}) were subplot treatments. The main plot size was 30 × 9 m, and subplot size was 6 × 9 m.

Tillage operations in Exp. 2 were exactly the same as those performed in Exp. 1 during the 1993/94 and 1994/95 seasons (Table 3.1).

Sweet corn (hybrid "Mellow gold") was planted at 3 cm depth on May 10, 1994 and May 15, 1995 using a modified four-row "John Deere 752" no-till drill. The row spacing was 1 m in 1994 and 0.76 m in 1995. The plant population was approximately 67,000 plants ha^{-1} in 1994 and 87,000 plants ha^{-1} in 1995. Corn harvests were on September 6, 1994 and September 7, 1995.

Nitrogen fertilizer (urea, 46% N) was broadcast by hand, at the rates indicated in Figure 3.3, on the soil surface immediately after corn planting. Phosphorus fertilizer was placed at 7.5 cm depth into the soil by the no-till drill during corn planting according to soil testing recommendations (Neufeld, 1980). Potassium fertilizer was not applied since the soil was high in potassium (Table A. 2). The same herbicides were applied in Exp. 2 as in the Exp. 1.

Preceding crops for sweet corn in this experiment was bean in 1993 and sweet corn in 1995. During 1993/94 winter spring barley (Ladner common no.1) was grown as cover crop on the site where Exp. 2 was conducted following spring, while during 1994/95 winter tetraploid annual ryegrass Westerwolds (*Lolium multiflorum* L. cv. Aubade) was grown as cover crop. Seeding rate was 100 kg ha^{-1} for spring barley and 25 kg ha^{-1} for annual ryegrass and seedings were done on September 21, 1993 and September 12, 1994.



1 = 0 kg N/ha
2 = 50 kg N/ha
3 = 100 kg N/ha
4 = 150 kg N/ha
5 = 200 kg N/ha

Figure 3.3. Layout of Exp. 2 established in the spring 1994.

3.2. Data collection

3.2.1. Cover crops

Samples of spring barley and winter wheat cover crops on Exp. 1 were taken by hand clipping a 0.5 × 0.5 m area and then analysed for dry biomass production and N concentration. Cover crop samples were taken in the late fall/early winter (before killing frosts) and then again in the spring (before cover crop killing with herbicides). At fall/winter sampling time, i.e. on December 4, 1992; November 21, 1993; and November 21, 1994 winter wheat had reached the tillering stage (growth stage 23 to 25) and spring barley the stem elongation stage (growth stage 31) according to the Zadoks system of describing growth stages (Zadoks, et al. 1974). Spring samplings of cover crops were done on April 22, 1993; March 29, 1994; and March 30, 1995, when both winter wheat and spring barley were in the stem elongation stage (growth stage 31 to 33) with the difference that spring barley was dying out and winter wheat was continuing its growth.

During all fall/winter samplings and 1993 spring sampling cover crops were harvested from six randomly selected 0.5 × 0.5 m areas. In spring of 1994 and 1995, four replications of cover crop samples were collected from NST and ST. All plant tissue samples were dried at 65°C in a forced-air oven for determining dry matter yield. Samples were ground, digested at 360°C for 2.5 hours with an addition of conc. H_2SO_4 and Li_2SO_4 (Parkinson and Allen, 1975) and then analyzed for N concentration using a Lachat Autoanalyzer (Lachat Instruments, Milwaukee, WI). Total N content was calculated by multiplying N concentration by dry matter yield.

Line transect measurements (for the percent of the soil surface covered with residues) were made for both NST and ST treatments before cover crop killing with herbicides and then again immediately after corn planting (Laflen et al., 1981). A rope marked at ten randomly spaced points was laid at a 45° angle relative to the row (two replicates per plot) and the points which came in contact with crop residue were summed and expressed as a percent of the total points. Surface residue cover encompassed cover crop and weed residues, as well as corn residue from previous year.

3.2.2. Slug Population

Slug population density was determined approximately at 5 am on May 13, 1994 and May 21, 1995. Slugs present in a 0.5 × 0.5 m area were counted on each plot with zero N application on Exp. 1 (Figure 3.2). Taxonomy of slugs was determined using a guideline by Runham and Hunter (1970).

The main drawback of a direct count approach in assessing the slug population is that it is subject to variation, in that an unknown and probably variable proportion of the slug population in an area is active on any given night (Port and Port, 1989). In this study direct counts of the slug populations were performed early in the morning, but probably a better time for the direct counts would be at night (Barnes and Weil, 1944 and 1945), since slugs are nocturnal animals. However, if direct numbers may not be representative of the slug population, relative comparisons should be.

3.2.3. Earthworm Population

An assessment of earthworm numbers was done on Exp. 1 (Figure 3.2) by a hand-sorting method (Zicsi, 1962; Tisdall, 1978). Earthworms were obtained by digging a 0.25 × 0.25 m area to a 20 cm depth within each plot with zero N application on Exp. 1. Due to the destructiveness of the sampling method, earthworm population assessment was done only at the end of this study (November 18, 1995), about two months after late summer tillage. Taxonomy of earthworms was determined using a guideline by Reynolds (1977).

3.2.4. Soil Bulk Density and Aeration Porosity

Soil bulk density (ρ_b) and aeration porosity (ε_a) were measured by the core method (Blake and Hartge, 1986a). Intact soil cores (7.3 cm diameter and 7.5 cm length) were collected from all plots on Exp. 1 on August 26, 1993, April 25, and August 17, 1994, April 23, June 1, July 15, and July 29, 1995. All cores were sampled from 0-7.5 cm depth, one core per plot, and used for determination of both ρ_b and ε_a. The cores were wrapped in plastic in the field to prevent soil loss, and trimmed to the ends of the cylinder in the laboratory. Prior to analysis, soil cores were stored at 4°C to decrease biological activity. Soil cores were weighed, then progressively saturated in a container with tap water for 12 hours. After saturation, the cores were weighed and placed on a tension table which contained a tension medium of silicon carbide sand (grit 400). Aeration porosity, i.e. soil pores having diameter>50 μm, was determined on a tension table set at 6 kPa of matric suction (Danielson and Sutherland, 1986). Cores were dried for 24 hours at 105°C and ρ_b was determined as the mass of dry soil per volume of field-moist soil.

3.2.5. Soil Compaction

Soil penetration resistance (PR), measured by penetrometer, is one of the commonly used indexes for characterizing management-induced changes in soil compaction (Bradford, 1986). The penetration resistance was measured before spring tillage (on April 29, 1994 and April 23, 1995) and after spring tillage (on May 25, 1993; June 24, 1993; June 1, 1994; May 16, 1995, and June 1, 1995) on Exp. 1 (Figure 3.2). Soil resistance to penetration was measured to the 60 cm depth, at intervals of 1.5 cm, using a "Rimik" hand-pushed 13-mm diameter cone (30°) penetrometer with data logger (Agridry Rimik PTY Ltd., Toowoomba, QLD, Australia). Three profiles were recorded at each plot with zero N application on Exp. 1, while no PR measurements were done on plots with application of 150 kg N ha^{-1}.

Since wheel traffic patterns were not strictly maintained from year to year, random PR measurements were obtained without regard to wheel tracks.

To get the most useful interpretation of the PR measurements, gravimetric soil water contents were also determined on composite samples taken at 0-15, 15-30, 30-45, and 45-60 cm depths at the time of PR measurements. Due to the dependence of soil strength on soil water content, the field data were then corrected to a standard water content using the method proposed by Busscher and Sojka (1987). Correction of PR to a single soil water content allowed comparisons of absolute PR differences that were not dependent on changes in the soil water content associated with residue cover and tillage.

The Busscher-Sojka model uses a logarithmic empirical relationship among ρ_b, gravimetric water content (θ), and PR (Equation 3.1). The advantage of this method is that when the empirical equation at one water content is subtracted from another at a different water content the ρ_b, which remains constant for a given sample, will cancel (Equation 3.2).

$$\log(PR) = a\log(\rho_b) + b\log(\theta) + c \tag{3.1.}$$

$$\frac{PR_1}{PR_2} = \left(\frac{\theta_1}{\theta_2}\right)^b \tag{3.2.}$$

Subscripts 1 and 2 indicate corrected and uncorrected conditions, respectively.

The constant b was determined by measuring ρ_b, water content, and PR in the laboratory using a repacked soil (that had been sieved through 6-mm sieve) in 7.3 cm diameter by 7.5 cm length cores. The cores with various soil bulk densities were saturated from the bottom up by raising the water slowly up to 2 cm below the surface of the core. The soil cores were allowed to evaporate, and PR was measured at various water contents, representing the seasonal variation in the field. All data from each depth were then substituted into the Busscher-Sojka model, giving b values of -2.15, -2.10, -2.26, and -1.86 for the 0-15, 15-30, 30-45, and 45-60 cm depths, respectively (Table 3.2).

Table 3.2. Relationship among penetration resistance (PR), bulk density (ρ_b), and water content (θ) at four different depths.

Depth (cm)	Equation	n	r^2	P
0-15	$\log(PR) = 1.95\log(\rho_b) - 2.15\log(\theta) - 4.57$	20	0.946	0.0001
15-30	$\log(PR) = 1.41\log(\rho_b) - 2.10\log(\theta) - 2.87$	17	0.919	0.0001
30-45	$\log(PR) = 3.07\log(\rho_b) - 2.26\log(\theta) - 7.78$	12	0.948	0.0001
45-60	$\log(PR) = 3.30\log(\rho_b) - 1.86\log(\theta) - 8.43$	10	0.861	0.001

Data for PR measured in the field were corrected from field measured water contents at sampling (Table A. 3 and Table A. 4) to the reference water content of 0.33 kg kg^{-1} for all depths using the Busscher-Sojka model. Water content value of 0.33 kg kg^{-1} was chosen because it represents an average value observed in the corresponding depths when the measurements were conducted.

3.2.6. Aggregate Stability

Soil aggregate stability samples were taken from 0-5 cm depth on April 21, June 1, August 17, and October 19, 1994, and then on April 23, June 1, July 28, and October 11, 1995. Three soil sub-samples were taken randomly within each plot with zero N application on Exp. 1 (Figure 3.2) and mixed to make a composite sample. Soil samples were not taken on plots with application of 150 kg N ha^{-1}. Samples were transported to the laboratory in a closed, plastic containers and stored in the refrigerator at 4°C until analysis to reduce biological activity.

The structural stability of each sample was assessed using a variation of the wet sieving method (Yoder, 1936). Field moist samples were sieved using a 6-mm sieve and collected on a 2-mm sieve. The pre-sieved 2-6 mm moist sample (of about 10 g) was placed on the top of the nest of sieves with openings of 2.00, 1.00, and 0.25 mm and wetted by a humidifier for 20 minutes to minimize disruption caused by air trapping. Wet sieving was performed for 10 minutes in a motor-driven mechanical device with a vertical stroke of 2.5 cm at a rate of 30 strokes per minute. The motion of the system had both an upward stroke and an oscillating action through an angle of 30° (Hermawan, 1995). After the sieves were removed from the water the proportion of material retained on each sieve was oven dried at

105°C for 12 hours, weighed, and expressed as a percentage of the total soil. Soil aggregate water content was determined gravimetrically on another field-moist subsample for each stability measurement.

The results were expressed as the mean weight diameter (MWD), which represents the sum of the mean diameter of each size fraction (D_i) and the proportion of the sample weight occurring in the corresponding size fraction (W_i) (Van Bavel, 1949). The summation was carried out over all four size fractions, including the one that passed the 0.25-mm sieve ($MWD = \sum_{i=1}^{4} W_i D_i$). In addition to MWD, the proportion of water stable aggregates retained on each sieve was also determined (Kemper and Chepil, 1965). Corrections were made for the sand fraction retained on each sieve to avoid biased interpretations of water stable aggregates. For this purpose, 40 g of air dry 2-6 mm aggregates was treated with dispersing agent (Na-hexametaphosphate) and mechanical stirrer. The suspension was then washed through the stack of sieves used for wet sieving and sand fractions were collected from each sieve. The average of the sand fraction for the twelve samples per whole area of Exp. 1 was used for correction.

3.2.7. Soil Water Content

Soil water content was measured with a neutron meter (CPN 503DR Hydroprobe, using a 50 mCi ^{241}Am-Be source). One access tube was installed to a depth of 80 cm on plots with zero N application on the second and fourth replications of Exp. 1 (Figure 3.2). Measurements employing the neutron probe started on June 4, 1993, May 19, 1994, and May 16, 1995 and were taken at approximately weekly intervals through the whole growing season. At each sampling time readings were replicated two times per plot. Replicated 30-second counts were obtained at 10, 20, and 40 cm depths in 1993, while in the following two years an additional depth (15 cm) was introduced.

3.2.8. Soil Temperature

Soil temperature measurements were taken on plots with zero N application in the forth replication on Exp. 1 (Figure 3.2). The thermocouples were used to measure soil temperature at the planting depth (3 cm) and at 20 cm depth in the row. Soil temperature data were measured every minute and averaged hourly. The copper-constant thermocouples were inserted horizontally through the side of small pits on June 1, 1993, April 13, 1994, and April 12, 1995. The thermocouples were connected to the data logger (Campbell Scientific Inc., Logan, Utah).

In the spring of 1993, a purchased data logger and thermocouples arrived late, therefore measurements for the first two weeks of 1993 corn growing season were not taken. During the 1993 growing season only one thermocouple per depth was used, but in 1994 and 1995, at the 3 cm depth readings were obtained from three thermocouples and readings for the 20 cm depth were obtained from two thermocouples. Thermocouples were placed approximately 0.5 m apart within the same plot. In 1994 and 1995 the thermocouples were removed from the soil on the day of spring discing and corn planting and reinstalled back into the soil on the same day.

3.2.9. Soil Nitrate

Throughout the sweet corn growing season soil samples were taken to monitor the available soil N. Soil samples were taken at 0-5, 5-15, and 15-25 cm depths on Exp. 1 Dates of soil sampling are presented in Table 3.3.

Five randomly selected soil samples were taken between the corn rows on each plot on Exp. 1 (Figure 3.2) and mixed thoroughly to form a composite sample. Samples were transported to the lab in coolers and stored in the refrigerator at 4°C until analysis. Available forms of soil N (NH_4 and NO_3) were determined on moist samples by extraction with 2 *M* KCl at an extraction ratio of 1:10 w/v (Keeney and Nelson, 1982). Soil extracts were analyzed on a Lachat Autoanalyzer (Lachat Instruments, Milwaukee, WI) using the phenol-hypochlorite reaction for NH_4 and the cadmium reduction reaction for NO_3. Soil water content was determined gravimetrically on another subsample prior to extraction. Available soil N concentrations are reported on an oven-dry (105°C) soil basis. Soil NO_3 was a dominant form of available N during this study and only soil NO_3 data are discussed.

3.2.10. Sweet Corn N and Yield

The aboveground portion of five corn plants was harvested from four center rows on each plot of Exp. 1, at seven to nine weeks after corn planting. Later in the growing season (i.e. at twelve weeks after corn planting) five ear leaf samples (the entire leaf at the ear node) were taken from five different plants in four center rows on each plot on Exp. 1. All these corn samples were dried to a constant weight at 65°C, ground, digested at 360°C for 2.5 hours with an addition of conc. H_2SO_4 and Li_2SO_4 (Parkinson and Allen, 1975), and analyzed for N concentration using a Lachat Autoanalyzer (Lachat Instruments, Milwaukee, WI).

Samples for sweet corn production assessment were taken from a 2 m length of the two center rows in each plot on Exp. 1 and Exp. 2. Stalk and cob fresh weights were obtained on these samples. After weighing, five randomly selected stalks and five cobs from each plot were used for moisture determination. Sweet corn production was expressed as dry biomass, dry cob yields, and fresh cob (i.e. marketable) yields.

At each sampling time, stages of corn development were recorded according to the staging system developed by Ritchie and Hanway (1982). Specific stage was defined when at least 50% of the plants per plot were in or beyond a particular stage (Table 3.3 and Table 3.4).

At the end of the 1994 growing season we were not able to obtain stalk weight since on August 19, 1994 corn plants were topped by mistake by workers from the food processing company.

Table 3.3. Soil and corn sampling dates on Exp. 1 for 1993-1995 growing seasons.

Date	Soil sampling	Corn sampling	Stages of corn development		Description
			NST	ST	
May 20, 1993	X	None	None	None	Before N application and after corn planting
Jul 13, 1993	X	X	V6	V7	8th week after corn planting
Aug 13, 1993	X	X	R1	R1	12th week after corn planting
Sep 16, 1993	X	None	R3	R3	Corn harvest
May 10, 1994	X	None	None	None	Before N application and after corn planting
Jul 7, 1994	X	X	V6	V8	8th week after corn planting
Aug 6, 1994	X	X	R1	R2	12th week after corn planting
Sep 6, 1994	X	None	R3	R3	Corn harvest
May 15, 1995	X	None	None	None	Before N application and after corn planting
Jul 5, 1995	X	X	V5	V7	7th week after corn planting
Jul 21, 1995	X	X	V7	V9	9th week after corn planting
Aug 10, 1995	X	X	R1	R2	12th week after corn planting
Sep 6, 1995	X	None	R3	R3	Corn harvest

V5=vegetative stage-fifth leaf; V6=vegetative stage-sixth leaf; V7= vegetative stage-seventh leaf; V9= vegetative stage-ninth leaf; R1=reproductive stage-silking; R2=reproductive stage-blister; R3=reproductive stage-milk.

Table 3.4. Corn sampling dates on Exp. 2 for 1994 and 1995 growing seasons.

Date	Corn sampling	Stages of corn development		Description
		NST	ST	
May 11, 1994	None	None	None	Before N application and after corn planting
Jul 7, 1994	X	V6	V8	8th week after corn planting
Aug 6, 1994	X	R1	R2	12th week after corn planting
Sep 6, 1994	None	R3	R3	Corn harvest
May 15, 1995	None	None	None	Before N application and after corn planting
Jul 5, 1995	X	V5	V8	7th week after corn planting
Jul 21, 1995	X	V7	V12	9th week after corn planting
Aug 11, 1995	X	R1	R2	12th week after corn planting
Sep 6, 1995	None	R3	R3	Corn harvest

V5=vegetative stage-fifth leaf; V6=vegetative stage-sixth leaf; V7= vegetative stage-seventh leaf; V8= vegetative stage-eighth leaf; R1=reproductive stage-silking; R2=reproductive stage-blister; R3=reproductive stage-milk.

3.3. Statistical Analysis

Both Exp. 1 and Exp. 2 were laid out as split-block, randomized complete block design with four replications. The split-block is a variation of the split-plot design and it is usually used in tillage and fertilizer experiments that require the use of ordinary farm equipment (LeClerg et al., 1962; Little and Hills, 1978). Generally, in the split-block design sub-plot treatments are arranged in strips across each replication, due to relatively large size of the farm equipment. In the case of Exp. 1 and Exp. 2, main treatment (tillage) was arranged in strips across each replication, which placed a restriction on randomization (Antal Kożak, personal communication). Exp. 1 was replicated with a different cover crop on an adjacent site and a combined or pooled analysis of variance was accomplished by considering the cover crop species as an additional factor in the experiment and treating it as if it were the smallest experimental unit (Gomez and Gomez, 1984).

The homogeneity of variance (Bartlett test) and the normal distribution of the data (chi-square test) were tested. Logarithmic and square-root transformations were made, where appropriate, prior to statistical analysis. The general linear model procedure in the SAS package (SAS Institute, 1990) was used.

The mathematical model for Exp. 1 was:

$$y_{ijlq} = \mu + \beta_i + \tau_j + \gamma_{ij} + \alpha_l + \varepsilon_{il} + \omega_{jl} + \varepsilon'_{ijl} + \pi_q + \theta_{jq} + \rho_{lq} + \psi_{jlq} + \varepsilon''_{i(jl)q} \qquad \textbf{(3.3.)}$$

It this model y_{ijlq} is the observation, μ is the true mean of the population from which all data came, β_i is the blocking effect, τ_j is the treatment effect, γ_{ij} is the block × treatment interaction effect, i.e. experimental error (1), α_l is the subunit effect, ε_{il} is the experimental error (2), ω_{jl} is the treatment × subunit interaction effect, ε'_{ijl} is the experimental error (3), π_q is the sub-sub unit effect, θ_{jq} is the treatment × sub-sub unit effect, ρ_{lq} is the subunit × sub-sub unit effect, ψ_{jlq} is the treatment × subunit × sub-subunit effect, and $\varepsilon''_{i(jl)q}$ is the experimental error (4). All treatments, except blocks, were considered fixed in determining the components of variance.

The F-test for significance (Table 3.5) was set up by evaluating components of variance. According to the components of variance, the observed mean square for blocks cannot be tested in Exp. 1. Error (1) is appropriate for testing the tillage treatment, while error (2) is appropriate for testing the N rate effects. The interaction of main treatment (tillage) and sub-treatment (N rate) is tested by error (3). Effects of cover crop species and interactions T × C, N × C, and T × N × C were all tested against the error (4). None of the experimental errors could be tested in Exp. 1.

Table 3.5. Outline of the pooled analysis of variance for measurements replicated over two cover crops for split-block design used in Exp. 1.

Source of variation	df	Symbol	Components of variance
Blocks, B	n-1	β_i	$kmp\sigma^2_B$
Tillage, T	k-1	τ_j	$mp\sigma^2_{EE(1)} + nm\sigma^2_T$
B × T, Error (1)	(n-1)(k-1)	γ_{ij}	$mp\sigma^2_{EE(1)}$
N rate, N	m-1	α_l	$kp\sigma^2_{EE(2)} + nkp\sigma^2_N$
B × N, Error (2)	(n-1)(m-1)	ε_{il}	$kp\sigma^2_{EE(2)}$
T × N	(k-1)(m-1)	ω_{jl}	$p\sigma^2_{EE(3)} + np\sigma^2_{T\times N}$
B × T × N, Error (3)	(n-1)(k-1)(m-1)	ε'_{ijl}	$p\sigma^2_{EE(3)}$
Cover crop, C	*p-1*	π_q	$\sigma^2_{EE(4)} + nkm\sigma^2_C$
T × C	*(k-1)(p-1)*	θ_{jq}	$\sigma^2_{EE(4)} + nm\sigma^2_{T\times C}$
N × C	*(m-1)(p-1)*	ρ_{lq}	$\sigma^2_{EE(4)} + nk\sigma^2_{N\times C}$
T × N × C	*(k-1)(m-1)(p-1)*	ψ_{jlq}	$\sigma^2_{EE(4)} + n\sigma^2_{T\times N\times C}$
Error (4)	*km(n-1)(p-1)*	$\varepsilon''_{i(jl)q}$	$\sigma^2_{EE(4)}$
Total	$nkmp$-1		

The mathematical model for Exp. 2 was:

$$y_{ijlq} = \mu + \beta_i + \tau_j + \gamma_{ij} + \alpha_l + \varepsilon_{il} + \omega_{jl} + \varepsilon'_{ijl} \qquad \textbf{(3.4.)}$$

In this model y_{ijlq} is the observation, μ is the true mean of the population from which all data came, β_i is the blocking effect, τ_j is the treatment effect, γ_{ij} is the block × treatment interaction effect, i.e. experimental error (1), α_l is the subunit effect, ε_{il} is the experimental error (2), ω_{jl} is the treatment × subunit interaction effect, and ε'_{ijl} is the experimental error (3). All treatments, except blocks, were considered fixed in determining the components of variance.

Table 3.6. Outline of analysis of variance for split-block design used in Exp. 2.

Source of variation	df	Symbol	Components of variance
Blocks, B	n-1	β_i	$km\sigma_B^2$
Tillage, T	k-1	τ_j	$m\sigma_{EE(1)}^2 + nm\sigma_T^2$
B × T, Error (1)	(n-1)(k-1)	γ_{ij}	$m\sigma_{EE(1)}^2$
N rate, N	m-1	α_l	$k\sigma_{EE(2)}^2 + nk\sigma_N^2$
B × N, Error (2)	(n-1)(m-1)	ε_{il}	$k\sigma_{EE(2)}^2$
T × N	(k-1)(m-1)	ω_{jl}	$\sigma_{EE(3)}^2 + n\sigma_{T\times N}^2$
B × T × N, Error (3)	(n-1)(k-1)(m-1)	ε'_{ijl}	$\sigma_{EE(3)}^2$
Total	nkm-1		

The F-test for significance (Table 3.6) was set up by evaluating components of variance. According to the components of variance, the observed mean square for blocks cannot be tested in Exp. 2. Error (1) is appropriate for testing the tillage treatment, while error (2) is appropriate for testing the N rate effects. The interaction of main treatment (tillage) and sub-treatment (N rate) is tested by error (3). None of the experimental errors could be tested in Exp. 2. Mean values were compared using Duncan's multiple range test following a significant F-test.

Depending on the sample collection the following statistical analyses were performed:

1. The statistical differences in dry matter yields, N concentrations, and N contents between the two cover crops on Exp. 1 obtained during fall sampling and spring 1993 were determined by the *t*-test. Dry matter yield, N concentration, and N content data obtained in spring 1994 and 1995 were analyzed as a 2^2 factorial experiment in a

randomized complete block design involving two tillage systems, two cover crop species, and four replications.

2. Data for slug population assessments were analyzed as 2^2 factorial experiment in a randomized complete block design involving two tillage systems, two cover crop species, and four replications.

3. Data for earthworm population assessments were analyzed as 2^2 factorial experiment in a randomized complete block design involving two tillage systems, two cover crop species, and four replications.

4. Data for ρ_b and ε_a were analyzed as a split-block, randomized complete block design, with four replications and with tillage as the main treatment, N rate as the sub-treatment, and cover crop species as the sub-subtreatment (Table 3.5).

5. Water-corrected PR data were analyzed as 2^2 factorial experiment in a randomized complete block design involving two tillage systems, two cover crop species, and four replications. Water-corrected PR data were analyzed for six selected depths (1.5, 7.5, 15.0, 22.5, 45.0, and 60.0 cm) separately.

6. In the analysis of variance for aggregate stability date of sampling was considered as an additional factor in the experiment and it was treated as a smallest experimental unit (Gomez and Gomez, 1984). Therefore, aggregate stability parameters were analyzed as a split-block, randomized complete block design with four replications and with tillage as the main treatment, cover crop species as the sub-treatment, and date of sampling as the sub-subtreatment.

7. Soil water content data were analyzed as 2^2 factorial experiment in a randomized complete block design involving two tillage systems, two cover crop species, and two replications.

8. Data for soil NO_3 were analyzed as a split-block, randomized complete block design, with four replications and with tillage as the main treatment, N rate as the sub-treatment, and cover crop species as the sub-subtreatment (Table 3.5). Soil NO_3 data were analyzed for each depth separately.

9. Data for sweet corn N concentration and yield on Exp. 1 were analyzed as a split-block, randomized complete block design, with four replications and with tillage as the main treatment, N rate as the sub-treatment, and cover crop species as the sub-subtreatment (Table 3.5).

10. Data for sweet corn yield on Exp. 2 were analyzed as a split-block, randomized complete block design, with four replications and with tillage as the main treatment, and N rate as the sub-treatment (Table 3.6).

4. EXPERIMENTAL CONDITIONS

4.1. Weather in the Western Fraser Valley during the Study Period

The soil climate in the western Fraser Valley is characterized by a mild mesic soil temperature class and a subhumid soil moisture regime (Clayton et al., 1977). Winters in this region are mild, cloudy, and wet and summers are relatively cool and dry. The western Fraser Valley has one of the longest frost-free periods in Canada, extending from April 15 to October 21 (Luttmerding, 1981a). The combination of year-round moderate temperatures, high rainfall, and the lack of long, cold winters gives this region a wider range of possible crops compared to the rest of Canada.

Air temperature and precipitation measurements were obtained from the Environment Canada station at Vancouver International Airport. The lowest monthly temperatures were observed between December and February during all three years of study (Figure 4.1). Average monthly temperatures recorded during December 1992 and January and February 1993 were lower than the long-term averages. On the other hand, average monthly temperatures for the period December-February in 1994 and 1995 were above the long-term averages. Mean temperatures from March to May during all years of this study were slightly above the long-term values. For the June-December period there were no differences in mean temperatures between the years of study and the long-term average.

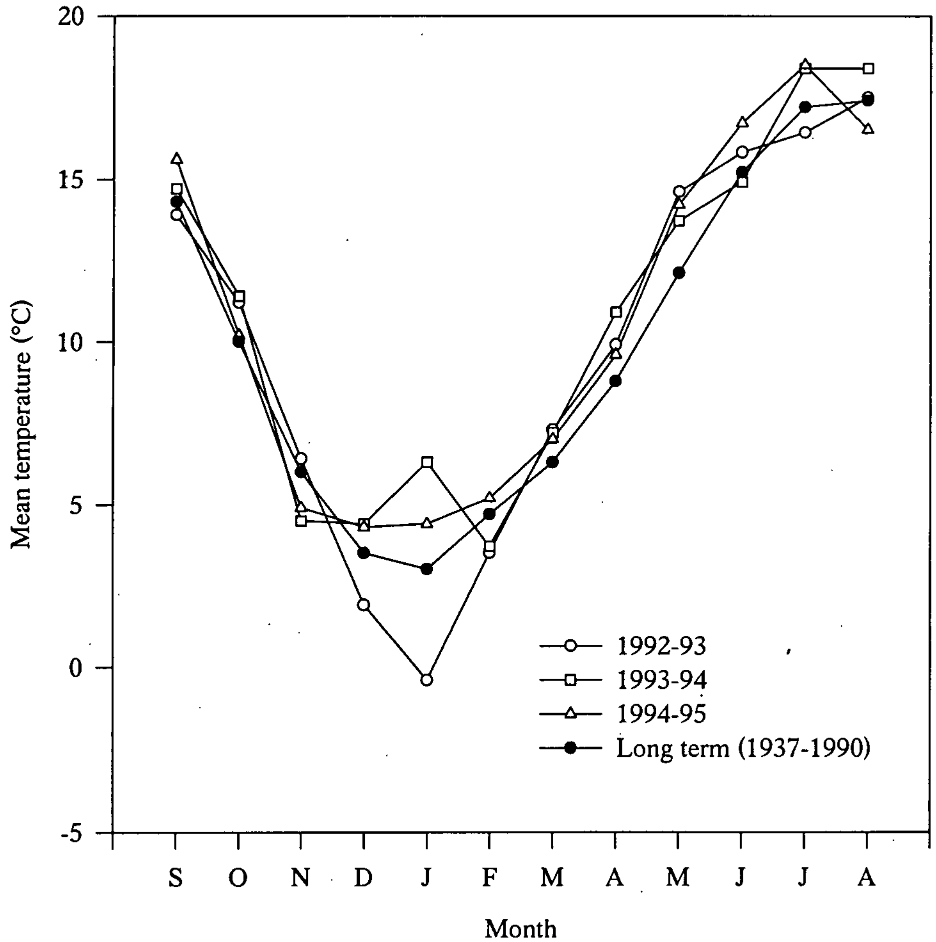


Figure 4.1. Monthly average air temperatures for the western Fraser Valley as recorded at Vancouver International Airport station. *(Source: Environment Canada, Vancouver, and Canadian Climate Normals for British Columbia).*

More than three-quarters of the rainfall in the western Fraser Valley occurs in the October-April period, resulting in 921 mm of precipitation (average for 1937-1990 period) during a period in which evapotranspiration is low. The long-term average precipitation for the sweet corn growing season (May through August) in the western Fraser Valley is 182 mm, while the cumulative precipitation for this period in 1993, 1994, and 1995 were 226, 156, and 186 mm, respectively (Figure 4.2).

Daily snowfalls of more then 10 cm were recorded in mid December 1992 and early January 1993, resulting in 4 to 25 cm of continuous snow cover on the ground for about three weeks (Figure 4.3). In contrast, daily snowfalls of less then 7.5 cm were recorded five times in February and March 1994, covering the ground slightly for only two days. During 1995, daily snowfalls ranging from 1 to 14 cm occurred only three times. Average (1937-1990) cumulative monthly snowfall values for the Vancouver International Airport station range from 0.5 cm in April to 20.6 cm in January, while normal snow cover on the ground is 1 cm in January and February and 4 cm in December.

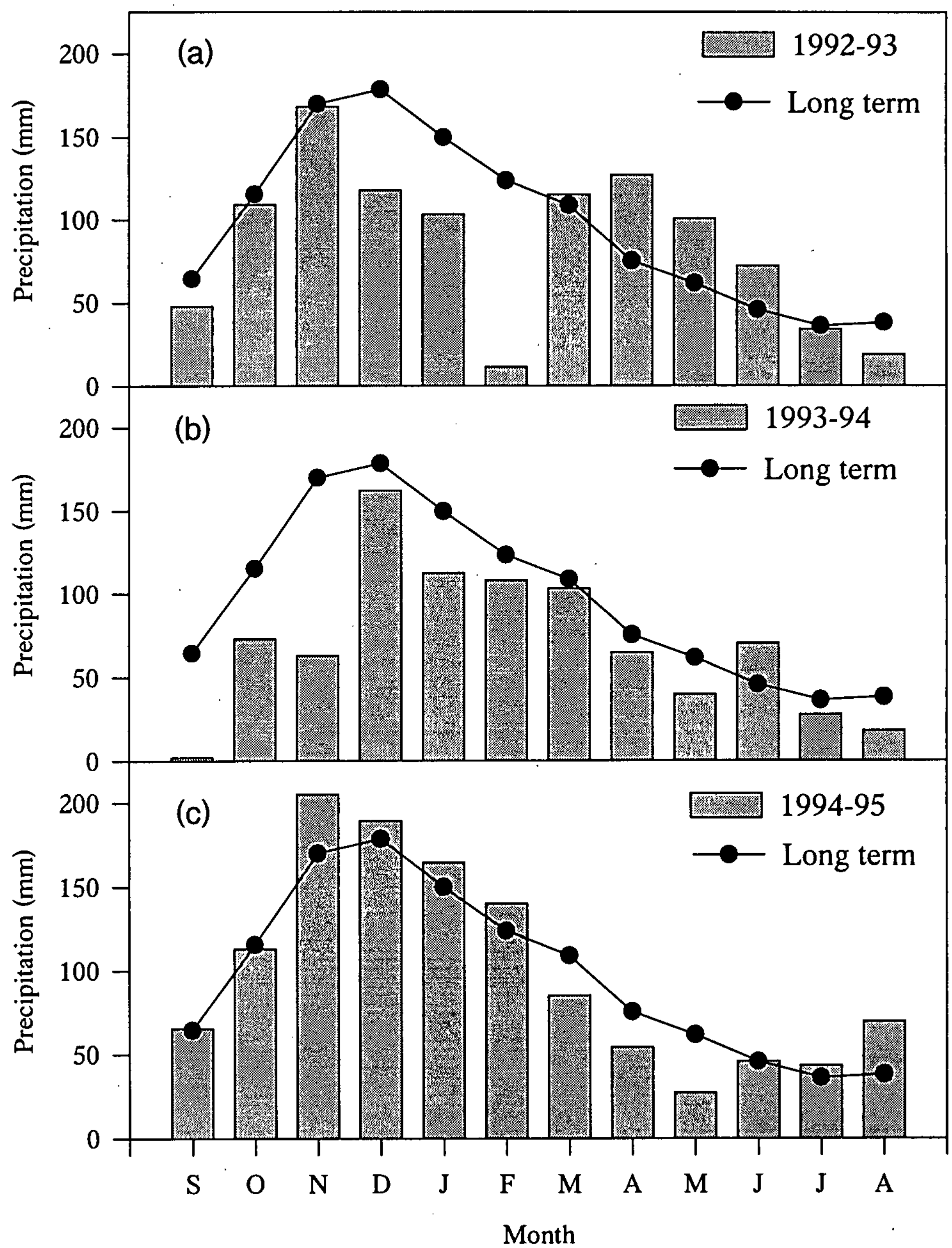


Figure 4.2. Monthly average precipitation for the western Fraser Valley as recorded at Vancouver International Airport station. 1992/93 (a), 1993/94 (b), and 1994/95 (c). *(Source: Environment Canada, Vancouver, and Canadian Climate Normals for British Columbia).*

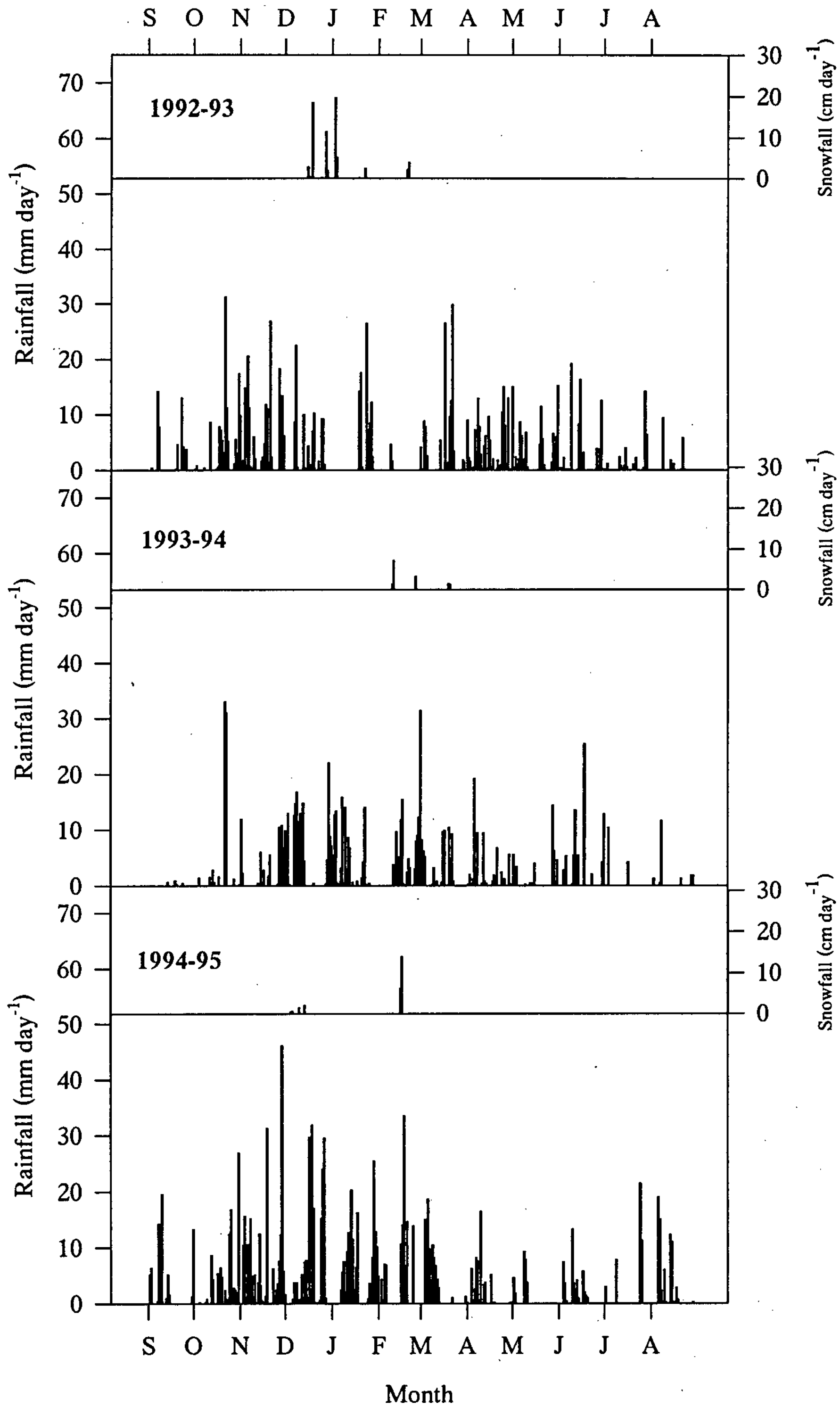


Figure 4.3. Rainfall and snowfall distribution for the western Fraser Valley as recorded at Vancouver International Airport station. 1992/93, 1993/94, and 1994/95. *(Source: Environment Canada, Vancouver, and Canadian Climate Normals for British Columbia).*

4.2. Cover Crop Performance

Spring barley and winter wheat cover crops were an important component of the conventional tillage system in this study. Since differences in biomass production and N concentration between spring barley and winter wheat can affect soil characteristics differently it was important to determine cover crop performance during our study.

Winter wheat produced significantly higher dry matter biomass in comparison to spring barley in the fall of 1992 and 1994. In these two years N concentrations were not significantly different between spring barley and winter wheat (Table 4.1). In the fall of 1993, spring barley had higher dry biomass and N concentration than winter wheat.

Table 4.1. Dry matter biomass and N concentration of two cover crops in the fall (standard error of the mean in brackets).

Fall	Cover crop	Dry matter biomass ($t\ ha^{-1}$)	N concentration ($g\ kg^{-1}$)
1992	Spring barley	1.9 (0.09)	25.6 (0.38)
	Winter wheat	2.7 (0.19)*	23.7 (1.04)
1993	Spring barley	1.2 (0.04)*	50.9 (1.27)*
	Winter wheat	0.6 (0.03)	40.8 (1.31)
1994	Spring barley	1.3 (0.22)	30.7 (1.82)
	Winter wheat	1.7 (0.23)*	33.2 (1.09)

* Indicate significant difference between cover crops (P=0.05) using the *t*-test.

Biomass of winter wheat observed in the spring was consistently higher than the spring barley biomass, since the latter cover crop was winter-killed. A greater amount of cover crop residue was observed for NST in comparison to ST in the spring 1995 (Table 4.2 and Table 4.3). Dry matter biomass produced by these two cover crops was similar to regional averages in the western Fraser Valley (Bomke et al., 1996), but was lower than biomass production generally reported in humid regions. For example, winter wheat dry matter yields obtained in this study were lower by approximately 50% than winter wheat yields reported in studies by Moody et al. (1963) in Virginia; Holderbaum et al. (1990) in Maryland; and Ehlers and Claupein (1994) in Germany. Spring barley dry matter yield obtained in our study was about one quarter of spring barley yield reported by Holderbaum et al. (1990) in Maryland.

Table 4.2. Analysis of variance (F-ratios) for the effects of tillage and type of cover crop on dry matter biomass (t ha^{-1}), N concentration (g kg^{-1}) and N content (kg ha^{-1}) of spring barley and winter wheat.

Source of	df	1994			1995		
variation		Dry matter	N conc.	N content	Dry matter	N conc.	N content
Block	3	1.53	1.82	2.21	0.14	3.07	0.70
Tillage, T	1	0.53	0.40	0.00	17.55**	0.00	19.34**
C.crop, C	1	175.69**	18.92**	60.26**	331.02**	28.86**	186.09**
T × C	1	0.01	0.54	0.31	1.12	1.52	0.52

*, ** Significant at the 0.05 and 0.01 probability levels, respectively.

Spring barley had higher N concentration than winter wheat in the spring of 1994 and 1995 (Table 4.3). In addition, N concentrations of spring barley were in excess of 20 g kg^{-1}, the approximate level required for a net mineralization of N from plant residues (Black, 1968). Such high N concentration is probably due to relatively high N uptake by spring barley prior to the killing frost. Nafuma and Bomke (1994) made similar observations with winter-killed spring cereals in the western Fraser Valley. On the other hand, N concentration of spring barley in the spring of 1993 and N concentration of winter wheat at spring samplings in all three years of our study were low and probably resulted in immobilization of the soil N. It is interesting to note that the winter wheat residues had a N concentration of approximately 17 g kg^{-1} in 1994 and 1995, which is close to the critical value required for a net mineralization.

Table 4.3. Dry matter biomass (t ha^{-1}) and N concentration (g kg^{-1}) of two cover crops in the spring (standard error of the mean in brackets).

Cover crop	Tillage system	Dry matter biomass	N concentration
		Spring 1993	
Spring barley		1.7 (0.09)	10.1 (0.42)
Winter wheat		3.4 (0.30)*	9.3 (0.26)
		Spring 1994	
Spring barley		1.4 (0.08)	25.5 (0.25)**
Winter wheat		3.4 (0.21)**	17.2 (0.56)
		Spring 1995	
Spring barley		1.1 (0.21)	21.9 (1.51)**
Winter wheat		4.1 (0.18)**	16.9 (0.46)
	NST	2.9 (0.20)**	
	ST	2.2 (0.16)	

*,** Significant at the 0.05 and 0.01 probability levels, respectively.

Nitrogen content of spring barley residues decreased from fall to spring by 18 to 30 kg ha^{-1} depending on the sampling year (Figure 4.4), while N content of winter wheat residues decreased by 31 kg ha^{-1} from fall 1992 to spring 1993. During the other two seasons N content of winter wheat residues increased from fall to spring, which was probably caused by N uptake following fall sampling. Air temperature observed immediately after fall cover crop sampling probably had an effect on winter wheat growth and N uptake. For example, average air temperature for December 1992 was 1.9°C, which is quite low for this region and which probably inhibited winter wheat N uptake. Therefore, winter wheat N content decreased from fall 1992 to spring 1993. Air temperatures in December 1993 and 1994 were 4.5 and 4.3°C, respectively. These relatively mild winter temperatures probably allowed winter wheat cover crop to grow and eventually take up soil N, which in turn resulted in an increase of winter wheat N content from fall to spring sampling in 1993/94 and 1994/95 seasons.

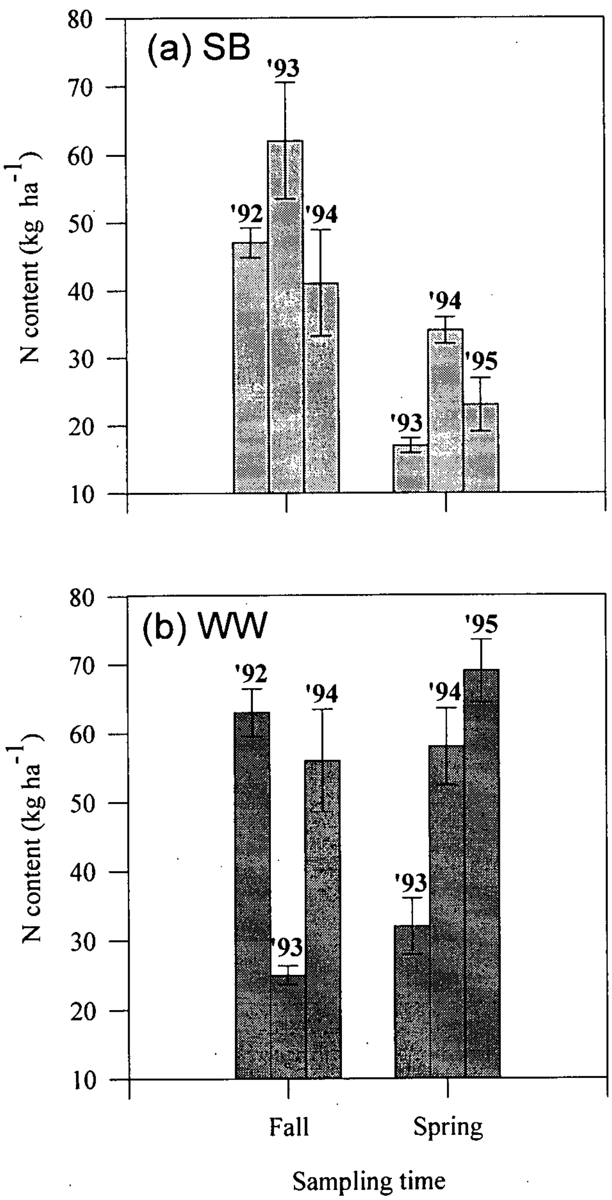


Figure 4.4. Nitrogen content in spring barley (a) and winter wheat (b) cover crops sampled in fall and spring. Error bars represent standard error of the mean (n=8).

The soil surface covered by residues on NST plots just before cover crop killing by herbicides (April) ranged from 69 to 79% with spring barley and from 66 to 96% with winter wheat (Table 4.4). At the same time, ST plots had 61 to 67% coverage with spring barley and 64 to 89% coverage with winter wheat. The relatively high soil coverage under the spring barley cover crop was due to the presence of weeds, especially chickweed (*Stellaria media* L.), that filled in bare spots.

Table 4.4. Percent of the soil covered with residues just before herbicide application (April) and after corn planting (May).

Year	Spring barley				Winter wheat			
	NST		ST		NST		ST	
	April	May	April	May	April	May	April	May
1993	73	32	65	5	77	57	70	25
1994	69	40	61	3	66	48	64	23
1995	79	36	67	0	96	78	89	31

Spring discing incorporated plant residues into the soil, accordingly percentages of the soil cover on ST plots were lower than on NST plots after corn planting (May). Nevertheless, relatively high soil coverage of 31% was observed in 1995 after corn planting on ST plots where winter wheat cover crop was grown, mainly due to the presence of chickweed. It is interesting to note that this is higher than the required minimum (i.e. 30%) for the residue cover for an inclusion into the conservation tillage-planting system according to the Conservation Technology Information Center definition (1991).

In conclusion, in the spring of all three years of this study spring barley cover crop left less residues on the soil surface than winter wheat cover crop. Also, N concentration of spring barley, observed in spring, was higher than N concentration of winter wheat residues in two out of three years. Nitrogen content of spring barley decreased from fall to spring, while N content of winter wheat generally increased during the same period. Percentages of the soil covered with residues were relatively high on ST plots where winter wheat cover crop was grown, due to the combination of high biomass production and presence of weeds.

4.3. Slug Population

Slugs are listed as the most serious noninsect pest encountered in conservation tillage systems for corn production (Gregory and Musick, 1976; Phillips, 1984). In the first year of this study there was no corn damage due to slugs and therefore, no slug counts were done in 1993. The lack of noticeable slug damage during the 1993 growing season might have been caused by the low air temperatures during the 1992/93 winter (Figure 4.1), since Mellanby (1961) and Hunter (1966) reported that slug populations decline after hard winters. Relatively mild 1993/94 and 1994/95 winters (Figure 4.1) favored slug survival and in the spring of 1994 and 1995 high slug populations were observed in this study. Similar observations were made in corn and peas experiments at Agassiz, B.C. (Stan Freyman, personal communication).

Slug population in this study consisted mainly of banded slug (*Arion circumscriptus* Johnston) and *A. hortensis* Ferussac, two very common pest species in gardens and greenhouses in the western North America. Tillage had a significant effect on slug populations in both 1994 and 1995 (Table 4.5). Slug numbers were greater in NST than in

ST treatments (Table 4.6). Differences in slug populations between the two cover crops were not significant.

Table 4.5. Analysis of variance (F-ratios) for the effects of tillage and cover crop species on slug population.

Source of variation	df	1994	1995
Block	3	1.14	0.35
Till, T	1	23.04**	33.92**
Cover crop, C	1	0.81	4.33
T × C	1	0.09	1.56

** Significant at 0.01 probability level.

Lower slug populations in ST than NST observed in this study are not surprising, since soil cultivation leads to direct injury of slugs and exposes them to predation of birds and small mammals (South, 1980). On the other hand, conservation tillage provides a favorable habitat for slugs due to the lack of soil disturbance and the presence of shelter created by the crop residues on the soil surface. Higher slug populations in conservation tillage than in conventional tillage were also reported by Petersen et al. (1986) in a sweet corn study in Oregon, Hammond and Stinner (1987) in a soybean/corn study in Ohio, and Carter et al. (1988) in a study conducted at Prince Edward Island with spring barley and spring wheat.

Increased slug population in NST may also have been related to the greater accessibility of corn seeds in the drill slits to slugs in NST than in ST. Similarly, in a no-till study conducted by Hughes and Gaynor (1984) in New Zealand slug damage was reduced whenever conditions favored closure of no-till drill slits. In our study most of the drill slits on NST plots stayed open due to soil smearing occurring along the walls of the slit.

Table 4.6. Number of slugs per m^2 under two tillage systems (standard error of the mean in brackets).

Tillage-planting system	May 13, 1994	May 21, 1995
NST	17 (2.1)	15 (2.5)
ST	1 (0.6)	1 (0.7)

In addition, increased slug population in NST could also be enhanced by locating Exp. 1 on the same site for three consecutive years.

4.4. Earthworm Population

The number of earthworms was significantly higher in NST than ST treatments (Table 4.7 and Table 4.8), despite the fact that the assessment was done two months after late summer tillage that was carried out on both tillage treatments. Thus, higher numbers of earthworms observed in NST probably represents a residual effect of the elimination of spring tillage during the previous three years. Numerous studies have also reported larger earthworm populations under conservation than conventional tillage (Barnes and Ellis, 1979; De St. Remy and Daynard, 1982; House and Parmelee, 1985), due to less soil disturbance by cultivation, better food supply in a form of crop residues, and better insulation on the soil surface.

Table 4.7. Analysis of variance (F-ratios) for the effects of tillage and cover crop species on total numbers of earthworms per m^2.

Source of variation	df	Total number of earthworms per m^2
Block	3	1.28
Till, T	1	6.82*
Cover crop, C	1	5.72*
T × C	1	1.78

*, Significant at 0.05 probability level.

Table 4.8. Number of earthworms per m^2 under two tillage systems (standard error of the mean in brackets).

Tillage-planting system	Total number of earthworms per m^2	Number of *Lumbricus terrestris* per m^2
NST	198 (40.2)	12 (5.9)
ST	104 (20.9)	6 (2.9)

Type of cover crops also had an effect on the number of earthworms, since higher numbers were observed under spring barley than under winter wheat (Table 4.7 and Table 4.9). This could be a result of better food supply in form of decaying root material provided by the winter-killed spring barley.

Table 4.9. Number of earthworms per m^2 under two cover crops (standard error of the mean in brackets).

Cover crop	Total number of earthworms per m^2	Number of *Lumbricus terrestris* per m^2
Spring barley	196 (43.3)	16 (5.2)
Winter wheat	106 (25.5)	2 (2.0)

The main earthworm species present in this study was a shallow-burrowing, introduced lumbricid (*Lumbricus rubellus*). Deep-burrowing species, such as *Lumbricus terrestris* was also present, but in smaller numbers than *L. rubellus* (Table 4.8 and Table 4.9).

In a study by Hermawan (1995) on Westham Island, B.C. the average number of shallow burrowing earthworms counted in the spring under several cover crops was 65 per m^2. The higher earthworm numbers observed in the fall in our study than in the former study could be due to more favorable soil conditions (i.e. water and temperature) for earthworm activity in the top 20 cm.

5. EFFECTS OF TILLAGE-PLANTING SYSTEMS AND COVER CROP SPECIES ON SOIL PHYSICAL CHARACTERISTICS

5.1. Soil Bulk Density and Aeration Porosity

In general, measurements of ρ_b and ε_a during the study showed no difference between NST and ST (Table 5.1 and Table 5.2). On only one of the sampling dates, July 5, 1995, was ρ_b higher and lower ε_a for NST compared to ST (Figure 5.1). Tillage also had a significant effect on ρ_b, but no effect on ε_a, on August 17, 1994, when ρ_b again was greater under NST than under ST (Figure 5.2). Both tillage systems produced ε_a values that were above the critical value of 0.10 m^3 m^{-3}, which is an indication of adequate soil aeration (Greenland, 1981).

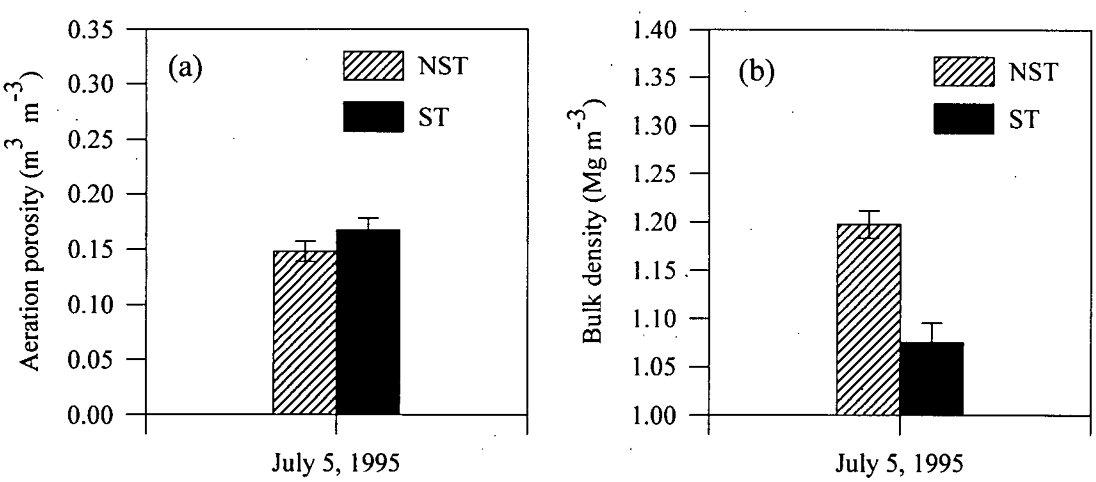


Figure 5.1. Aeration porosity (a) and bulk density (b) obtained under two tillage systems and two cover crops on July 5, 1995. Error bars represent standard error of the mean (n=8).

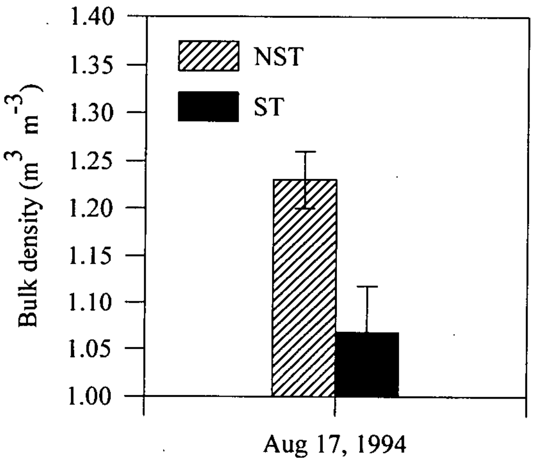


Figure 5.2. Bulk density obtained under two tillage systems on August 17, 1994. Error bars represent standard error of the mean (n=16).

During the study period ρ_b and ε_a values obtained with two cover crops were similar. Cover crops affected both ρ_b and ε_a on the first sampling date only (Table 5.1 and Table 5.2). At that time, higher ρ_b and lower ε_a were observed under ST than under NST with spring barley and the opposite was true with winter wheat (Figure 5.3). In addition, ρ_b was greater with winter wheat than with spring barley cover crop on July 29, 1995 (Figure 5.4).

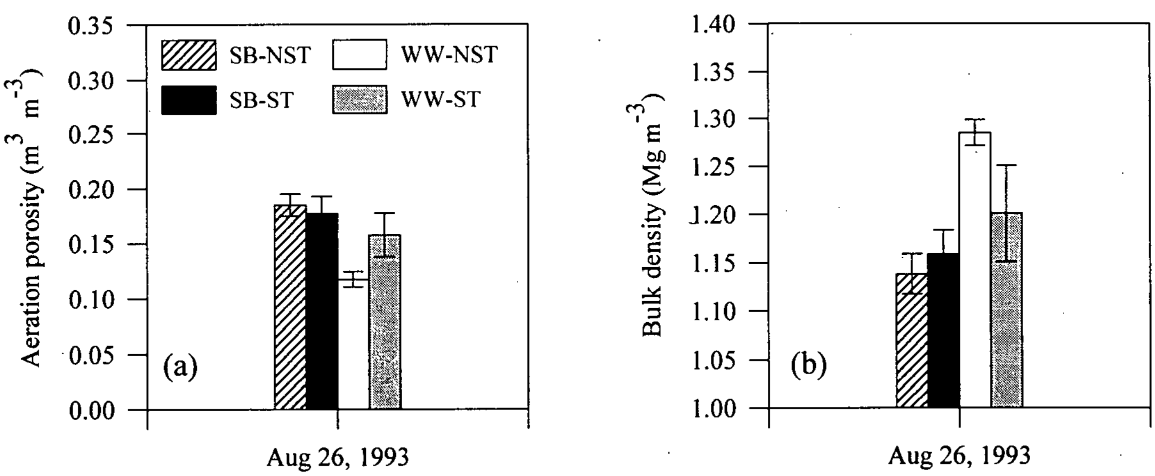


Figure 5.3. Aeration porosity (a) and bulk density (b) obtained under two tillage systems and two cover crops on August 26, 1993. Error bars represent standard error of the mean (n=8).

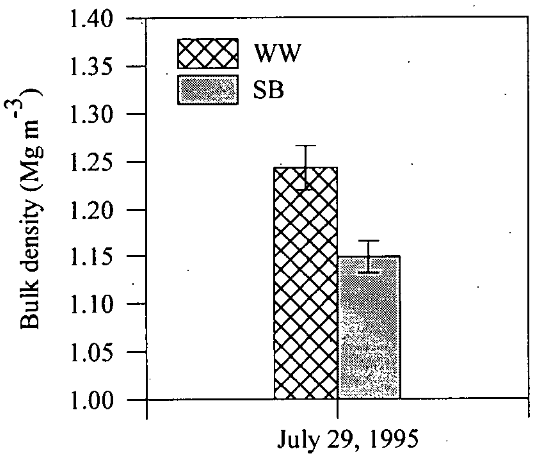


Figure 5.4. Bulk density obtained under two cover crops on July 29, 1995. Error bars represent standard error of the mean (n=16).

Data from different sampling dates were combined to relate ρ_b to ε_a (Figure 5.5) and a close relationship ($r^2 = 0.729^{**}$) was found. This relationship illustrated that a critical ε_a of 0.10 m^3 m^{-3} would require a ρ_b of 1.33 Mg m^{-3}, which is higher than 1.22 Mg m^{-3}, the average ρ_b for NST treatment, and 1.14 Mg m^{-3}, the average ρ_b for ST treatment. Thus ρ_b and ε_a in these cropping systems are unlikely to be limiting for plant growth.

Studies comparing effects of conventional and conservation tillage systems on ρ_b and ε_a have produced variable results, apparently depending largely on soil type, climatic conditions, cropping sequence, and number of years after initiation of conservation tillage (McFarland et al., 1990). The results of continuous conventional and conservation tillage treatments on ρ_b and ε_a are not consistent and at times are contradictory. Some studies (Gantzer and Blake, 1978; Hammel, 1989; Rhoton et al., 1993) showed greater ρ_b under no-till than under conventional tillage, whereas other studies showed no difference in ρ_b due to the tillage treatments (Blevins et al., 1983; Tollner et al., 1984; Hill and Cruse, 1985).

In this study there was no evidence of a consistent pattern in ρ_b and ε_a values under NST and ST. These two tillage-planting systems were carried out for only three years and that was not enough time to attain a stabilized values of ρ_b and ε_a. Pidgeon and Soane (1977) reported that a minimum of three years was required for soils under no-tillage to reach an equilibrium ρ_b after which no further changes in ρ_b were observed. Hill and Cruse (1985) also observed similar ρ_b values between no-till and conventional tillage (fall moldboard plowing followed by spring discing) at a site near Ames, Iowa that was in the same tillage systems for just two years. On the other hand, long-term effects of tillage systems on ρ_b and ε_a were reported in a study by Heard et al. (1988) when nine years of no-tillage on silty clay loam in Indiana resulted in higher ρ_b at 7.5-23.5 cm depth compared to moldboard plowing.

Generally, there was no effect of cover crop species on ρ_b and ε_a. The lack of differences in ρ_b and ε_a between two cover crops is probably caused by the short duration of this study combined with a relatively small difference in residue biomass left on the soil surface by spring barley and winter wheat.

Table 5.1. Analysis of variance (F-ratios) for the effects of tillage, N rate, and cover crop species on aeration porosity ($m^3\ m^{-3}$).

Source of variation	df	Date of sampling						
		Aug 26, 1993[1]	Apr 25, 1994	Aug 17, 1994	Apr 23, 1995[2]	Jun 1, 1995	Jul 5, 1995	Jul 29, 1995
Till, T	1	2.46	7.64	2.19	3.39	8.24	336.00**	1.44
N rate, N	1	1.21	1.71	3.53	0.06	1.09	1.47	0.01
T × N	1	0.04	3.37	2.02	0.32	1.55	0.38	1.64
Cover crop, C	1	42.83**	0.05	0.42	0.05	0.02	0.45	4.45
T × C	1	17.01**	19.75**	0.50	1.72	7.30*	0.00	1.29
N × C	1	21.65**	7.11*	0.01	1.22	2.01	1.54	0.01
T × N × C	1	0.02	0.05	0.50	1.76	0.35	0.33	0.16

*, ** Significant at the 0.05 and 0.01 probability levels, respectively. [1] Square root transformation applied prior to analysis. [2] Log_{10} transformation applied prior to analysis.

Table 5.2. Analysis of variance (F-ratios) for the effects of tillage, N rate, and cover crop species on bulk density ($Mg\ m^{-3}$).

Source of variation	df	Date of sampling						
		Aug 26, 1993	Apr 25, 1994[1]	Aug 17, 1994	Apr 23, 1995	Jun 1, 1995[2]	Jul 5, 1995	Jul 29, 1995[2]
Till, T	1	0.56	5.13	20.05*	5.44	5.01	34.39*	1.78
N rate, N	1	0.14	0.29	0.17	1.08	1.25	0.40	0.03
T × N	1	0.05	3.10	1.39	0.28	0.73	0.19	0.08
Cover crop, C	1	76.56**	0.04	2.15	0.13	1.09	1.29	6.87*
T × C	1	15.60**	11.32**	0.50	4.75	0.59	0.95	2.23
N × C	1	4.20	1.11	1.24	0.21	1.08	2.82	0.16
T × N × C	1	1.56	0.45	0.78	0.21	0.96	0.01	0.02

*, ** Significant at the 0.05 and 0.01 probability levels, respectively. [1] Square root transformation applied prior to analysis. [2] Log_{10} transformation applied prior to analysis.

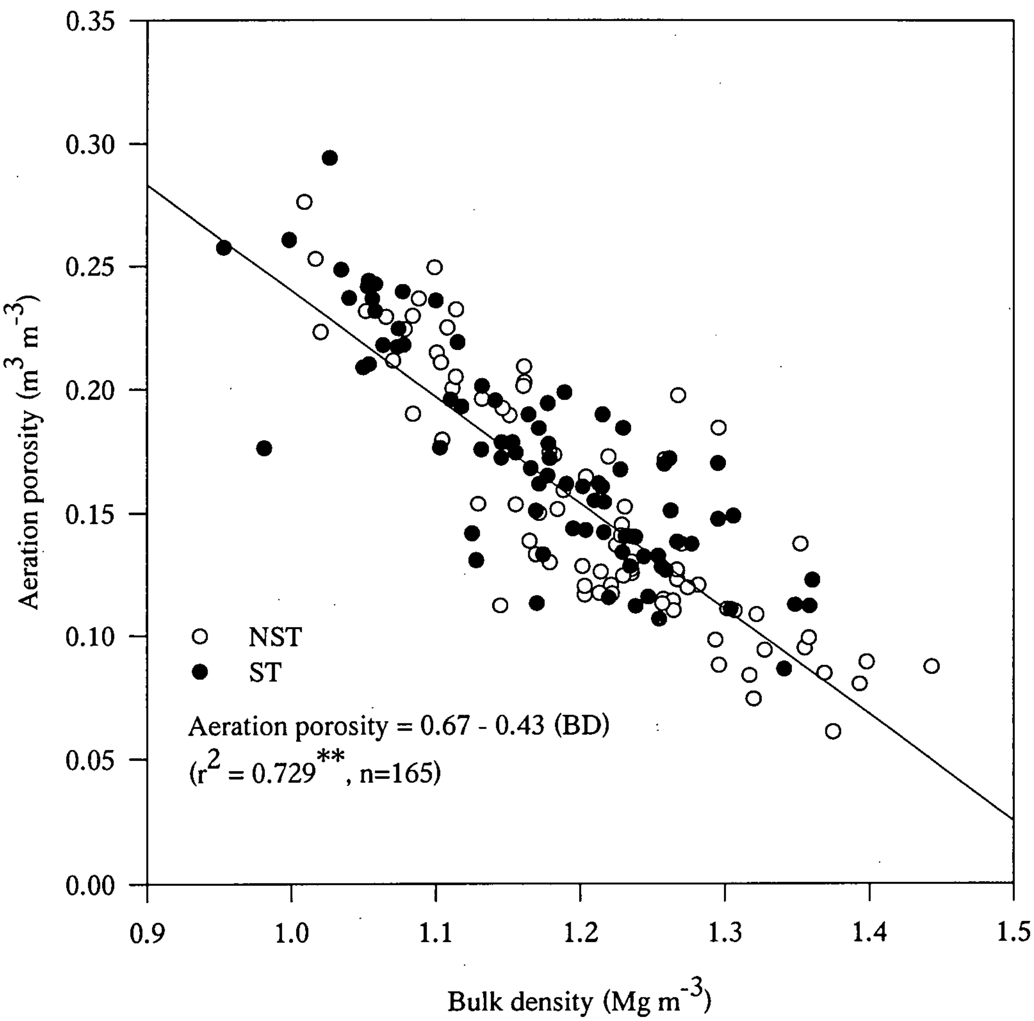


Figure 5.5. Relationship between bulk density and aeration porosity. ** significant at 0.01 probability level.

5.2. Soil Compaction

On May 25, 1993, two weeks after spring tillage, PR in the upper part of the soil profile (up to 15 cm depth) in the NST plots approached 1500 kPa and was much higher than in the ST plots that had been loosened by spring tillage (Table 5.3 and Figure 5.6a). At 15 cm depth PR under ST became higher than under NST, which is not surprising since the primary spring discing was done at 15 cm depth (Figure 5.6). The presence of a tillage pan was observed at 15-25 cm under ST. The only effect of cover crop species on PR was observed at 22.5 cm depth, where PR with spring barley was 1600 kPa and with winter wheat 1200 kPa.

Penetration resistance measurements taken a month later, on June 24, 1993, show a similar trend (Table 5.3 and Figure 5.6b). Again, PR near the soil surface (i.e. at 1.5 and 7.5 cm depths) was significantly higher under NST than under ST, regardless of cover crop. Readings of PR in the top 10 cm under NST were as high as 1700 kPa.

In the spring of 1994 the first set of PR measurements was taken on April 29, 1994, one day before spring discing. At this date the effect of tillage on PR was observed at 7.5 and 15 cm depths (Table 5.4). Conservation (NST) tillage had higher PR than ST at 7.5 cm depth and the opposite was true at 15 cm depth (Figure 5.7a). Higher PR at 15 cm depth in ST than in NST is probably a result of a long-term primary, spring discing at this depth. There was no effect of cover crop species on PR.

One month after the 1994 spring discing (i.e. on June 1) PR at 1.5, 7.5, and 60 cm depths were higher under NST than under ST. Penetrometer readings in the top 10 cm under

NST were high, approaching 2250 kPa (Figure 5.7b). Such high PR values could be limiting for root growth. Type of cover crop, again, had no effect on PR.

On April 23, 1995, one week before spring tillage, there were no differences in PR between the two tillage systems (Table 5.5). At 1.5 and 7.5 cm depths significantly higher PR values were recorded under spring barley than under the winter wheat cover crop (Table 5.5 and Figure 5.8a). At the time of cover crop killing with herbicides in 1995 the average soil surface coverage was 73% with spring barley and 93% with winter wheat (Table 4.4). Lower surface protection with spring barley residues may have increased chances of crust formation on the soil surface and resulted in higher PR at 1.5 cm depth under spring barley than under winter wheat. Although we did not measure cover crop root biomass it is very likely that winter wheat, which survived winter and continued its growth in spring, had higher root biomass than winter-killed spring barley cover crop. Lower root biomass provided by spring barley could have resulted in higher PR at 7.5 cm depth relative to PR under winter wheat.

On May 16, 1995, two weeks after spring tillage, PR was higher under NST than under ST at the 1.5, 7.5, 15 and 45 cm depths (Table 5.6). Penetrometer readings in the top 10 cm under NST were approximately 1750 kPa (Figure 5.8b). At 22.5 cm depth PR with spring barley was 1900 kPa and 1500 kPa with winter wheat. Cover crop species also had a significant effect on PR at 45 cm depth, where PR with spring barley was 1900 kPa and 1400 kPa with winter wheat. Higher PR observed at these depths under spring barley could be a result of lower root biomass left in the soil by spring barley than by winter wheat.

On June 1, 1995, one month after spring cultivation, PR values were still higher under NST than under ST at 1.5, 7.5, 15 and 22.5 cm depths (Table 5.6 and Figure 5.8c). Again, the top part of the soil profile under NST had quite high PR, approaching 2000 kPa (Figure 5.8c). In the first 7.5 cm average PR with spring barley was 1000 kPa and with winter wheat 800 kPa.

After spring tillage, higher PR was observed with NST than ST within top 15 to 20 cm of the soil profile in all three years. At this time of measurement PR ranged from 1500 to 2250 kPa and could be restrictive for corn emergence, seedling growth, or root penetration. On several occasions high PR was also observed in ST at approximately 15 cm depth due to formation of the tillage pan caused by long-term primary spring discing to this depth. The presence of a tillage pan at 15 cm depth was noticed after spring tillage in 1993, when PR approached 2000 kPa, and before spring tillage in 1994, when PR approached 2500 kPa. These high PR values could also be restrictive for root growth and penetration into deeper parts of the soil profile.

The effect of cover crop species on PR was observed either before spring tillage (on April 23, 1995) or after spring tillage (on May 25, 1993; May 16, 1995; and June 1, 1995), when higher PR were measured under spring barley than under winter wheat. Spring barley grown as a cover crop in this region leaves relatively low amounts of residue on the soil surface, which result in poor soil surface protection and high surface PR values. On the other hand, winter wheat survives the winter in this region and continues to grow in spring, producing good soil protection. This leads to lower surface PR under winter wheat than under spring barley cover crop. In addition, winter-killed spring barley probably leaves less root residues in the soil than winter wheat. This could have resulted in higher PR under spring barley than under winter wheat at lower depths; 22.5 cm on May 25, 1993, 7.5 cm on April 23, 1995 and June 1, 1995, and 45 cm on May 16, 1995.

Similar to our findings, higher PR within the upper soil profile has been observed under no-tillage than under conventional, moldboard plowing systems in continuous, long-term studies by Bauder et al. (1981), Hammel (1989), and Hill (1990), as well in a short-term (i.e. three years) study conducted by Gregorich et al. (1993).

Table 5.3. Analysis of variance (F-ratios) for the effects of tillage and cover crop species on corrected PR (kPa) at depths of 1.5, 7.5, 15, 22.5, 45, and 60 cm on May 25 and June 24, 1993.

Source of variation	df	May 25, 1993						June 24, 1993					
		Depth (cm)						Depth (cm)					
		1.5[1]	7.5	15.0	22.5	45.0	60.0	1.5	7.5	15.0	22.5	45.0	60.0
Block, B	3	3.53	20.81**	8.20**	0.73	0.61	0.30	0.75	0.07	0.23	2.75	1.18	0.26
Till, T	1	259.71**	127.41**	22.73**	4.07	4.79	0.01	49.05**	27.97**	0.34	4.56	0.27	0.44
C.crop, C	1	4.05	1.83	4.77	25.57**	0.01	0.11	0.07	0.07	1.50	0.83	0.18	0.58
T × C	1	2.93	0.01	0.71	3.12	0.08	0.03	0.84	0.86	3.37	0.01	0.59	0.05

*, ** Significant at the 0.05 and 0.01 probability levels, respectively. [1] Square root transformation applied prior to analysis.

Table 5.4. Analysis of variance (F-ratios) for the effects of tillage and cover crop species on corrected PR (kPa) at depths of 1.5, 7.5, 15, 22.5, 45, and 60 cm on April 29 and June 1, 1994.

Source of variation	df	April 29, 1994						June 1, 1994					
		Depth (cm)						Depth (cm)					
		1.5	7.5	15.0	22.5	45.0	60.0	1.5	7.5	15.0	22.5	45.0	60.0
Block, B	3	0.17	1.17	1.12	0.44	0.35	1.29	1.58	0.66	0.36	0.65	0.29	4.06*
Till, T	1	0.64	10.98**	5.78*	1.74	1.34	0.06	120.14**	73.44**	0.42	0.03	4.92	7.55*
C.crop, C	1	1.34	3.47	1.51	1.75	2.30	0.62	0.86	2.38	0.16	0.16	0.08	1.86
T × C	1	3.49	3.91	0.37	0.15	0.01	0.01	0.75	2.31	1.24	1.07	0.06	1.08

*, ** Significant at the 0.05 and 0.01 probability levels, respectively.

Table 5.5. Analysis of variance (F-ratios) for the effects of tillage and cover crop species on corrected PR (kPa) at depths of 1.5, 7.5, 15, 22.5, 45, and 60 cm on April 23, 1995.

Source of variation	df	April 23, 1995					
		Depth (cm)					
		1.5	7.5[1]	15.0	22.5	45.0	60.0
Block, B	3	1.80	0.27	0.51	0.10	1.08	0.26
Till, T	1	0.12	0.32	0.16	2.89	1.06	2.37
Cover crop, C	1	34.80**	23.27**	1.94	0.05	0.35	1.36
T × C	1	1.28	3.34	0.01	0.02	6.03*	4.93

*, ** Significant at the 0.05 and 0.01 probability levels, respectively. [1] Log_{10} transformation applied prior to analysis.

Table 5.6. Analysis of variance (F-ratios) for the effects of tillage and cover crop species on corrected PR (kPa) at depths of 1.5, 7.5, 15, 22.5, 45, and 60 cm on May 16 and June 1, 1995.

Source of variation	df	May 16, 1995 Depth (cm)						June 1, 1995 Depth (cm)					
		1.5	7.5	15.0	22.5	45.0	60.0	1.5[1]	7.5	15.0	22.5	45.0	60.0
Block, B	3	0.59	0.57	0.38	0.31	1.00	3.10	2.49	0.90	2.20	0.90	0.29	0.03
Till, T	1	41.85**	97.82**	6.11*	4.13	23.40**	3.54	60.31**	231.74**	51.27**	15.98**	0.29	0.16
C.crop, C	1	0.47	1.81	0.03	13.99**	12.72**	1.39	5.64*	5.31*	0.01	0.23	2.46	0.80
T × C	1	2.03	25.40**	10.56**	3.06	1.54	6.79*	3.24	0.22	0.40	0.10	8.50*	0.76

*, ** Significant at the 0.05 and 0.01 probability levels, respectively. [1] Square root transformation applied prior to analysis.

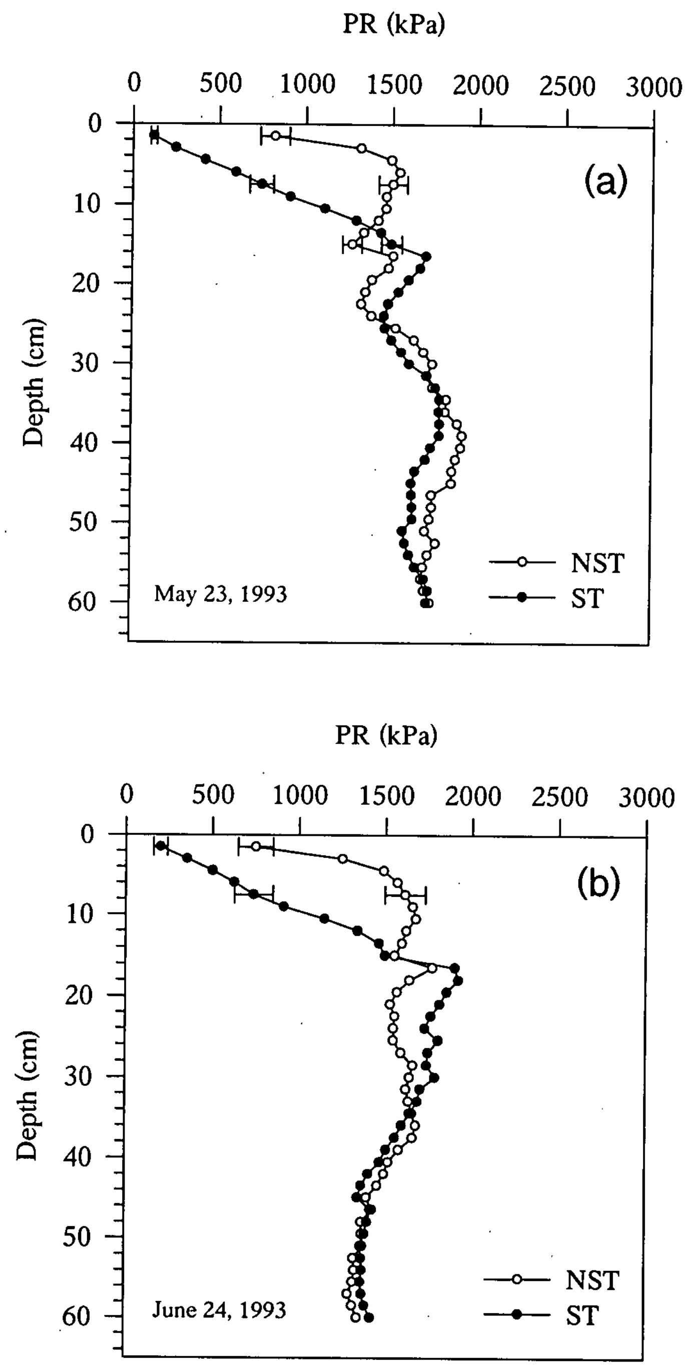


Figure 5.6. Soil penetration (PR) in relation to depth on May 25, 1993 (a) and June 24, 1993 (b). Error bars represent standard error of the mean (n=48) and they are shown only on means that are significantly different (P<0.05).

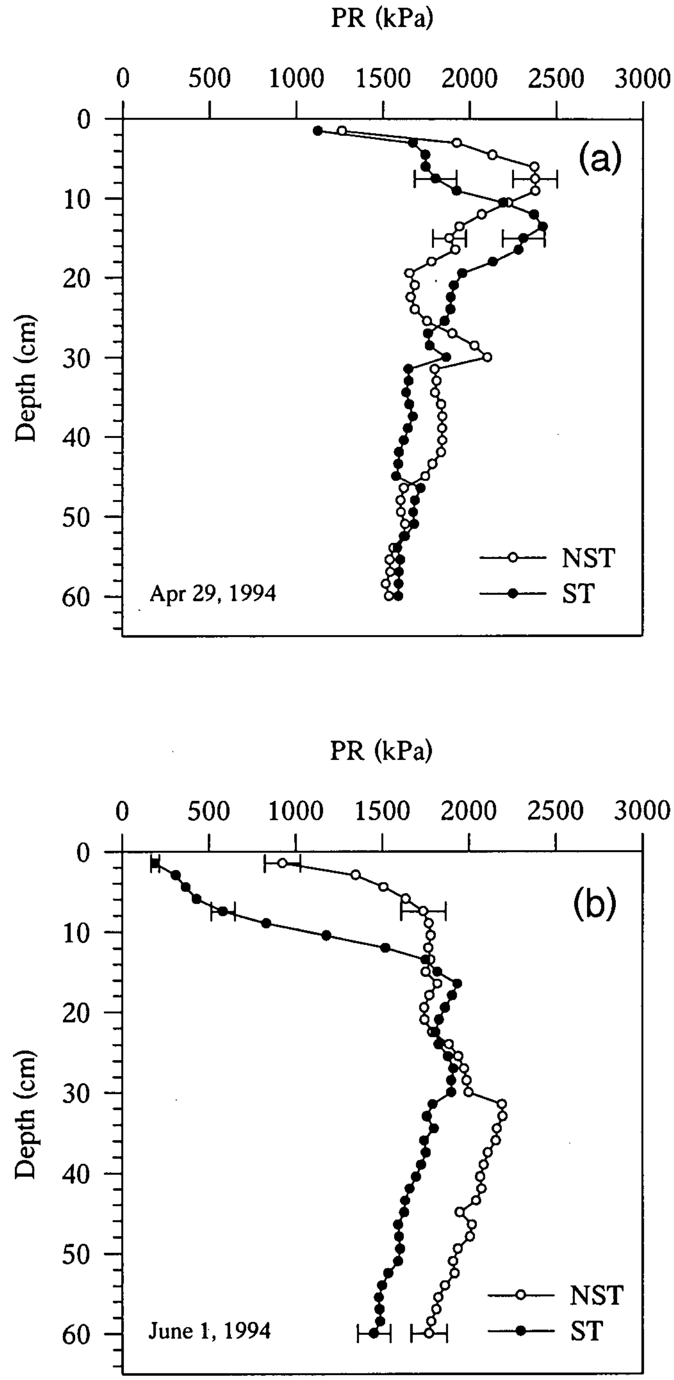


Figure 5.7. Soil penetration (PR) in relation to depth on April 29, 1994 (a) and June 1, 1994 (b). Error bars represent standard error of the mean (n=48) and they are shown only on means that are significantly different ($P<0.05$).

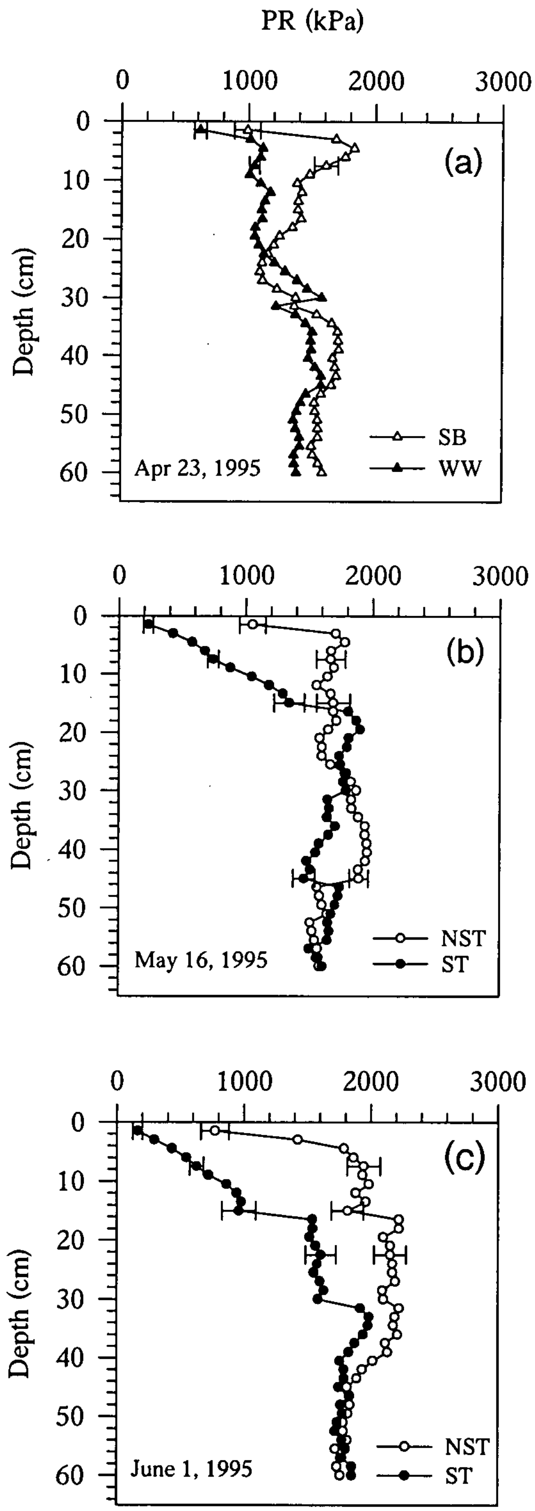


Figure 5.8. Soil penetration (PR) in relation to depth on April 23, 1995 (a), May 16, 1995 (b), and June 1, 1995 (c). Error bars represent standard error of the mean (n=48) and they are shown only on means that are significantly different (P<0.05). SB=spring barley; and WW=winter wheat.

5.3. Aggregate Stability

Tillage and cover crop species did not have a significant effect on aggregate stability parameters during 1994 and 1995 (Table 5.7 and Table 5.8). Since NST was executed for the first time in spring of 1993 there was not enough time for significant improvement in soil aggregation. Hamblin (1980) reported that only a slight increase in soil structural stability developed after three to eight years of direct drilling in comparison with conventional discing on clay to sandy loam soils in Australia. Carter (1992a) showed that direct drilling over three to five years improved structural stability at the soil surface as compared to moldboard plowing of a fine sandy loam on Prince Edward Island.

The relatively high clay content (Table A. 2) and presence of montmorillonite and vermiculite clay minerals (Luttmerding, 1981b) in Gleysols in the western Fraser Valley could constitute another reason for the lack of tillage effect. The high degree of "native" aggregation in fine-textured soils appears to limit the improvement of soil aggregation induced by conservation tillage systems. Franzluebbers and Arshad (1996) observed that macroaggregation and MWD increased with increasing clay content, thereby reducing the potential of zero-tillage to improve these characteristics in soils with high clay contents in the Peace River region of northern Alberta and British Columbia.

Table 5.7. Analysis of variance (F-ratios) for the effects of tillage, cover crop species and date of sampling on MWD, size-distribution of water-stable aggregates, and aggregate water content during 1994 growing season.

Source	df	MWD (mm)	Water-stable aggregates (mm) 2-6	1-2	0.25-1	<0.25	Water[2] (kg kg^{-1})
Till, T	1	0.22	0.33	3.60	0.09	0.01	0.33
C.crop, C	1	3.48	3.88	1.12	1.40	3.06	1.09
T × C	1	0.33	0.34	0.28	0.13	0.30	4.15
Date, D	3	126.16**	107.18**	19.85**	25.13**	163.82**	306.01**
T × D	3	1.30	1.29	0.80	0.12	1.47	1.00
C × D	3	0.60	0.62	0.64	0.13	0.51	4.21*
T × C × D	3	2.01	2.06	1.58	2.54	1.41	0.68

*, ** Significant at the 0.05 and 0.01 probability levels, respectively. [2] Log_{10} transformation applied prior to analysis.

Relatively low amounts of residues left on the soil surface by spring barley and winter wheat (Table 4.3) did not result in improvement of soil aggregation. In a study by Hermawan (1995) on a similar soil, the highest MWD and 2-6 mm aggregate fraction were observed under annual ryegrass cover crop that provided 8.6 t ha^{-1} of dry biomass. In addition to the high above-ground biomass, annual ryegrass has high root density in the top 15 cm of soil, which also enhances aggregate stability (Stone and Buttery, 1989). It is not very likely that winter wheat and especially spring barley, seeded as cover crops in our study, had root densities high enough to enhance aggregate stability over just three years.

Table 5.8. Analysis of variance (F-ratios) for the effects of tillage, cover crop species and date of sampling on MWD, size-distribution of water-stable aggregates, and aggregate water content during 1995 growing season.

Source	df	MWD	Water-stable aggregates (mm)				Water
		(mm)	2-6[2]	1-2[2]	0.25-1	<0.25[2]	(kg kg^{-1})
Till, T	1	0.41	0.70	0.01	5.77^{+}	0.04	2.41
C. crop, C	1	1.19	2.48	6.67^{+}	0.02	0.06	0.35
T × C	1	0.98	0.77	3.15	8.96^{+}	1.64	0.39
Date, D	3	22.50**	18.94**	10.59**	48.90**	24.64**	55.87**
T × D	3	2.58^{+}	2.81^{+}	2.05	4.69**	1.31	4.60**
C × D	3	1.18	1.11	1.22	1.18	1.36	11.68**
T × C × D	3	1.83	2.22	1.70	11.16**	0.71	0.91

+, *, ** Significant at the 0.10, 0.05 and 0.01 probability levels, respectively. [2] Log_{10} transformation applied prior to analysis.

The effect of the date of sampling was significant in both years indicating that temporal variation in aggregate stability was important (Table 5.7). The temporal variation of MWD was larger in 1994 than in 1995 (Figure 5.9a). Gravimetric aggregate water contents of the 0-5 cm soil layer showed the opposite patterns to MWD except for the last sampling date (Figure 5.9b). A significant reduction in structural stability corresponds to higher soil water content, which usually exists in the field from late fall to early spring in the western Fraser Valley. During this period soils are very prone to structural breakdown when mechanically disturbed, especially when left unprotected. Similar patterns of seasonal variation in aggregate stability were also reported by Perfect et al. (1990), Reinert et al. (1991), Chan et al. (1994), and Hermawan (1995).

The temporal variation in aggregate stability was attributed to the variation of soil water content at sampling, since water content explained 59% of the variation in MWD values (Figure 5.10). This is in an agreement with the work by Angers et al. (1992) and Hermawan and Bomke (1996) that most temporal variation in aggregate stability is caused by soil water content at sampling.

The magnitude of temporal variation varied with aggregate size class both in 1994 and 1995. Temporal variation was highest in the 2-6 mm and the <0.25 mm fractions (which varied inversely to the 2-6 mm size fraction). For example, the 2-6 mm size fraction accounted for 80% of the aggregates (by weight) in August 1994 and 26% of the aggregates in October 1994 (Figure 5.11). A similar situation was observed in 1995 when the 2-6 mm size fraction varied from 62% in August to 39% in October under NST and from 58% in August to 38% in October under ST (Figure 5.12). It seems that the 2-6 mm aggregates in this soil are breaking down directly into the <0.25 mm fraction. A similar observation was made by Hermawan (1995) on a badly degraded Gleysol at Westham Island, BC.

Temporal fluctuations in aggregate stability parameters were quite large and exceeded the differences caused by tillage and cover crop species. The short duration of this study accompanied with high silt and clay content in this soil, and relatively small difference in residue biomass production between spring barley and winter wheat resulted in lack of differences in aggregate stability between tillage systems and two cover crops. Soil water content variation during the growing season was strongly correlated to observed temporal fluctuations in aggregate stability.

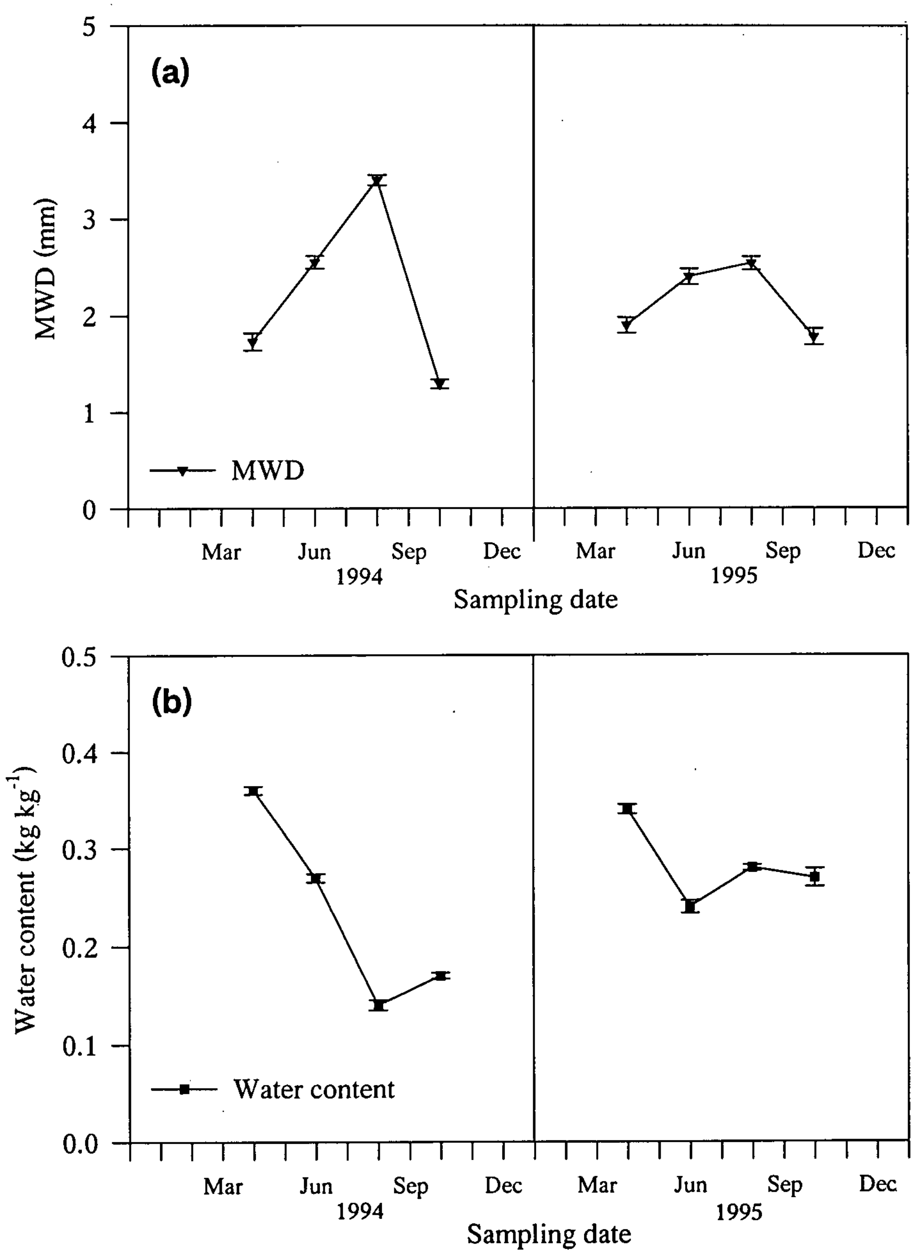


Figure 5.9. Temporal variation of mean weight diameter-MWD (a) and aggregate water content (b). Error bars represent standard error of the mean (n=32).

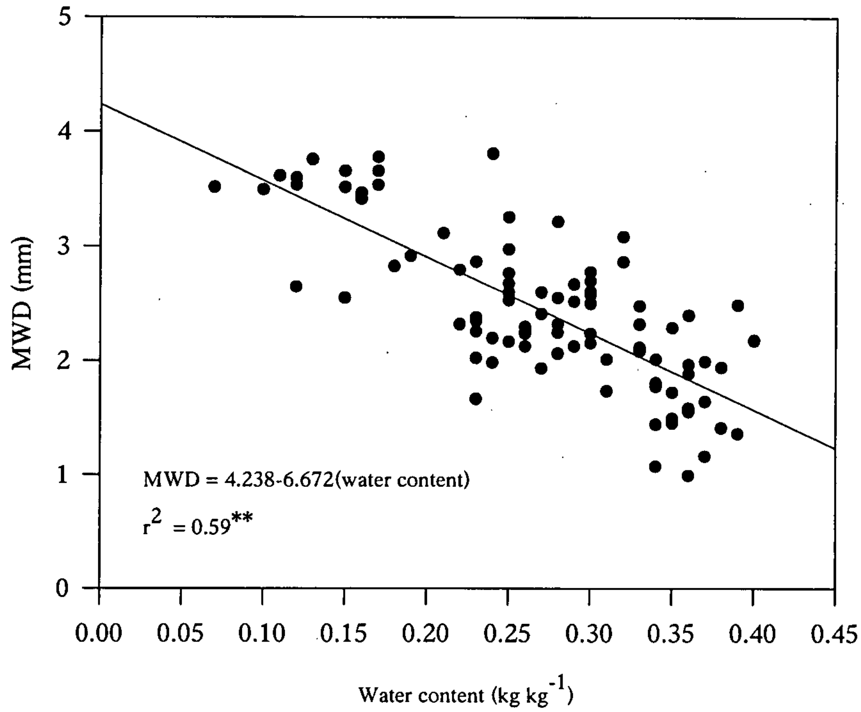


Figure 5.10. Relationship between mean weight diameter-MWD and aggregate water content. ** significant at 0.01 probability level.

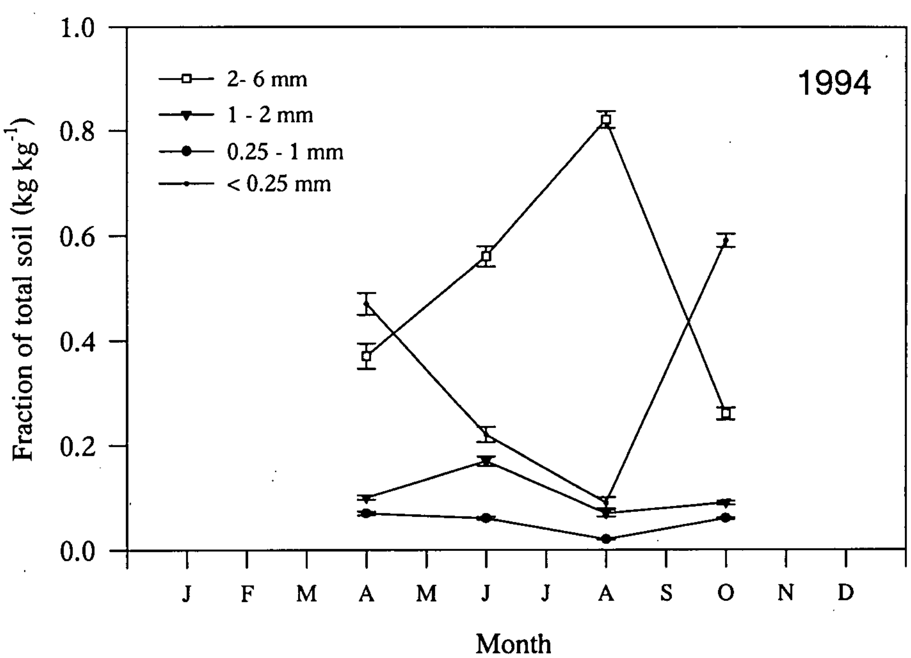


Figure 5.11. Temporal variation of aggregate size fractions during 1994. Error bars represent standard error of the mean (n=32).

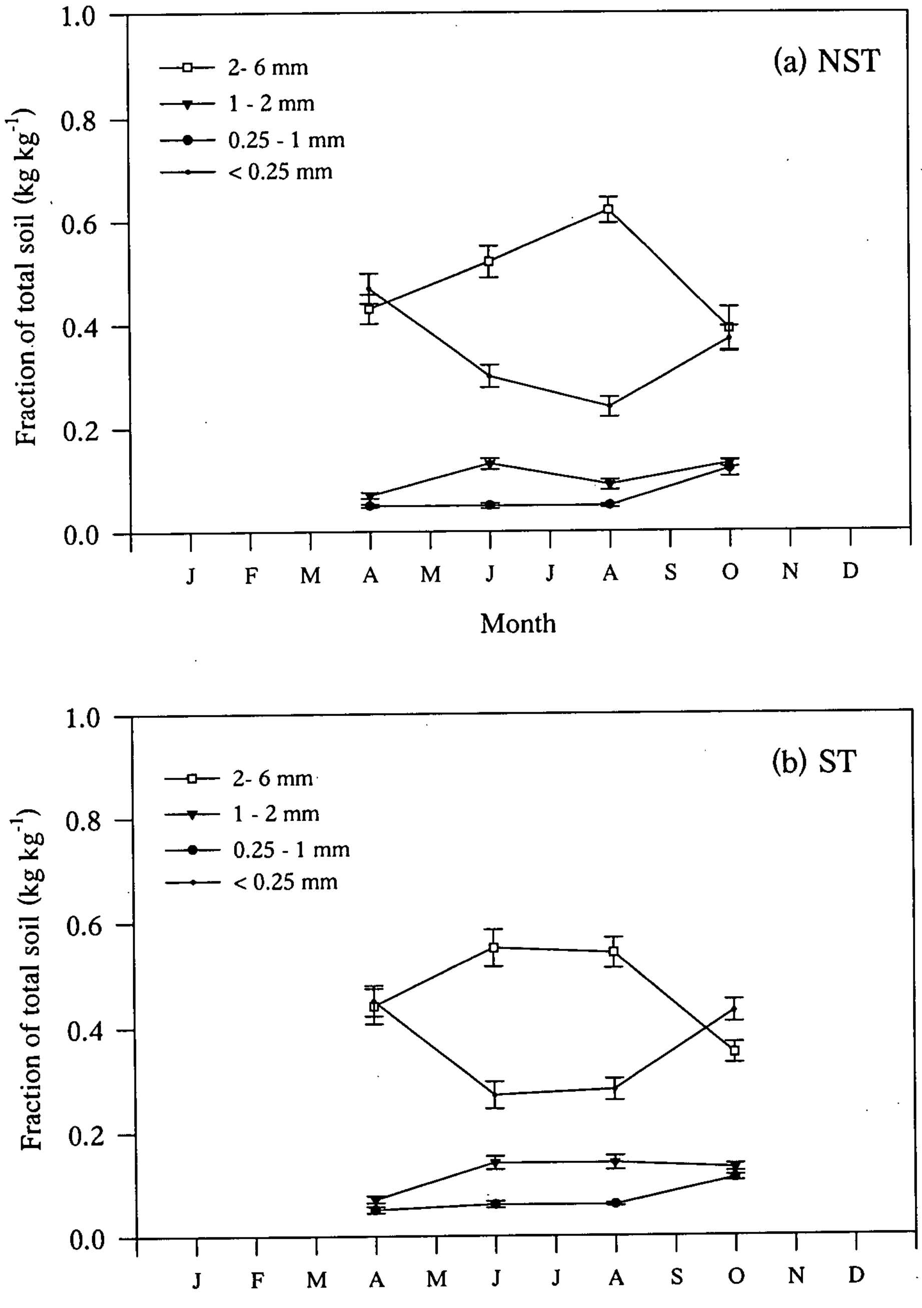


Figure 5.12. Temporal variation of aggregate size fractions under no-spring tillage-NST (a) and spring tillage-ST (b) during 1995. Error bars represent standard error of the mean (n=16).

5.4. Soil Water Content

During 1993, neither the type of cover crop, nor tillage had an effect on soil water content at 10 and 40 cm depths (Table 5.9). On most dates of measurement in 1993, soil water content was lower under NST than under ST at the 20 cm depth (Figure 5.13). Differences in soil water content at 20 cm depth become more important during the last month of the 1993 growing season.

During the 1994 growing season neither the type of cover crop, nor tillage had a significant effect on soil water content (Table 5.10 and Table 5.11), with an exception of two last dates of measurement when soil water content at 40 cm depth in spring barley plots was 0.45 m^3 m^{-3} and 0.35 m^3 m^{-3} in winter wheat plots.

During mid August of 1995 soil water contents at 10 cm depth were lower under NST than under ST (Table 5.12). The effect of cover crop species on soil water content at 15 cm depth was evident only on May 26 and June 1, 1995 when winter wheat had higher soil water content than spring barley (Table 5.12). Significantly drier soil was observed under NST than under ST at 15 cm depth on June 1 and June 8, 1995 and during the last month of 1995 growing season. The effect of tillage system was most obvious at 20 cm depth, since on most dates of measurement in 1995 NST was drier than ST (Table 5.13 and Figure 5.14b). On May 26 and June 8, 1995 soil water contents were lower under spring barley than under winter wheat. Significant difference in soil water contents between tillage systems at 40 cm depth was observed on June 1, 1995, when NST was drier than ST (Table 5.13). At this date soil water content was also lower under spring barley than under winter wheat.

Several studies (Blevins et al., 1971; Pidgeon and Soane, 1977; Johnson et al., 1984) have reported greater soil water contents under conservation tillage relative to conventional tillage systems. The effect of conservation tillage on soil water content depends on the degree of reduction in tillage, the length of time that the tillage system is practiced and amount and type of residues left on the soil surface. In the studies cited above, zero-till had no cultivation, while in conventional tillage systems fall, moldboard plowing was followed by two discings (Blevins et al., 1971, and Johnson et al., 1984) or by two harrowings before planting and light harrowing followed with rolling after planting (Pidgeon and Soane, 1977). These tillage systems were quite different from tillage systems in this study. In addition, winter cover crops in this study were grown on both tillage systems, while in the studies cited above soil was either left bare or covered with stalks over the winter.

Measurements of soil water content during three years showed either no difference between the two tillage systems or even lower soil water contents at 20 cm depth under NST than under ST. There are several possible explanations for this. First, pronounced soil crack formation is common on the Westham and the Crescent Gleysols in the western Fraser Valley due to presence of montmorillonite and vermiculite clay minerals (Luttmerding, 1981b). Soil crack formation could result in rapid capillary rise and higher water losses by evaporation, which was also noticed in studies by Darwent and Bailey (1981), Hammel et al. (1981), and Carefoot et al. (1990). In our study cracks in the soil without spring tillage were left undisturbed over the warmest part of the year, allowing for greater water losses by evaporation than in the soil tilled in spring. This could reduce soil water content in NST in comparison to ST. Second, silty clay loam Gleysols in the western Fraser Valley are susceptible to surface crusting (Abbaspour, 1988) due to high silt content, relatively low soil organic matter, and unstable soil structure. Crust formation might reduce the infiltration of rainfall water into the soil. Somewhat drier soil conditions observed with NST than with ST could be a result of crust presence in NST treatment, especially since relatively high PR was observed after spring tillage in the top few centimeters of the soil with NST (Figure 5.6; Figure 5.7, and Figure 5.8).

Effects of cover crop type on soil water content were rarely observed. On few occasions when cover crop type had a significant effect on soil water content spring barley treatment was drier than winter wheat treatment.

Table 5.9. Analysis of variance (F-ratios) for the effects of tillage and cover crop species on soil water content ($m^3 m^{-3}$) at three depths during 1993 growing season.

Date of sampling	Depth of measurement (cm) 10 Block	Till	C.crop	T × C	20 Block	Till	C.crop	T × C	40 Block	Till	C.crop	T × C
Jun 10	0.07	0.75	0.35	0.72	0.82	9.65^{+}	6.70^{+}	4.29	28.75^{*}	0.30	1.30	5.79^{+}
Jun 17	0.00	0.44	0.36	0.69	0.37	10.04^{*}	2.25	6.26^{+}	19.31^{*1}	1.33^{1}	0.00^{1}	4.40^{1}
Jun 24	0.19	0.19	0.15	1.25	0.82	3.29	0.18	2.36	5.94^{+1}	0.00^{1}	0.22^{1}	2.54^{1}
Jun 30	0.03	0.35	0.08	1.34	0.18	14.99^{*}	9.19^{+}	9.19^{+}	9.64^{+}	0.07	0.15	2.50
Jul 08	0.77	0.64	0.02	1.79	1.11	4.02	0.00	2.62	5.63^{+1}	0.22^{1}	0.23^{1}	2.02^{1}
Jul 15	0.33	0.20	0.18	1.24	0.38	7.63^{+}	0.91	2.94	4.55	0.05	0.22	3.18
Jul 23	0.40	0.29	0.13	0.53	0.95^{2}	5.52^{+2}	0.05^{2}	3.00^{2}	4.74^{1}	0.41^{1}	0.16^{1}	2.24^{1}
Jul 30	0.25	0.47	0.47	0.88	1.36	13.05^{*}	1.12	1.63	2.39	0.00	0.03	1.74
Aug 05	1.20	0.87	0.12	0.54	1.41	3.24	0.00	1.22	2.98	0.25	0.39	1.30
Aug 11	1.34	1.24	0.08	0.55	2.24	5.38	0.00	1.52	1.30	0.52	0.15	0.94
Aug 19	1.57	1.38	0.16	0.51	3.17	5.40	0.01	1.74	0.96	0.93	0.13	0.85
Aug 26	2.00	1.84	0.18	1.12	3.45	6.89^{+}	0.05	2.04	0.65	0.83	0.05	1.17
Sep 09	4.88	3.75	0.72	1.66	5.93^{+}	10.58^{*}	0.30	2.10	0.09	1.00	0.00	1.41
Sep14	4.59	3.73	0.46	0.97	6.47^{+2}	12.21^{*2}	0.54^{2}	4.14^{2}	0.08	0.83	0.01	1.12
Sep 16	4.98^{2}	4.92^{2}	0.83^{2}	2.15^{2}	4.85	9.64^{+}	0.28	2.20	0.03	0.83	0.01	1.17

+, *, ** Significant at the 0.10, 0.05 and 0.01 probability levels, respectively. [1] Square root transformation applied prior to analysis. [2] Log_{10} transformation applied prior to analysis.

Table 5.10. Analysis of variance (F-ratios) for the effects of tillage and cover crop species on soil water content ($m^3 m^{-3}$) at 10 and 15 cm depths during 1994 growing season.

Depth of sampling	Depth of measurement (cm) 10				15			
	Block	Till	Cover crop	T × C	Block	Till	Cover crop	T × C
May 27	0.05	1.11	0.01	0.02	0.02	2.53	0.23	0.05
Jun 01	0.00	1.48	0.04	0.01	0.01	2.46	0.13	0.00
Jun 09	0.00	1.55	0.06	0.06	0.00	2.62	0.36	0.04
Jun 16	0.11	1.33	0.34	0.03	0.01	2.41	0.61	0.00
Jun 24	0.13	0.38	0.01	0.09	0.13^1	1.04^1	0.16^1	0.21^1
Jun 29	0.29	1.11	0.00	0.01	0.13	1.16	0.13	0.09
Jul 07	0.19	0.66	0.00	0.00	0.20	1.31	0.03	0.17
Jul 13	0.60^1	1.71^1	0.01^1	0.01^1	0.34	2.43	0.00	0.09
Jul 21	0.62	1.60	0.08	0.00	0.55^2	1.93^2	0.05^2	0.01^2
Jul 25	0.82	1.83	0.05	0.00	0.73^2	2.25^2	0.04^2	0.00^2
Aug 05	0.85^1	1.91^1	0.15^1	0.07^1	0.66^2	2.26^2	0.16^2	0.00^2
Aug 09	0.91	2.05	0.27	0.00	0.88^2	1.91^2	0.22^2	0.00^2
Aug 17	0.87	1.53	0.39	0.05	0.65^1	1.78^1	0.30^1	0.02^1
Aug 23	1.00	1.68	0.32	0.44	1.00^1	1.57^1	0.53^1	0.10^1
Sep 06	1.00^1	0.72^1	0.45^1	0.64^1	1.00	0.97	0.62	0.20

+, *, ** Significant at the 0.10, 0.05 and 0.01 probability levels, respectively. [1] Square root transformation applied prior to analysis. [2] Log_{10} transformation applied prior to analysis.

Table 5.11. Analysis of variance (F-ratios) for the effects of tillage and cover crop species on soil water content ($m^3 m^{-3}$) at 20 and 40 cm depths during 1994 growing season.

Depth of sampling	Depth of measurement (cm)							
	20				40			
	Block	Till	Cover crop	T × C	Block	Till	Cover crop	T × C
May 27	0.24	5.85^{+}	0.10	0.39	4.69	7.82^{+}	5.59^{+}	0.97
Jun 01	0.13	6.42^{+}	0.05	0.18	2.68	2.90	2.26	0.40
Jun 09	0.02	3.97	0.06	0.21	1.53	3.42	1.75	0.51
Jun 16	0.21^{2}	2.39^{2}	0.14^{2}	0.07^{2}	1.41	1.28	0.50	0.13
Jun 24	0.24	1.76	0.09	0.40	1.79	2.07	1.02	0.01
Jun 29	0.06	5.22	0.00	0.35	0.71	3.69	1.73	0.71
Jul 07	0.00^{2}	2.15^{2}	0.03^{2}	0.05^{2}	1.70	2.79	1.33	0.16
Jul 13	0.10^{2}	2.86^{2}	0.07^{2}	0.06^{2}	1.42	2.55	2.41	0.33
Jul 21	0.29	3.08	0.16	0.01	0.83	1.35	3.04	0.20
Jul 25	0.37^{1}	4.70^{1}	0.24^{1}	0.04^{1}	0.40	0.36	1.88	0.00
Aug 05	0.17	3.06	0.52	0.00	0.64^{1}	0.20^{1}	2.39^{1}	0.01^{1}
Aug 09	0.39	3.24	0.39	0.00	0.59^{1}	0.29^{1}	2.42^{1}	0.00^{1}
Aug 17	0.07	2.27	1.14	0.00	0.65^{2}	0.09^{2}	2.50^{2}	0.01^{2}
Aug 23	1.00	1.32	4.41	0.00	1.00	7.14^{+}	86.01^{**}	11.45^{*}
Sep 06	1.00	1.21	2.94	0.06	1.00	4.74	47.10^{**}	3.42

+, *, ** Significant at the 0.10, 0.05 and 0.01 probability levels, respectively. [1] Square root transformation applied prior to analysis. [2] Log_{10} transformation applied prior to analysis.

Table 5.12. Analysis of variance (F-ratios) for the effects of tillage and cover crop species on soil water content ($m^3\ m^{-3}$) at 10 and 15 cm depths during 1995 growing season.

Depth	Depth of measurement (cm)							
of	10				15			
sampling	Block	Till	Cover crop	T × C	Block	Till	Cover crop	T × C
May 26	0.38	1.18	1.74	0.29	2.48^{2}	5.08^{2}	5.85^{+2}	0.82^{2}
Jun 01	3.77	2.47	4.60	0.85	5.68^{+2}	8.11^{+2}	6.64^{+2}	0.92^{2}
Jun 08	0.24^{2}	0.72^{2}	0.36^{2}	0.27^{2}	2.42	6.20^{+}	0.69	1.42
Jun 15	0.28	1.58	0.13	12.22^{*}	0.22	4.24	3.33	3.12
Jun 22	3.33	0.51	0.04	10.62^{*}	1.04	3.42	3.66	2.75
Jun 29	2.34	2.91	0.12	6.66^{+}	1.94^{1}	4.01^{1}	0.54^{1}	2.21^{1}
Jul 05	1.04	1.78	0.18	2.01	1.83	4.03	0.86	2.51
Jul 14	0.56^{1}	3.79^{1}	0.11^{1}	3.93^{1}	0.67^{1}	2.96^{1}	0.18^{1}	2.21^{1}
Jul 18	0.84	2.53	0.14	4.30	3.89	5.35	0.57	4.91
Aug 03	2.13	2.02	0.02	5.79^{+}	2.15^{2}	3.61^{2}	0.04^{2}	3.44^{2}
Aug 11	1.00	1.00	1.00	1.00	0.03	3.23	0.06	3.09
Aug 17	0.13^{2}	8.50^{+2}	0.34^{2}	4.67^{2}	0.01	6.92^{+}	0.12	2.68
Aug 24	0.47	8.04^{+}	1.16	4.62	2.00	5.81^{+}	0.01	2.31
Aug 31	2.99	3.26	0.17	1.73	6.31^{+2}	10.74^{*2}	0.13^{2}	4.96^{2}
Sep 06	4.25	2.36	1.47	2.62	3.20	2.62	0.01	2.49

+, *, ** Significant at the 0.10, 0.05 and 0.01 probability levels, respectively. [1] Square root transformation applied prior to analysis. [2] Log_{10} transformation applied prior to analysis.

Table 5.13. Analysis of variance (F-ratios) for the effects of tillage and cover crop species on soil water content ($m^3\ m^{-3}$) at 20 and 40 cm depths during 1995 growing season.

Depth of sampling	Depth of measurement (cm)							
	20				40			
	Block	Till	Cover crop	T × C	Block	Till	Cover crop	T × C
May 26	0.73	30.06^{*}	8.79^{+}	1.39	6.63^{+}	0.63	0.04	0.37
Jun 01	2.60	19.15^{*}	3.52	0.00	36.98^{**}	22.18^{*}	6.32^{+}	5.02
Jun 08	3.00	66.67^{**}	12.00^{*}	1.53	157.38^{**}	61.48^{**}	15.37^{*}	17.93^{*}
Jun 15	0.03^{2}	2.25^{2}	2.40^{2}	0.32^{2}	5.43	0.16	1.79	0.43
Jun 22	0.04	11.88^{*}	2.04	1.16	2.03	0.28	2.51	0.63
Jun 29	2.34	14.87^{*}	1.81	1.21	13.81^{*}	4.16	2.54	0.00
Jul 05	1.24	7.48^{+}	0.74	1.03	12.07^{*2}	5.17^{2}	4.90^{2}	0.42^{2}
Jul 14	1.21	5.69^{+}	0.47	1.21	7.55^{+}	2.12	2.84	0.19
Jul 18	2.12^{1}	11.14^{*1}	0.13^{1}	1.86^{1}	9.68^{+}	3.95	5.54^{+}	0.55
Aug 03	0.65^{2}	4.41^{2}	0.02^{2}	0.31^{2}	6.68^{+}	0.53	0.92	0.00
Aug 11	0.06	5.92^{+}	1.26	1.65	5.07^{1}	1.03^{1}	0.07^{1}	0.05^{1}
Aug 17	0.03	3.54	0.31	0.37	7.99^{+}	0.02	0.02	0.01
Aug 24	0.74	5.54^{+}	0.48	0.41	8.72^{+}	0.03	1.32	0.01
Aug 31	1.76^{1}	3.92^{1}	0.22^{1}	0.19^{1}	10.96^{*2}	4.39^{2}	5.08^{2}	0.16^{2}
Sep 06	1.43	5.13	0.07	0.47	7.76^{+}	3.94	5.42	0.53

+, *, ** Significant at the 0.10, 0.05 and 0.01 probability levels, respectively. [1] Square root transformation applied prior to analysis. [2] Log_{10} transformation applied prior to analysis.

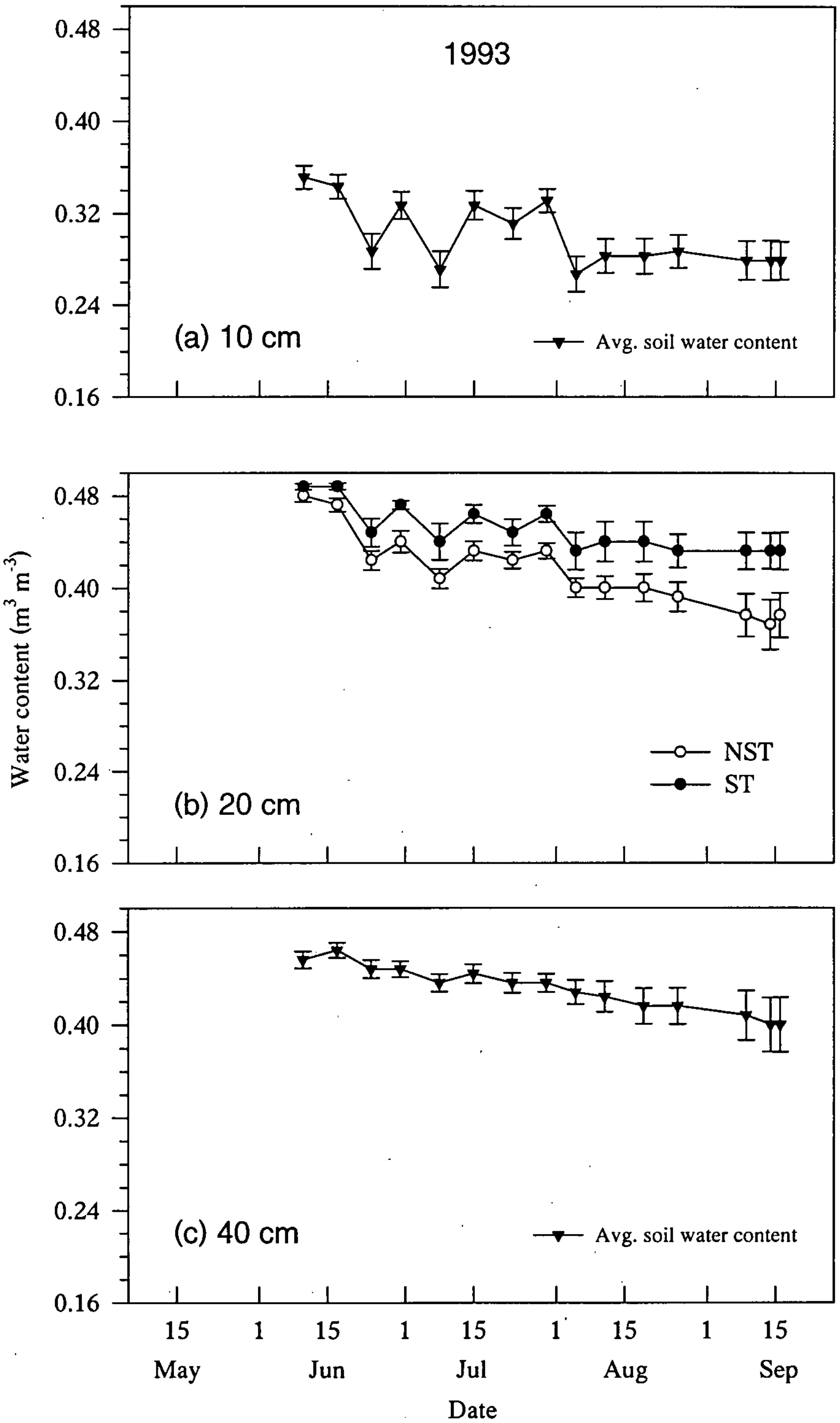


Figure 5.13. Average soil water contents at 10 cm (a), 20 cm (b), and 40 cm (c) depths during 1993 growing season. Error bars represent standard error of the mean.

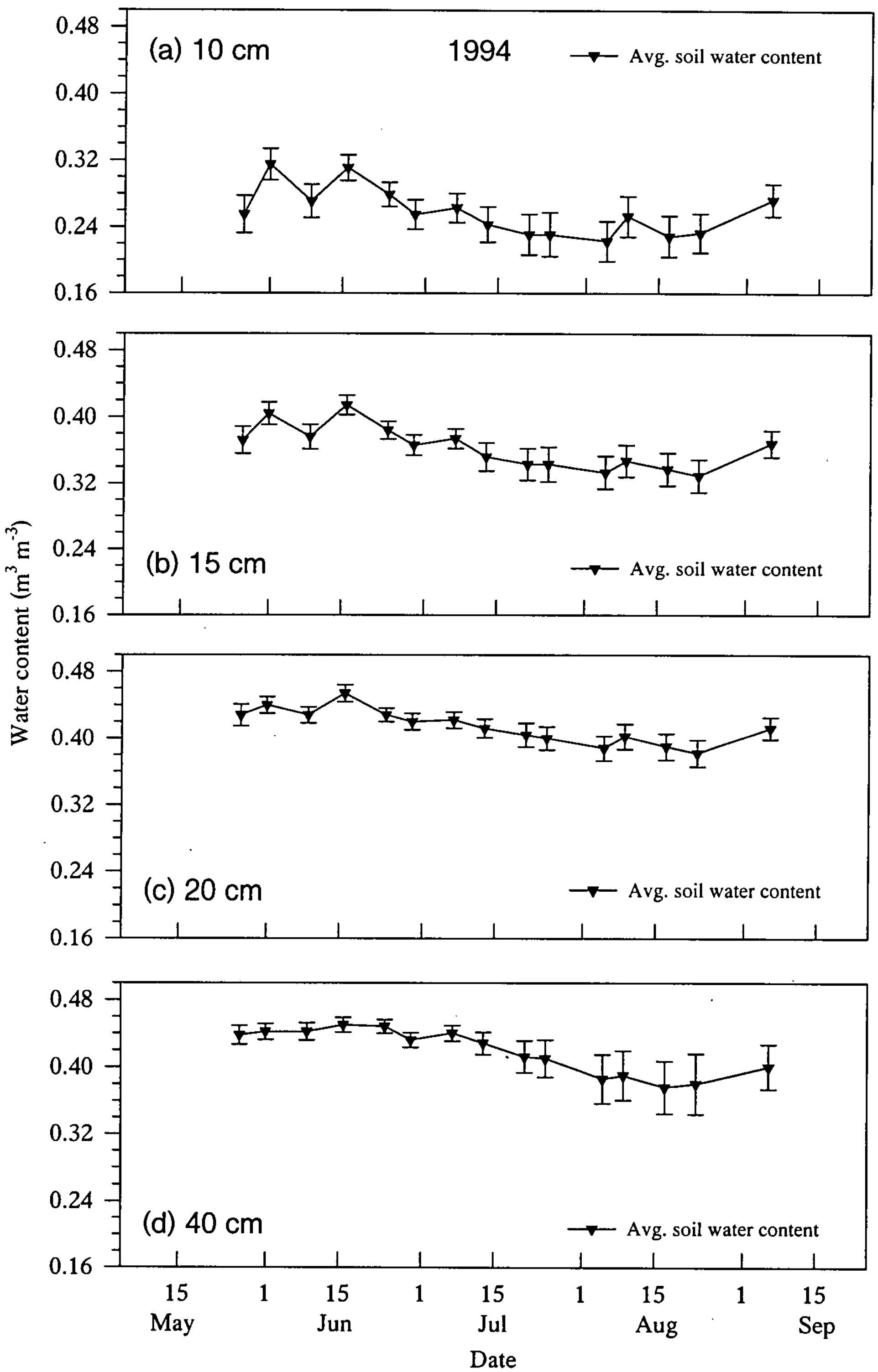


Figure 5.14. Average soil water contents at 10 cm (a), 15 cm (b), 20 cm (c), and 40 cm (d) depths during 1994 growing season. Error bars represent standard error of the mean.

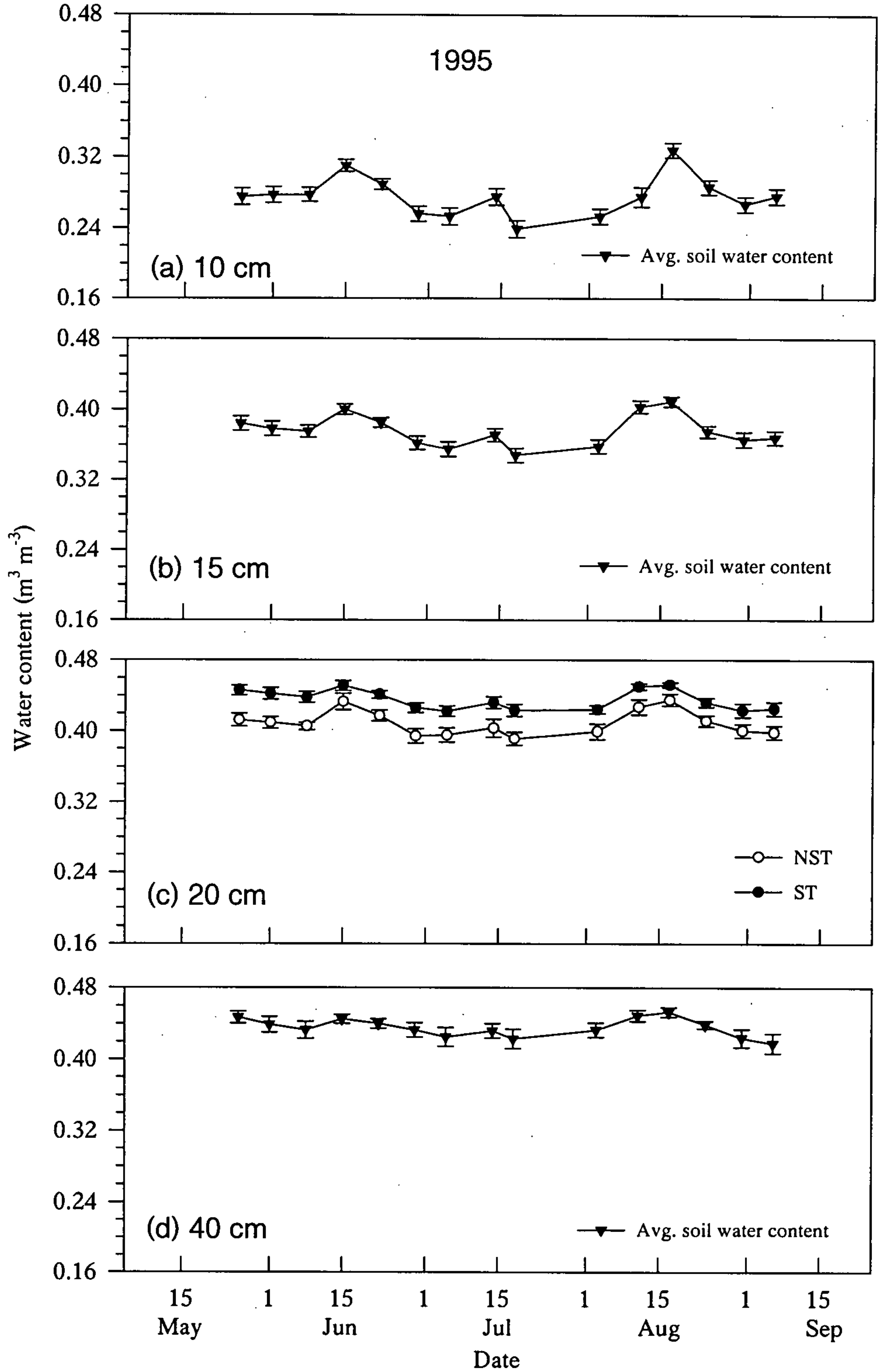


Figure 5.15. Average soil water contents at 10 cm (a), 15 cm (b), 20 cm (c), and 40 cm (d) depths during 1995 growing season. Error bars represent standard error of the mean.

5.5. Soil Temperature

During the three years, differences in daily maximum soil temperatures between two tillage systems were larger than the differences in daily minimum soil temperatures (Figures A.1-A.6). This is similar to observations made by van Wijk et al. (1959), Unger (1978), and Fortin and Pierce (1990). As expected, daily fluctuations in soil temperature were considerably lower at the 20 cm depth than at the 3 cm depth (Figures 5.16-5.21).

When daily maximum soil temperatures were measured before spring tillage in 1994 and 1995, they were usually lower under NST than under ST at the 3 cm depth (Figures A.1a-A.6a). The only exception was in 1995 with winter wheat cover crop when daily maximum soil temperatures were higher in NST than in ST by about 0.5 to 1°C for approximately two weeks before spring discing (Figure A. 6a).

During the three weeks following corn planting in 1994 and 1995, average daily soil temperatures, at both depths, were lower in NST than in ST treatment (Table 5.14). Although, there was a decrease in average daily soil temperatures under NST, they were well above 8-10°C, which is considered to be a minimum temperature range for corn emergence and early growth (Gardner et al., 1985). Spring barley and winter wheat cover crops, seeded in mid-September (which represents late seeding in this region) produced on average 1.3 t ha^{-1} and 3.7 t ha^{-1} of dry biomass, respectively (Table 4.3). These amounts of cover crop residues lowered daily maximum soil temperatures in NST relative to ST, but did not create problems for sweet corn growth. However, it is possible that early seeded cover crops (seeding in mid August), which usually produce 5-7 t ha^{-1} of dry matter in the western

Fraser Valley (Bomke et al., 1996), may cause a decrease in soil temperatures in early spring sufficient to delay emergence of the sweet corn.

Table 5.14. Averages of daily soil temperatures (°C) during three weeks following corn planting.

Depth	1994				1995			
(cm)	Spring barley		Winter wheat		Spring barley		Winter wheat	
	NST	ST	NST	ST	NST	ST	NST	ST
3	17.1	17.5	16.8	17.2	18.9	19.3	18.5	19.5
20	15.4	15.9	15.2	15.6	17.0	17.3	16.9	17.4

The decrease in average daily soil temperatures caused by NST in comparison to ST ranged from 0.4 to 1.0°C at 3 cm depth and from 0.3 to 0.5°C at 20 cm depth. The lower daily average soil temperature with NST in this study is less than the soil temperature decrease with conservation tillage systems reported in other studies (Johnson and Lowery, 1985; Griffith et al., 1988; Cox et al., 1990). The soil temperature response is primarily regulated by the energy available at the soil surface, which in turn is controlled by the degree of residue cover and the reflective and thermal characteristics of the residue and soil (Van Wijk et al., 1959; Van Doren and Allmaras, 1978; Gupta et al., 1983). Soil surface coverage of 40 and 36% with spring barley residues in NST after corn planting in 1994 and 1995, respectively (Table 4.4) resulted in a decrease of 0.4°C in daily average soil temperatures at 3 cm depth. On the other hand, 48 and 78% soil surface coverage with winter wheat residues in NST in 1994 and 1995 resulted in a decrease of 0.4 and 1.0°C in daily average soil temperatures at 3 cm depth.

Three to four weeks following corn planting, NST daily maximum soil temperatures, especially at 3 cm depth, started to rise and remained higher than ST daily maximum soil temperatures until the very end of the growing season (Figures 5.16a-5.21a). This was observed in all three years.

In 1994 and 1995 corn growth was reduced on NST plots due to the slug damage, which resulted in incomplete canopy closure and therefore higher daily maximum soil temperatures in NST compared to ST. In addition, lower soil water contents were observed in NST at 15 cm depth during the last month and at 20 cm depth during most of the 1995 growing season (Figure 5.15). This could also contribute to higher daily maximum soil temperatures in NST than in ST during later part of the 1995 growing season.

In 1993 there was no reduction of corn growth on NST treatment, so higher daily maximum soil temperatures in NST than in ST during the later part of the 1993 season cannot be contributed to differences in canopy closure and soil shading. In 1993 soil temperature measurements were obtained with only one thermocouple per depth. Under winter wheat cover crop at 3 cm depth NST constantly had higher daily maximum soil temperatures than ST (Figure A. 4a), which could be an indicator of improper thermocouple installation. Under spring barley cover crop NST daily maximum soil temperatures at 3 cm depth were on average 1.1°C higher than ST temperatures during last two months of the 1993 growing season (Figure A. 1a). The possible explanation for higher daily maximum soil temperatures in NST than in ST under spring barley during the last two months of the 1993 season could be in lower water contents observed in NST than in ST at 20 cm depth. This is somewhat confusing since there were no differences in soil water contents between two tillage systems at 10 cm depth in 1993.

Soil temperatures were generally lower under NST than under ST, either before spring discing and corn planting or during three to four weeks after corn planting. Despite the soil temperature reduction in NST, average daily soil temperatures in this tillage treatment were still above the lowest temperature required for corn emergence and early growth. Due to poor corn growth and lack of canopy closure on NST in 1994 and 1995, daily maximum soil temperatures were higher in NST than in ST from three to four weeks after planting to harvest.

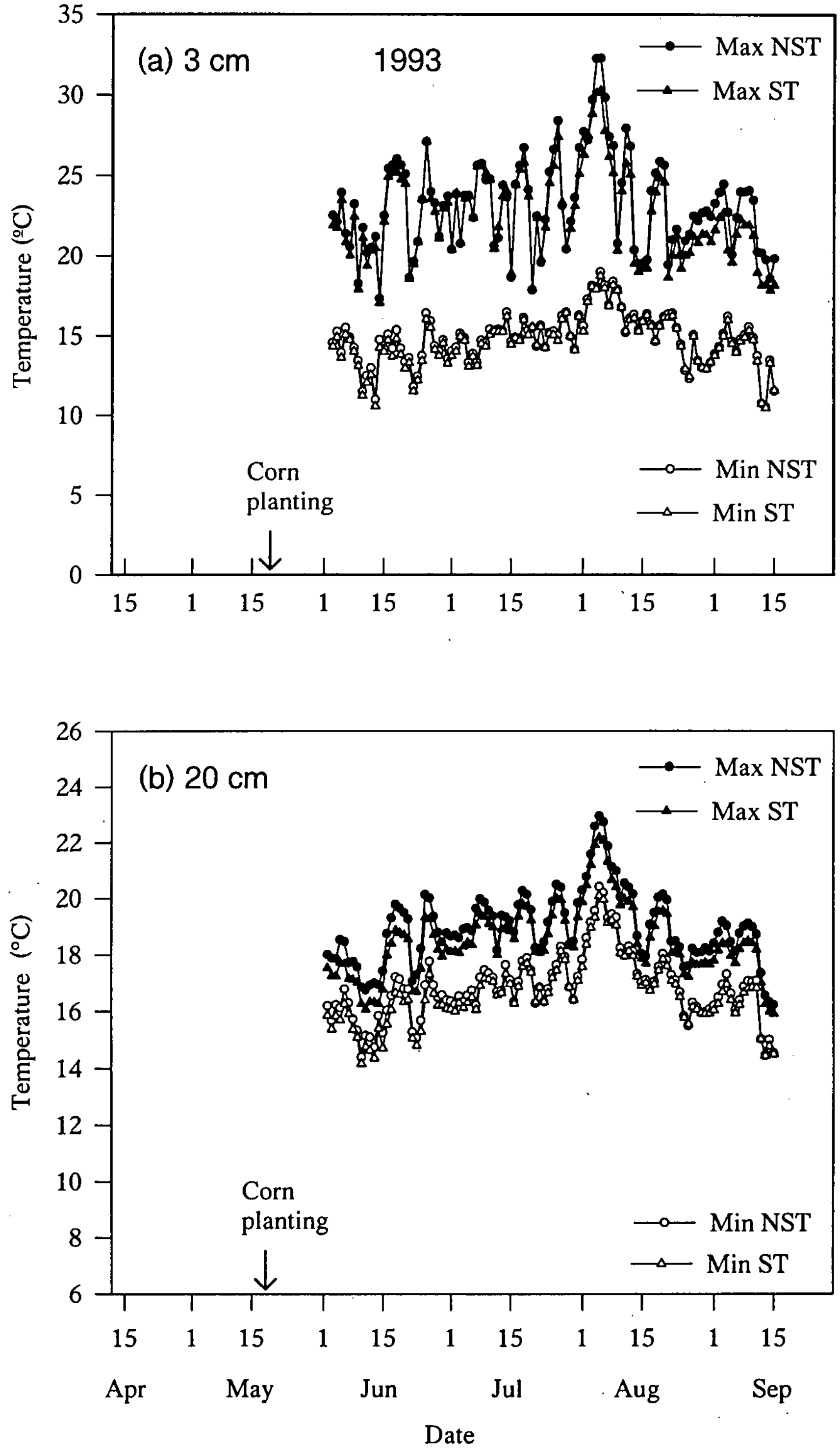


Figure 5.16. Daily maximum and minimum soil temperatures at 3 cm (a) and 20 cm (b) depths during 1993 growing season under spring barley.

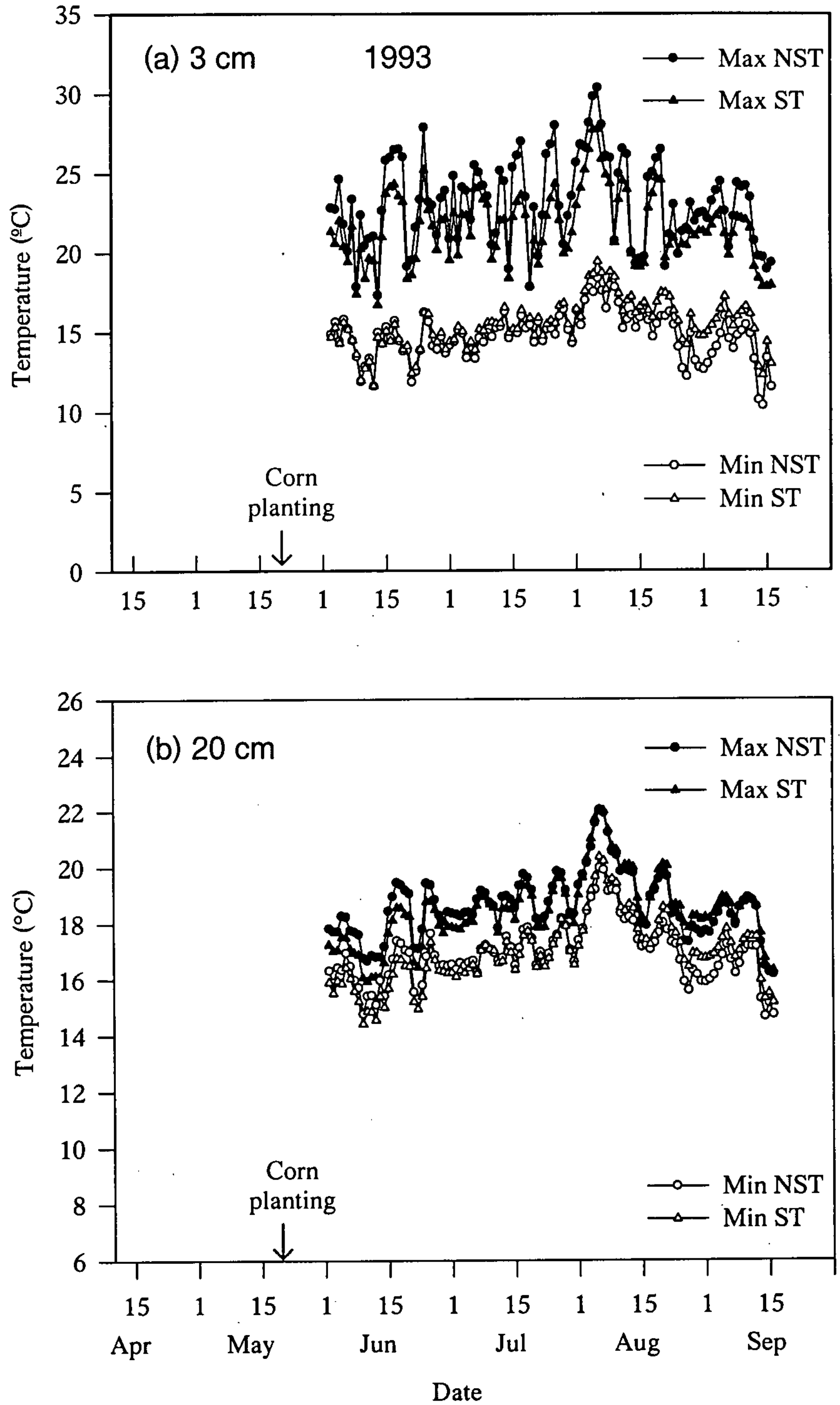


Figure 5.17. Daily maximum and minimum soil temperatures at 3 cm (a) and 20 cm (b) depths during 1993 growing season under winter wheat.

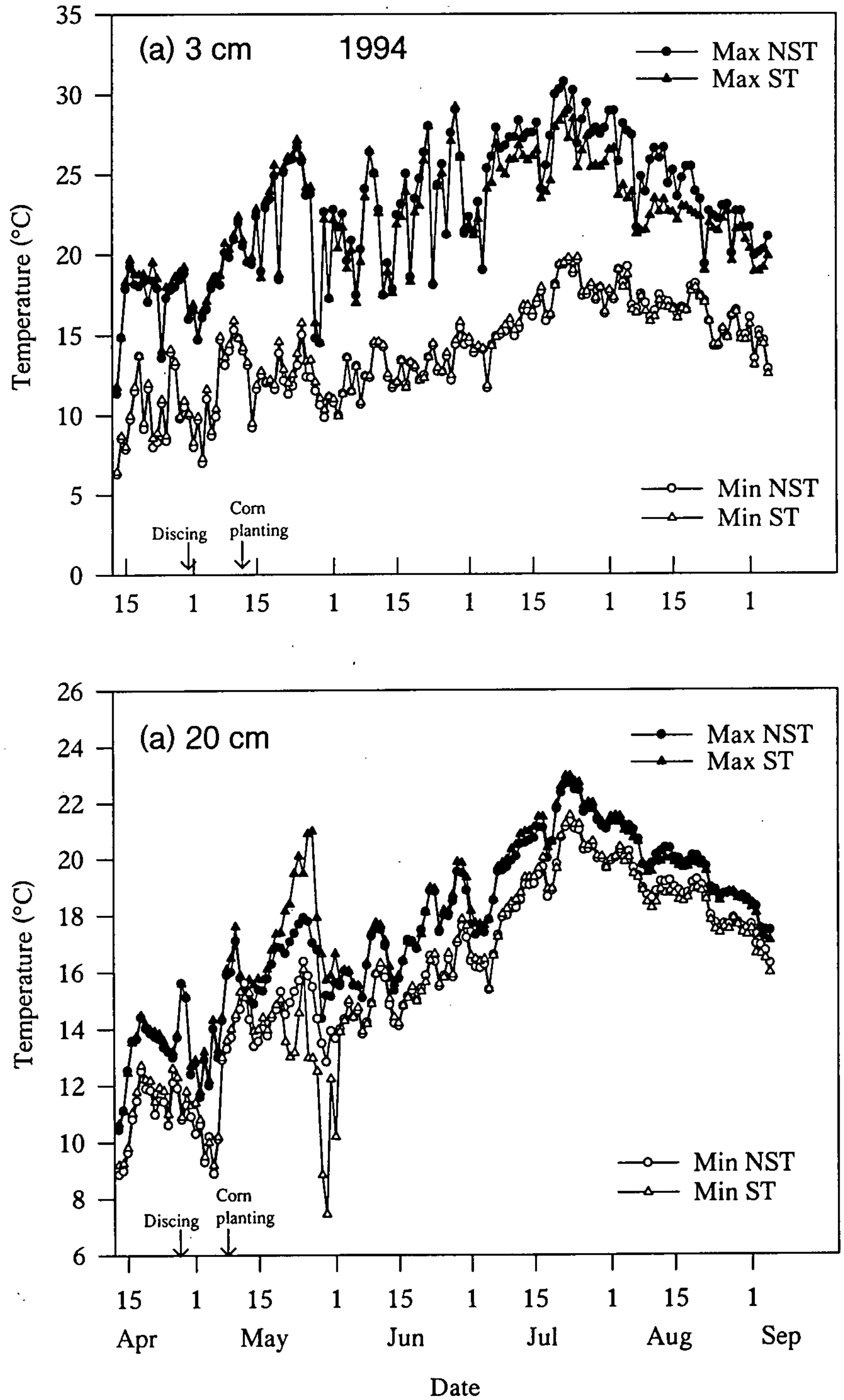


Figure 5.18. Daily maximum and minimum soil temperatures at 3 cm (a) and 20 cm (b) depths during 1994 growing season under spring barley.

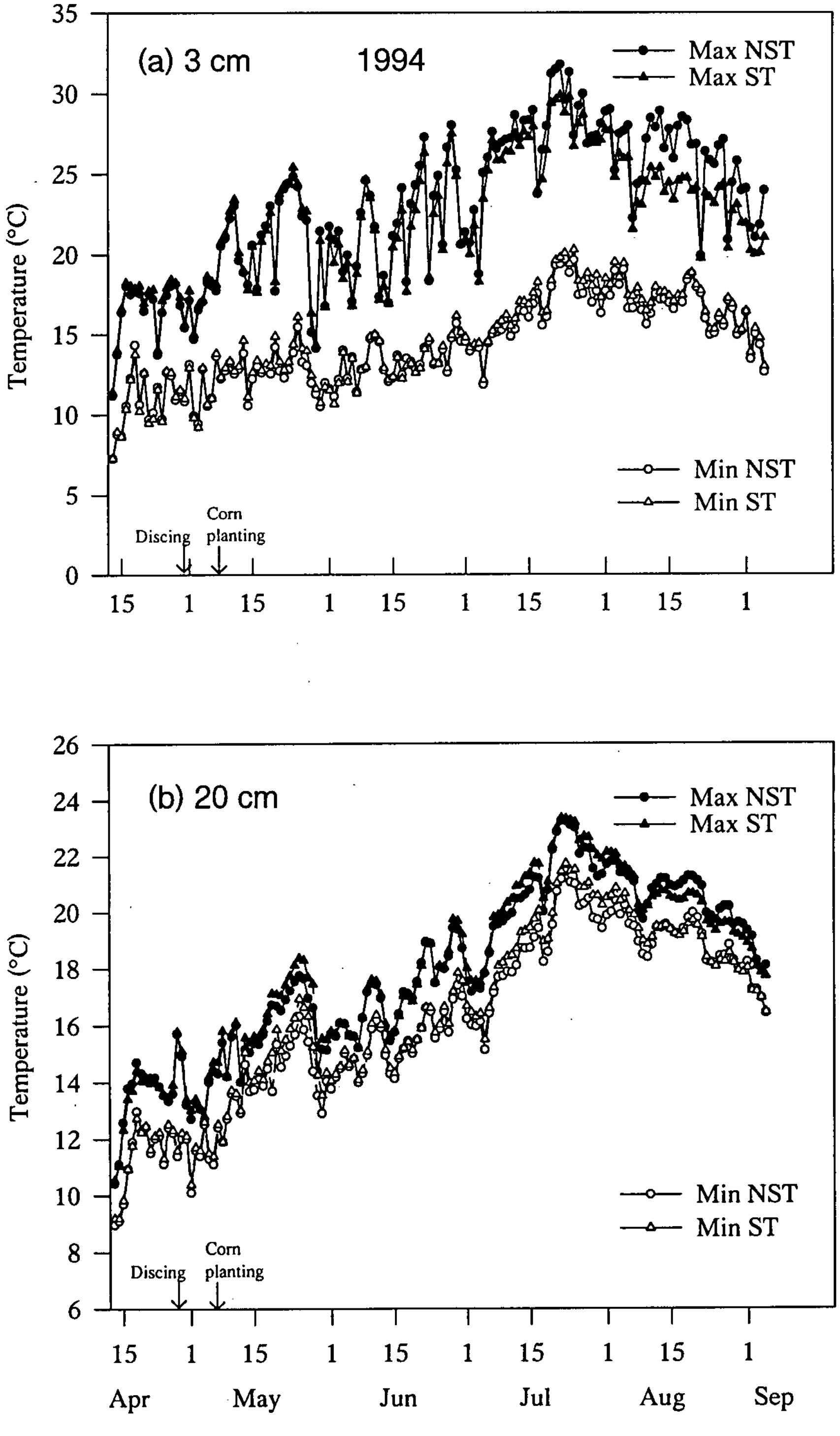


Figure 5.19. Daily maximum and minimum soil temperatures at 3 cm (a) and 20 cm (b) depths during 1994 growing season under winter wheat.

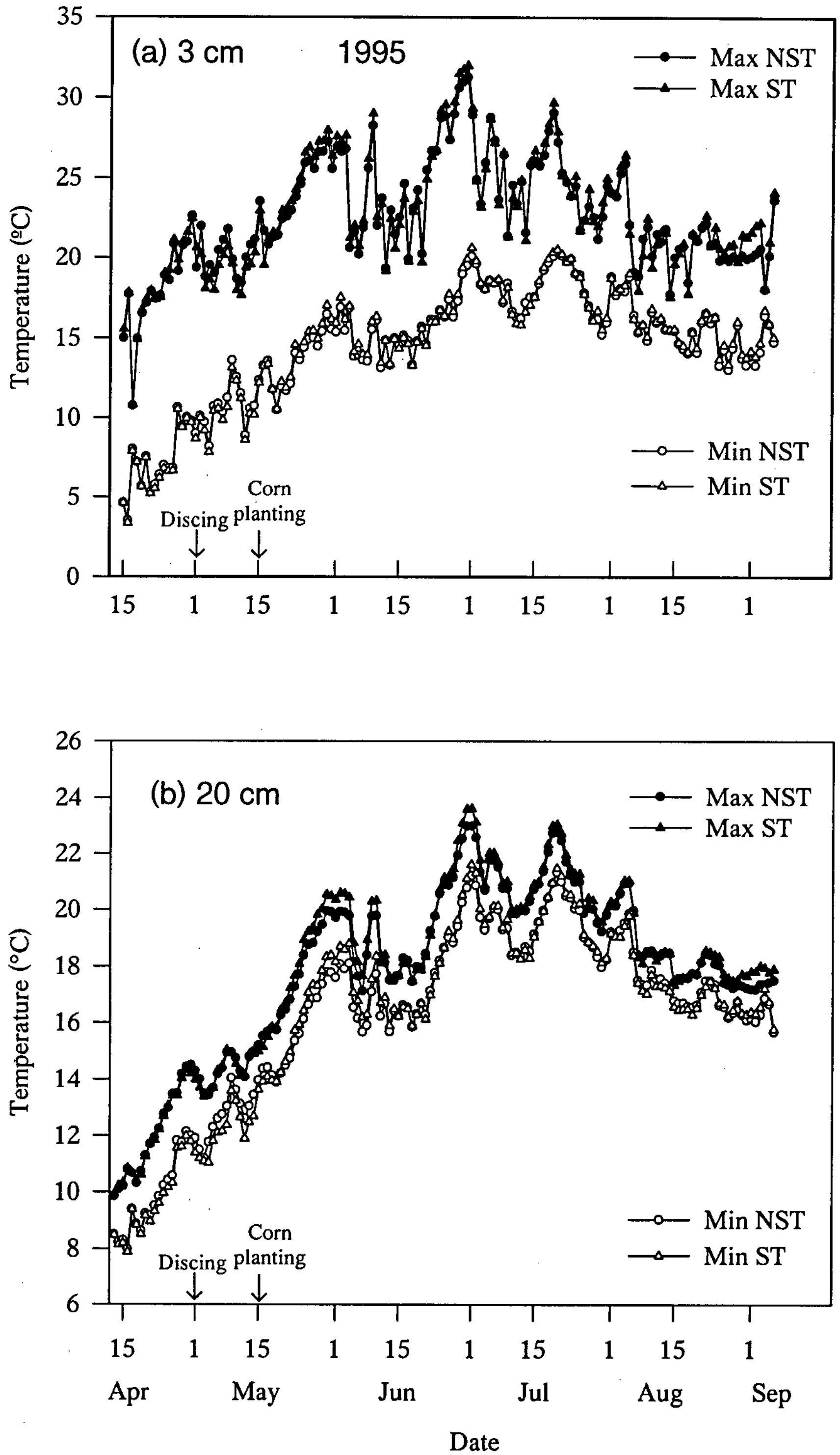


Figure 5.20. Daily maximum and minimum soil temperatures at 3cm (a) and 20 cm (b) depths during 1995 growing season under spring barley.

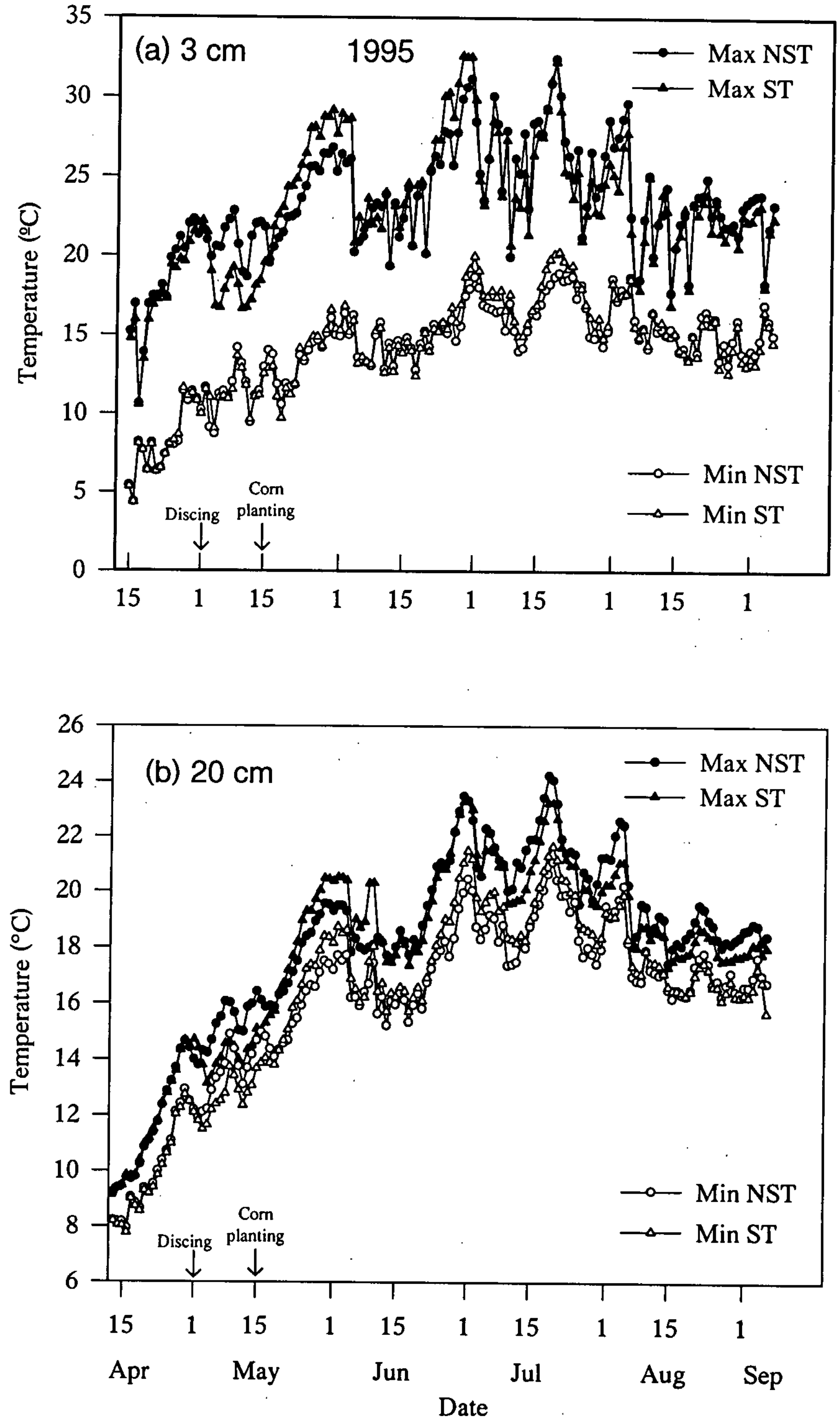


Figure 5.21. Daily maximum and minimum soil temperatures at 3 cm (a) and 20 cm (b) depths during 1995 growing season under winter wheat.

6. EFFECTS OF TILLAGE-PLANTING SYSTEMS AND COVER CROP SPECIES ON SOIL NITRATE AND SWEET CORN

6.1. Soil Nitrate

Application of 150 kg N ha^{-1} increased soil NO_3 concentration relative to the control in 1993 (Table 6.1). Only at 0-5 cm depth at week 12 and at 15-25 cm depth at harvest there was no difference between treatments with and without N application.

During the 1993 growing season soil NO_3 was consistently higher at all three depths under spring barley than under winter wheat (Figure 6.1). Nitrogen concentration of spring barley residues in the spring 1993 was 10.1 g kg^{-1} and of winter wheat residues 9.3 g kg^{-1}, while winter wheat biomass production was two times higher than spring barley production (Table 4.3). This probably caused slower N mineralization of winter wheat residues relative to spring barley residues.

At corn planting and at eight weeks after planting in 1993 greater soil NO_3 concentration was found after ST than NST with spring barley (Figure 6.1). At the same time, soil NO_3 concentrations were similar in both tillage systems with winter wheat. The tillage × cover crop species interaction was also significant at harvest time in the 1993 growing season. Higher NO_3 concentrations were observed at 0-5 cm and 5-15 cm depths in NST than ST with both cover crops, but greater differences in soil NO_3 between the two tillage systems were found under spring barley than winter wheat. Combined effects of higher soil temperatures in NST than in ST during second half of 1993 growing season (Figure 5.16 and Figure 5.17) together with better N mineralization of spring barley residues relative to winter wheat probably resulted in higher soil NO_3 concentrations in NST than in ST under the spring barley cover crop.

Higher soil NO_3 concentrations were observed at all depths in ST than NST from corn planting until 12 weeks after planting in 1994 (Figure 6.2). The only exception was at 5-15 cm depth at planting where there was no difference in soil NO_3 between two tillage systems. At the end of the 1994 season, i.e. at harvest, there was no difference in soil NO_3 between two tillage systems (Table 6.2 and Figure 6.2). Possible explanation for this could be due to a combined effect of soil temperatures and weed occurrence in two tillage systems. From corn planting to early July 1994 (i.e. seven to eight weeks after corn planting) there were no differences in soil temperatures between two tillage practices (Figure A. 2 and Figure A. 5) and this probably resulted in similar nitrification conditions in NST and ST. During the same period of time, high weed population on NST plots was probably taking up available soil N, which lowered soil NO_3 concentration in NST. After early July 1994, soil temperatures become much higher in NST than in ST, which probably increased soil nitrification in NST more so than in ST. Weed population was probably still taking up available soil N on NST plots, but possibly higher nitrification on NST could have reduced differences in soil NO_3 between two tillage systems. Hence, there was no tillage effect on soil NO_3 concentration at harvest time in 1994.

Application of 150 kg N ha^{-1} increased soil NO_3 concentration in comparison to the unfertilized control at all depths at eight weeks after corn planting, at 0-5 cm and 5-15 cm depths at 12 weeks after planting, and at 0-5 cm depth at harvest in 1994 (Figure 6.2). At corn planting in 1994 soil NO_3 was higher at all depths under spring barley than under winter wheat cover crop.

The effect of tillage on soil NO_3 was significant during later parts of the 1995 growing season, i.e. at 12 weeks after planting and at harvest, when higher concentrations of soil NO_3 were observed at 5-15 cm and 15-25 cm depths in NST than in ST (Table 6.3 and Figure 6.3). During latter part of 1995 growing season NST had higher soil temperatures than ST (Figure A. 3 and Figure A. 6), which probably increased nitrification and the amount of NO_3 formed in NST.

Once again, application of 150 kg N ha^{-1} led to significantly higher soil NO_3 concentration at all depths compared to control plots (Table 6.3).

At corn planting in 1995 soil NO_3 was higher under spring barley than under winter wheat cover crop at all depths of measurements. A similar situation was observed in 1994. Nitrogen concentrations of spring barley residues in 1994 and 1995 were above 20 g kg^{-1} (Table 4.3), which probably caused rapid mineralization of organic N and resulted in high soil NO_3 concentration at corn planting on the spring barley treatment. On the other hand, N concentrations of winter wheat residues in 1994 and 1995 were approximately 17 g kg^{-1} (Table 4.3) indicating a possibility of N mineralization latter during the corn growing season. Possible mineralization of winter wheat residues later in the season could explain the lack of differences in soil NO_3 between two cover crops during the latter parts of 1994 and 1995 seasons.

It has been observed that NO_3 concentrations are higher in conventionally tilled soils than in soils with reduced tillage (Thomas et al., 1973; Dowdell and Cannell, 1975; House et al., 1984; Sarrantonio and Scott, 1988; Dou et al., 1995). Differences in soil NO_3 concentration between tillage systems are related to the amount of crop residues and degree of incorporation, previous management, time since the tillage system was initiated, time of the year, climate, and soil type.

Primary spring tillage in this study was done by discing to 15 cm followed by secondary discing to 7.5 cm, which resulted in less residue incorporation relative to the moldboard plowing plus discing system used in studies by Thomas et al. (1973), Dowdell and Cannell (1975), and Sarrantonio and Scott (1988). Hence the differences in NO_3 levels between tillage systems in our study were less consistent than in the former studies.

Previous management is of great importance in determining the magnitude of conservation tillage effects on total and available soil N (Carter and Rennie, 1982; Doran and Power, 1983). Immediately after initiation of a no-till experiment on long-term bluegrass pasture in Kentucky soil NO_3 levels were higher in no-till plots than in moldboard plowed plots (Thomas et al., 1973). However, availability of soil N under no-till, on this same site, approached that of plowed treatment after approximately 10 years (Rice et al., 1986). When no-till is initiated on previously cultivated soil, differences in organic matter accumulation and N availability between no-till and conventional till are smaller than in situations when no-till is initiated on previously uncultivated soils, such as native sod. Soil in our study was in conventional tillage prior to establishment of NST, which could have minimized differences in NO_3 concentrations between NST and ST treatments.

During the latter parts of the 1993 and 1995 growing seasons higher concentrations of soil NO_3 were observed in NST than in ST, while in 1994 soil NO_3 was higher in ST than in NST at corn planting. As expected, application of urea fertilizer increased soil NO_3 concentration relative to the unfertilized soil. Higher concentrations of soil NO_3 were observed under spring barley than under winter wheat cover crop during the whole 1993 growing season and at corn planting in 1994 and 1995.

Table 6.1. Significance of sources of variation from analysis of variance (F-ratios) for soil NO_3 concentration (mg kg^{-1}) by depth during 1993 growing season.

Time of sampling	Depth (cm)	Source of variation						
		Till, T	N rate	T × N	Cover crop, C	T × C	N × C	T × N × C
Planting	0-5[1]	0.54	0.01	0.30	176.93**	39.91**	1.66	0.09
	5-15[2]	0.39	0.07	0.58	175.17**	0.70	2.45	0.26
	15-25[2]	0.71	0.86	0.18	509.04**	0.03	0.41	1.77
Week 8	0-5[2]	0.50	139.41**	2.77	8.46*	6.47*	4.21	2.26
	5-15[2]	0.14	57.23**	1.25	90.98**	6.62*	1.01	0.64
	15-25[2]	12.90*	20.92*	7.09	81.60**	8.73*	0.02	8.32*
Week 12	0-5	0.29	7.66	3.33	6.76*	2.35	7.56*	0.47
	5-15	3.13	39.59**	114.59**	16.15**	3.58	5.51*	0.13
	15-25	0.78	23.03*	0.02	46.87**	6.53*	10.97**	5.96*
Harvest	0-5	45.68**	20.19*	0.75	4.74	5.83*	4.67	2.00
	5-15[2]	98.63**	20.29*	0.09	4.82*	6.94*	8.73*	0.04
	15-25	1.59	9.76	0.81	4.42	1.77	4.71	0.21

*, ** Significant at the 0.05 and 0.01 probability levels, respectively.
[1] Square root transformation applied prior to analysis. [2] Log_{10} transformation applied prior to analysis.

Table 6.2. Significance of sources of variation from analysis of variance (F-ratios) for soil NO_3 concentration (mg kg^{-1}) by depth during 1994 growing season.

Time of sampling	Depth (cm)	Source of variation						
		Till, T	N rate	T × N	Cover crop, C	T × C	N × C	T × N × C
Planting	0-5	66.29**	0.05	1.55	6.91*	2.06	0.28	0.45
	5-15[2]	3.80	0.00	5.13	54.92**	0.42	0.14	2.78
	15-25	20.05*	3.94	0.17	103.09**	2.68	2.26	2.86
Week 8	0-5[1]	17.82*	653.38**	1.49	0.00	2.50	0.56	3.99
	5-15[2]	28.07*	154.76**	0.40	4.14	0.02	2.79	0.18
	15-25[2]	34.49**	30.59*	0.23	11.49**	1.61	0.77	0.08
Week 12	0-5[1]	21.43*	19.56*	6.04	0.02	1.17	3.10	3.86
	5-15	1.91	11.60*	28.51*	0.93	3.41	1.32	0.20
	15-25	1.31	7.84	0.41	2.79	0.39	0.00	4.15
Harvest	0-5	1.22	563.51**	5.19	1.92	0.35	0.05	0.03
	5-15[2]	0.53	1.34	4.00	1.74	13.26**	0.22	16.37**
	15-25	1.08	1.80	0.63	2.69	0.53	1.36	1.09

*, ** Significant at the 0.05 and 0.01 probability levels, respectively.
[1] Square root transformation applied prior to analysis. [2] Log_{10} transformation applied prior to analysis.

Table 6.3. Significance of sources of variation from analysis of variance (F-ratios) for soil NO_3 concentration (mg kg^{-1}) by depth during 1995 growing season.

Time of sampling	Depth (cm)	Source of variation						
		Till, T	N rate	T × N	Cover crop, C	T × C	N × C	T × N × C
Planting	0-5[2]	21.80*	2.09	2.56	73.67**	1.25	0.47	7.71*
	5-15[2]	1.95	1.20	1.89	124.77**	0.73	0.40	0.00
	15-25	1.15	6.71	1.19	103.64**	5.50*	4.71	1.47
Week 7	0-5	8.11	71.84**	0.01	0.63	0.16	0.18	0.63
	5-15[2]	11.37*	25.70*	6.52	0.93	4.50	0.91	1.36
	15-25	1.98	53.98**	37.94**	20.20**	0.47	4.89*	0.10
Week 9	0-5	0.22	88.62**	1.36	0.54	0.40	7.84*	0.01
	5-15	7.74	48.57**	4.26	0.01	0.20	1.74	1.87
	15-25	4.58	62.00**	0.42	2.02	0.17	0.04	1.12
Week 12	0-5[1]	4.44	41.03**	2.16	5.33*	1.14	0.68	12.60**
	5-15	46.88**	43.08**	0.55	1.13	0.24	0.36	1.95
	15-25	46.51**	24.40*	12.55*	13.32**	2.31	0.16	0.79
Harvest	0-5	1.73	36.99**	10.42	3.39	0.60	2.57	7.86*
	5-15[1]	13.14*	18.94*	10.52*	1.38	1.56	0.15	5.77*
	15-25[1]	12.31*	80.63**	0.24	4.55	1.27	1.50	1.90

*, ** Significant at the 0.05 and 0.01 probability levels, respectively.
[1] Square root transformation applied prior to analysis. [2] Log_{10} transformation applied prior to analysis.

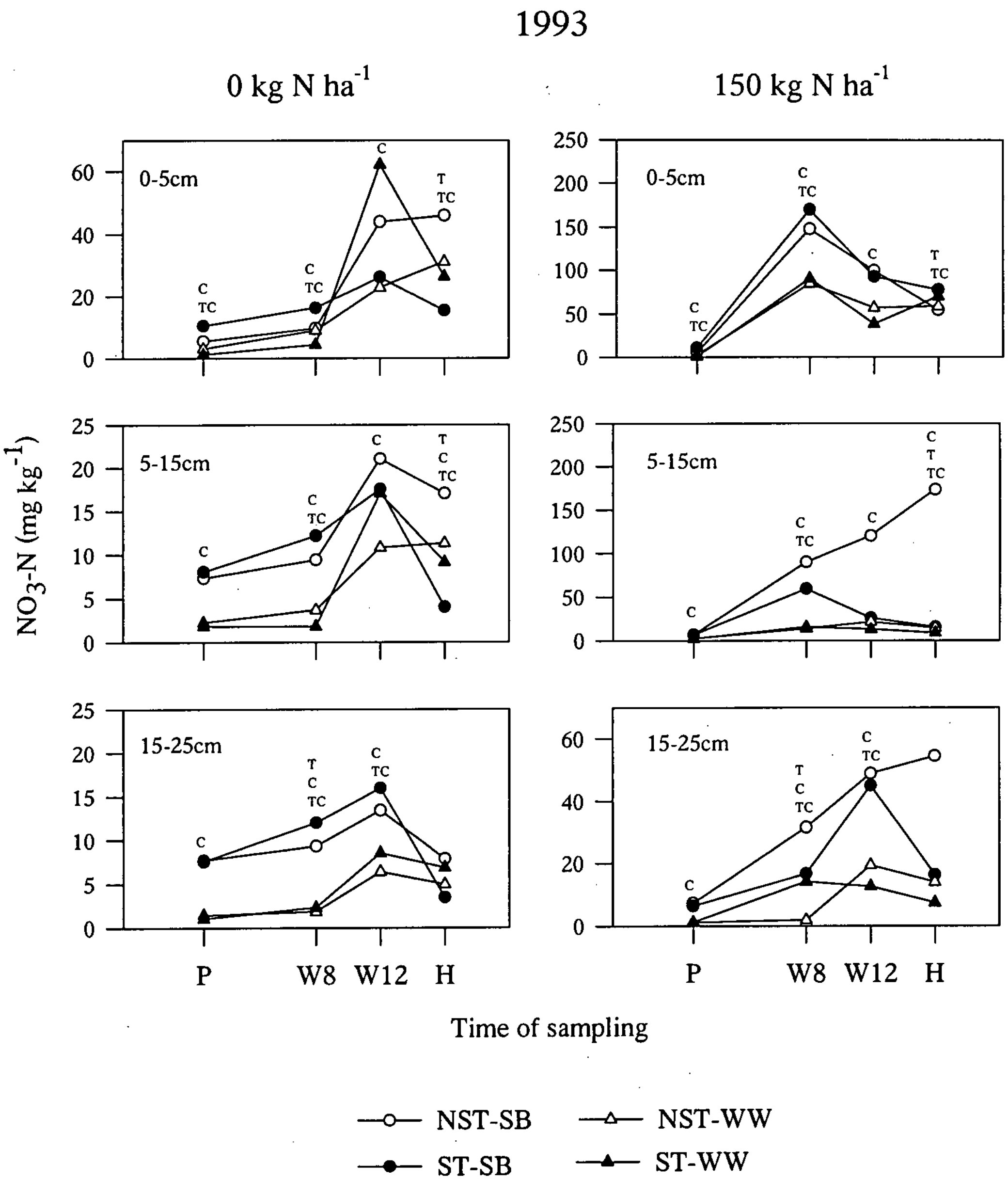


Figure 6.1. Soil NO_3 for two tillage systems and two N application rates under spring barley and winter wheat at varying depths in 1993. (T=tillage significant at 0.05 level; C=cover crop significant at 0.05 level; TC=interaction of tillage and cover crop significant at 0.05 probability level). P=planting time; W8=Week 8; W12=Week 12; H=harvest time.

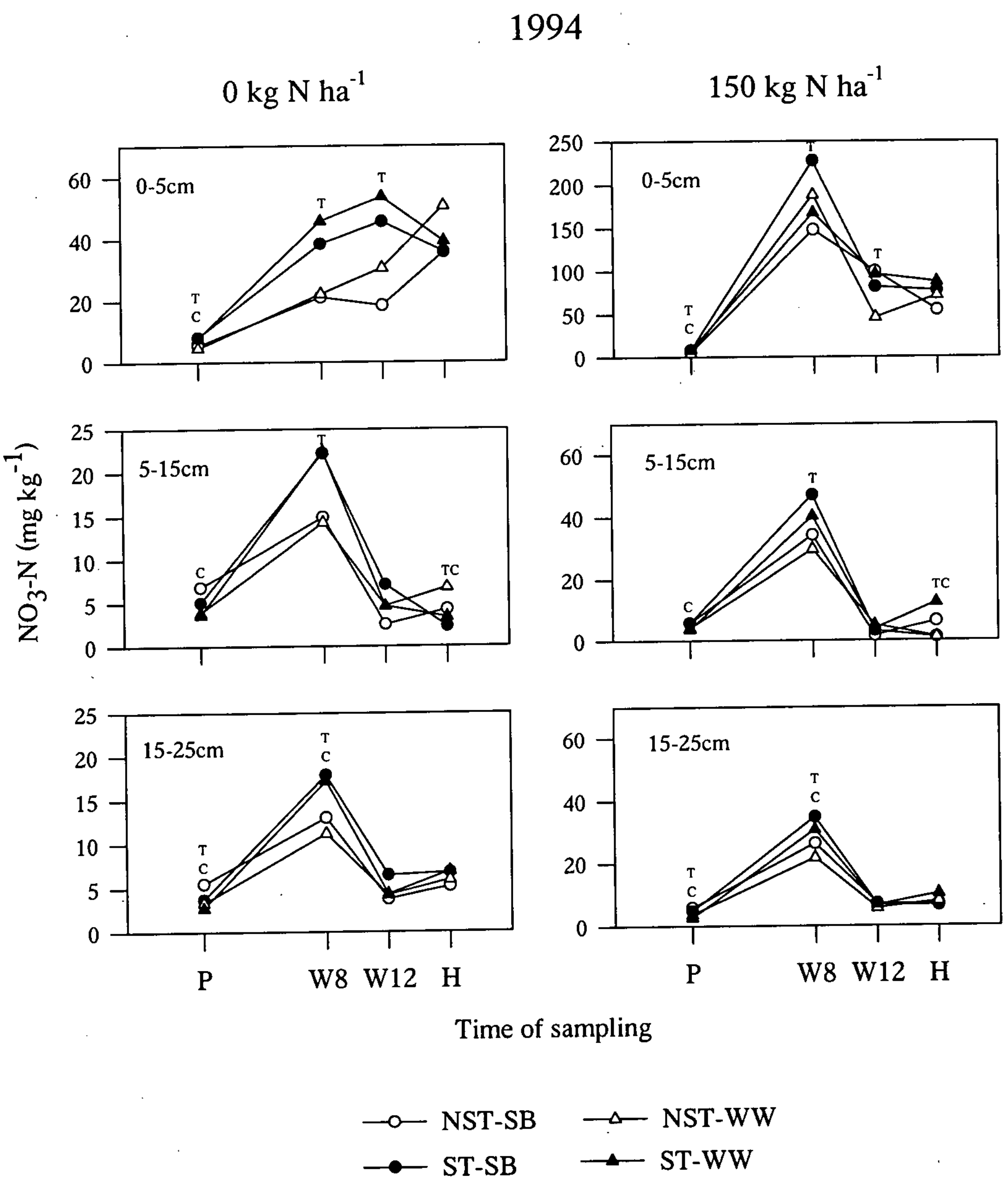


Figure 6.2. Soil NO_3 for two tillage systems and two N application rates under spring barley and winter wheat at varying depths in 1994. (T=effects of tillage significant at 0.05 level; C=cover crop significant at 0.05 level; TC=interaction of tillage and cover crop significant at 0.05 probability level). P=planting time; W8=Week 8; W12=Week 12; H=harvest time.

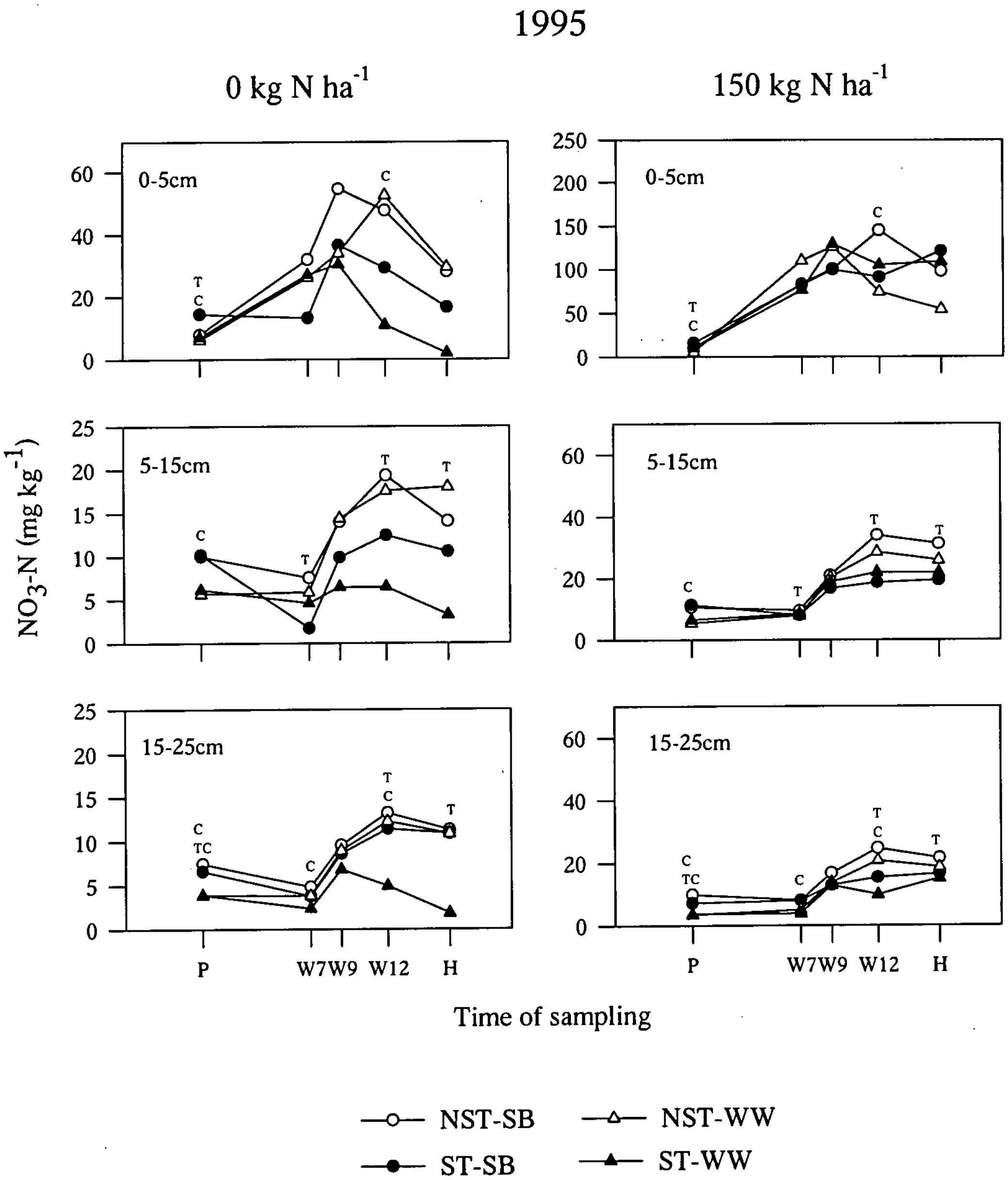


Figure 6.3. Soil NO_3 for two tillage systems and two N application rates under spring barley and winter wheat at varying depths in 1995. (T=effects of tillage significant at 0.05 level; C=cover crop significant at 0.05 level; TC=interaction of tillage and cover crop significant at 0.05 probability level). P=planting time; W7=Week 7; W9=Week 9; W12=Week 12; H=harvest time.

6.2. Sweet Corn Yield

Fresh cob yields obtained in 1993 were similar to or higher than the regional average of 11.3 t ha^{-1} (B.C. Annual Statistics, 1991). The N rate × cover crop species interaction was significant for sweet corn biomass, and dry and fresh cob yields in 1993. Efficiency of added N fertilizer was higher under winter wheat than under spring barley. Addition of 150 kg N ha^{-1} increased dry biomass, dry cob and fresh yield by 3.4, 2.6, and 11.1 t ha^{-1}, respectively in comparison to the control with winter wheat (Table 6.4, Table 6.5, and Table 6.6). The increase of dry biomass, dry and fresh cob yields caused by application of 150 kg N ha^{-1} relative to the control was 2.0, 1.4, and 6.6 t ha^{-1}, respectively on spring barley treatment. Greater sweet corn response to N application under winter wheat than under spring barley is caused by a lower soil NO_3 supply following winter wheat relative to spring barley observed throughout the 1993 growing season (Figure 6.1).

Table 6.4. Sweet corn dry biomass yield (t ha^{-1}) with two N application rates and two cover crops in 1993 (standard error of the mean in the brackets).

N application rate (kg ha^{-1})	Cover crop	
	Spring barley	Winter wheat
0	4.7 (0.47)	2.5 (0.33)
150	6.7 (0.70)	5.9 (0.57)

Table 6.5. Sweet corn dry cob yield (t ha^{-1}) with two N application rates and two cover crops in 1993 (standard error of the mean in the brackets).

N application rate (kg ha^{-1})	Cover crop	
	Spring barley	Winter wheat
0	2.5 (0.29)	1.0 (0.21)
150	3.9 (0.31)	3.6 (0.55)

Table 6.6. Sweet corn fresh cob yield (t ha^{-1}) with two N application rates and two cover crops in 1993 (standard error of the mean in the brackets).

N application rate (kg ha^{-1})	Cover crop	
	Spring barley	Winter wheat
0	12.0 (1.33)	5.8 (1.12)
150	18.6 (1.30)	16.9 (2.11)

During the 1994 growing season there were several problems on NST treatments, such as a high slug population (Table 4.6) and weed infestation, which resulted in drastic reduction of NST yield. Weed species observed during this study are listed in Table A. 5. Dry cob yield in ST was significantly higher than in NST, but was very low (Table 6.7).

Table 6.7. Sweet corn dry cob yield (t ha^{-1}) with two tillage systems in 1994 (standard error of the mean in the brackets).

Tillage system	Dry cob yield (t ha^{-1})
NST	0.1 (0.05)
ST	2.1 (0.18)**

** Significant at 0.01 probability level.

Addition of N fertilizer increased dry corn yield in comparison to the control (Table 6.8). The tillage × N rate interaction had a significant effect on fresh cob yield in 1994 (Table 6.9). The response of fresh cob yield to spring tillage was better on plots with N application than on control plots. Basically there was no fresh cob yield on NST with or without N application and the only satisfactory fresh cob yield was observed on ST with N application.

Table 6.8. Sweet corn dry cob yield (t ha^{-1}) with two N application rates in 1994 (standard error of the mean in the brackets).

N application rate (kg ha^{-1})	Dry cob yield (t ha^{-1})
0	0.8 (0.22)
150	1.4 (0.34)**

** Significant at 0.01 probability level.

Table 6.9. Sweet corn fresh cob yield (t ha^{-1}) with two tillage systems and two N application rates in 1994 (standard error of the mean in the brackets).

Tillage system	N application rate (kg ha^{-1})	
	0	150
NST	0.0 (0.00)	0.6 (0.54)
ST	8.1 (0.58)	12.4 (0.88)

In 1994, the N rate × cover crop interaction was significant for fresh cob yield (Table 6.10). Efficiency of added N fertilizer was higher under spring barley than under winter wheat cover crop, since addition of 150 kg N ha^{-1} increased fresh cob yield by 3.5 t ha^{-1} in comparison to the control with spring barley and by just 1.2 t ha^{-1} with winter wheat.

Table 6.10. Sweet corn fresh cob yield (t ha^{-1}) with two N application rates and two cover crops in 1994 (standard error of the mean in the brackets).

N application rate (kg ha^{-1})	Cover crop	
	Spring barley	Winter wheat
0	3.6 (1.36)	4.6 (1.76)
150	7.1 (2.37)	5.8 (2.04)

Low sweet corn yields on NST were measured again in 1995 (Table 6.11 and Table 6.12). This was the third consecutive year that Exp. 1 was located on the same spot, which contributed to the buildup of the weed problem. During the whole 1995 growing season both NST and ST treatments were infested by barnyard grass and even additional herbicide spraying did not completely suppress it. In addition, slug damage on NST treatment caused severe corn seedling damage and reduced stand. Hence higher dry and fresh cob yields were obtained with ST than with NST.

Table 6.11. Sweet corn fresh cob yield (t ha^{-1}) with two tillage systems in 1995 (standard error of the mean in the brackets).

Tillage system	Fresh cob yield (t ha^{-1})
NST	0.3 (0.20)
ST	7.0 (1.77)*

* Significant at 0.05 probability level.

Table 6.12. Sweet corn dry cob yield (t ha^{-1}) with two tillage systems in 1995 (standard error of the mean in the brackets).

Tillage system	Dry cob yield (t ha^{-1})
NST	0.1 (0.04)
ST	1.6 (0.42)**

** Significant at 0.01 probability level.

Nitrogen fertilizer application had a significant effect on dry cob yield, since higher dry cob yield was obtained with application of 150 kg N ha^{-1} than with no N application (Table 6.13).

Table 6.13. Sweet corn dry cob yield (t ha^{-1}) with two N application rates in 1995 (standard error of the mean in the brackets).

N application rate (kg ha^{-1})	Dry cob yield (t ha^{-1})
0	0.2 (0.12)
150	1.5 (0.44)*

* Significant at 0.05 probability level.

The tillage × cover crop species interaction was significant for sweet corn biomass production in 1995 (Table 6.14). Spring tillage increased sweet corn biomass by 2.2 t ha^{-1} in comparison to NST with spring barley cover crop and by 3.9 t ha^{-1} with winter wheat cover crop. Incorporation of cover crop residues into the soil on ST treatment probably helped the mineralization of organic N compared to the NST treatment where cover crop residues where left on the soil surface. In spring of 1995 winter wheat residue had 69 kg N ha^{-1}, while spring barley residue had only 23 kg N ha^{-1} (Figure 4.4). Therefore incorporation of winter wheat residues into the soil on ST treatment could have resulted in better sweet corn biomass production than when spring barley residues were disked into the soil.

Table 6.14. Sweet corn dry biomass yield (t ha^{-1}) with two tillage systems and two cover crops in 1995 (standard error of the mean in the brackets).

Tillage system	Cover crop	
	Spring barley	Winter wheat
NST	2.0 (0.53)	1.0 (0.12)
ST	4.2 (1.10)	4.9 (0.69)

The N rate × cover crop species interaction was also significant for whole plant biomass in 1995 (Table 6.15). Addition of urea fertilizer increased sweet corn biomass by 3.5 t ha^{-1} in comparison to the unfertilized control on spring barley plots, while increase was only 1.5 t ha^{-1} on winter wheat plots. Similar response was observed in 1994, which is an indication that winter wheat cover crop is a better N supplier than spring barley cover crop. Spring barley residues had high N concentration (Table 4.3), which probably contributed to their rapid mineralization early in the growing season. On the other hand, winter wheat residues had lower N concentration than spring barley, but N concentration was close to the critical value (of 20 g kg^{-1}) required for a net mineralization. In addition, N content of winter wheat residues was much higher than N content of spring barley residues (Figure 4.4). All this could result in better N supply by winter wheat than by spring barley cover crop and in turn in less response to the addition of N fertilizer with winter wheat than with spring barley. This is in agreement with soil NO_3 data that showed higher NO_3

concentration under spring barley than under winter wheat at the beginning of the 1994 and 1995 seasons (Figure 6.2 and Figure 6.3).

Table 6.15. Sweet corn dry biomass yield (t ha^{-1}) with two N application rates and two cover crops in 1995 (standard error of the mean in the brackets).

N application rate (kg ha^{-1})	Cover crop	
	Spring barley	Winter wheat
0	1.3 (0.39)	2.2 (0.87)
150	4.8 (0.87)	3.7 (1.02)

Only in the first year of this study, fresh corn yield obtained with NST was comparable to the regional average. This was due to lack of slug damage and weed infestation. Addition of 150 kg N ha^{-1} consistently increased sweet corn yields in comparison to the unfertilized control. Type of cover crop did not have a effect on the sweet corn production in this study. Efficiency of N fertilizer was higher under winter wheat than spring barley in 1993, and the opposite was true in 1994 and 1995. The effect of the N rate × cover crop species interaction on sweet corn yield depends on the soil available N and N concentration of the cover crop residues.

Table 6.16. Analysis of variance (F-ratios) for the effects of tillage, N rate, and cover crop species on sweet corn whole dry mass, dry and fresh cob yields (t ha^{-1}) on Exp. 1.

Source of variation	df	1993			1994			1995		
		Whole dry mass	Dry cob	Fresh cob	Whole dry mass	Dry cob	Fresh cob	Whole dry mass	Dry cob	Fresh cob
Tillage, T	1	5.73	1.67	0.54	-	278.39**	767.78**	38.55**	39.42**	19.65*
N rate, N	1	74.57**	34.40**	29.04*	-	33.95**	238.07**	14.24*	11.60*	9.48
T × N	1	0.04	8.82	2.47	-	9.57	11.24*	2.39	6.30	6.15
C. crop, C	1	26.13**	33.57**	48.70**	-	0.68	0.06	2.12	0.07	0.57
T × C	1	17.39**	53.25**	62.32**	-	0.01	0.70	17.54**	0.59	0.01
N × C	1	12.07**	19.96**	20.18**	-	4.79	5.21*	33.71**	3.45	2.72
T × N × C	1	7.54*	15.66**	16.10**	-	2.09	1.44	0.11	0.69	0.66

*, ** Significant at 0.05 and 0.01 probability levels, respectively.

6.2.1. Sweet Corn Response to Different N rates

In the spring of 1994 Exp. 2 was established to assess sweet corn response to different N rates under NST and ST and to determine the optimal N rate for sweet corn production for NST. During 1993/94 winter spring barley was grown as a cover crop and its biomass production in the spring of 1994 was 1.4 t ha^{-1} and a N concentration of 30.1 g kg^{-1}, which resulted in total N content of 41 kg ha^{-1}. During 1994/95 winter annual ryegrass was grown as a cover crop producing 4.4 t ha^{-1} of dry biomass, with N concentration of 20.8 g kg^{-1} and N content of 80 kg ha^{-1}.

Table 6.17. Analysis of variance (F-ratios) for the effects of tillage and N rate on sweet corn whole dry mass, dry and fresh cob yields (t ha^{-1}) on Exp. 2.

Source of variation	df	1994			1995		
		Whole dry mass	Dry cob	Fresh cob	Whole dry mass	Dry cob	Fresh cob
Tillage, T	1	-	110.87**	197.37**	206.94**	211.30**	186.66**
N rate, N	4	-	0.73	0.87	1.29	0.87	1.46
T × N	4	-	0.68	0.37	0.27	0.28	0.10

** Significant at 0.01 probability level.

Corn yields with NST were significantly lower than ST yields (Table 6.17), although this experiment was not located on exactly the same spot in 1994 and 1995. On NST plots, fresh cob yields were reduced by 54% in 1994 and by 78% in 1995 compared to ST (Table 6.18). Fresh cob yields obtained by ST were similar to yields obtained by Mr. Nottingham on the rest of his fields in 1994 and 1995 (Bert Nottingham, personal communication). On NST treatments sweet corn yielded poorly due to high weed populations, slug damage and lack of drill slit closure. This problem of open drill slits under NST was especially noticeable in 1995 after the annual ryegrass cover crop. Annual ryegrass left relatively large amounts of residues on the soil surface and some of the residues were pulled into the slits even further reducing slit closure.

Table 6.18. Sweet corn whole dry mass, dry and fresh cob yields (t ha^{-1}) with two tillage systems on Exp. 2 (standard error of the mean in the brackets).

Tillage-planting system	1994			1995		
	Whole dry mass	Dry cob	Fresh cob	Whole dry mass	Dry cob	Fresh cob
NST	-	1.5 (0.10)	7.5 (0.43)	2.2 (0.19)	0.8 (0.13)	3.7 (0.56)
ST	-	3.7 (0.15)	16.2 (1.15)	8.0 (0.44)	4.0 (0.19)	16.8 (1.82)

Sweet corn production was not affected by different N rates (Table 6.17). Corn yield on NST plots remained extremely low even with application of an excessive N rate, such as 200 kg ha^{-1}. Due to the poor performance of NST corn, it was impossible to determine an optimal N rate for sweet corn production under NST.

Several studies have demonstrated the feasibility of growing sweet corn with conservation tillage systems (Knavel et al., 1977; Bellinder and Warholic, 1988; Mohler, 1991), but only with efficient weed and pest control. Petersen et al. (1986) reported lower sweet corn yield with conservation tillage than with moldboard plowing, due to inadequate weed and slug control on silty clay loam in the Willamette Valley in Oregon. Mohler (1991) pointed out that untilled treatments generally have higher weed density than tilled treatments, which he attributed to the greater weed emergence and enhanced survival of weeds. Low sweet corn yields obtained with NST in our study in 1994 and 1995 confirm the importance of adequate weed and pest (i.e. slug) suppression. Possible solutions for the weed/pest problems with conservation tillage include (i) crop rotation, (ii) residue removal away from the rows, and (iii) application of a shallow spring tillage. The success of conservation tillage in the western Fraser Valley might be improved by growing crops, such as small grains or pea, that relatively quickly close canopy and hence manage to outcompete weeds.

6.3. Sweet Corn N

It is very difficult to establish N deficiency/sufficiency levels by plant analysis due to the complications caused by numerous factors associated with corn growth and by the transitory nature of N itself. Interrelated factors, such as stage of corn development, hybrid, climatic variables, fertilizer management, disease or pest attacks, deficiency or excess of another nutrient in the plant, have an effect on corn N concentration (Olson and Kurtz, 1982). Although plant responses can be measured, it is very difficult to identify and evaluate the combination of factors involved. Geraldson and Tyler (1990) reported rather wide sufficiency range, from 28 to 35 g kg^{-1}, of N concentrations in sweet corn ear leaf at silking. Sweet corn N concentrations observed in our study ranged from 14.9 g kg^{-1}, a deficient situation, to well in the sufficiency range, 31.6 g kg^{-1}.

Table 6.19. Analysis of variance (F-ratios) for the effects of tillage, N rate, and cover crop species on sweet corn N concentration (g kg^{-1}) on Exp. 1.

Source of variation	df	1993		1994		1995		
		Week 8	Week 12	Week 8	Week 12	Week 7	Week 9	Week 12
Tillage, T	1	8.12	0.31	41.30**	48.51**	0.22	8.86	2.62
N rate, N	1	126.50**	47.53**	351.17**	11.73*	33.68**	37.00**	8.52
T × N	1	0.02	0.22	0.12	0.03	0.01	0.50	2.25
Cover crop, C	1	48.47**	7.39*	13.31**	5.22*	10.80*	0.21	0.37
T × C	1	3.72	2.87	0.04	0.04	2.41	35.37**	16.72**
N × C	1	2.60	1.25	0.16	16.36**	0.85	2.94	0.08
T × N × C	1	0.03	2.46	2.05	0.11	1.86	1.10	0.80

*, ** Significant at 0.05 and 0.01 probability levels, respectively.

The effect of tillage on corn N concentration was not significant in 1993 (Table 6.19). As expected N fertilization increased corn N concentration at both sampling times in 1993 (Table 6.20).

Table 6.20. Sweet corn N concentration with two N application rates at Week 8 and Week 12 in 1993 (standard error of the mean in the brackets).

N application rate (kg ha^{-1})	N concentration (g kg^{-1})	
	Week 8	Week 12
0	25.2 (0.56)	26.0 (0.56)
150	29.9 (0.84)	31.0 (0.40)

Corn N concentrations were 3.4 g kg^{-1} higher on spring barley plots than on winter wheat plots at eight weeks after corn planting in 1993 and just 1.0 g kg^{-1} later in the season (Table 6.21). In addition, corn N concentrations decreased by 0.3 g kg^{-1} from eight to 12 weeks after planting on the spring barley treatment, while on winter wheat treatment there was an increase of 2.1 g kg^{-1} in corn N during this period. This supports the assumption that organic N from spring barley residue was mineralized relatively quickly, due to its higher N concentration (Table 4.3). As a result N mineralization from spring barley cover crop residues probably occurred early in the corn growing season, while organic N from winter wheat residues was probably slowly mineralized over longer period of time.

Table 6.21. Sweet corn N concentration with two cover crops at Week 8 and Week 12 in 1993 (standard error of the mean in the brackets).

Cover crop	N concentration (g kg^{-1})	
	Week 8	Week 12
SB	29.3 (0.88)	29.0 (0.74)
WW	25.9 (0.76)	28.0 (0.83)

At eight weeks after corn planting in 1994, corn N concentration was greater with ST than with NST (Table 6.22) and corn was sufficiently supplied with N in both tillage systems. Corn N concentration decreased from eighth to 12th week after planting and became higher with NST than with ST. At 12 weeks after corn planting, corn plants were deficient in N on both ST and NST.

Table 6.22. Sweet corn N concentration with two tillage systems at Week 8 and Week 12 in 1994 (standard error of the mean in the brackets).

Tillage system	N concentration (g kg^{-1})	
	Week 8	Week 12
NST	28.0 (0.97)	22.6 (0.92)
ST	30.2 (1.05)	21.2 (0.62)

As expected, corn was well supplied with N after application of 150 kg N ha^{-1} and at eight weeks after planting in 1994 corn N concentration was greater in fertilized than in unfertilized plots (Table 6.23).

Table 6.23. Sweet corn N concentration with two rates of N applications at Week 8 in 1994 (standard error of the mean in the brackets).

N application rate (kg ha^{-1})	N concentration (g kg^{-1})
0	26.7 (0.82)
150	31.6 (0.87)

Type of winter cover crop had a significant effect on corn N concentration at eight weeks after planting in 1994, since corn N concentration on spring barley plots was 3.2 g kg^{-1} higher than on winter wheat plots (Table 6.24). Similar observation was made at eight weeks after corn planting in 1993.

Table 6.24. Sweet corn N concentration with two cover crops at Week 8 in 1994 (standard error of the mean in the brackets).

Cover crop	N concentration (g kg^{-1})
SB	30.7 (0.99)
WW	27.5 (0.94)

The N rate × cover crop species interaction was significant at 12 weeks after corn planting in 1994 (Table 6.25). At this sampling date a larger increase in corn N concentration caused by urea application, occurred under spring barley than under winter wheat, but in spite of this corn was N deficient on spring barley treatment. Corn was sufficiently supplied with N on winter wheat treatment at 12 weeks after planting, probably due to a slower mineralization of N from winter wheat residues.

Table 6.25. Sweet corn N concentration (g kg^{-1}) with two rates of N application and two cover crops at Week 12 in 1994 (standard error of the mean in the brackets).

N application rate (kg ha^{-1})	Cover crop	
	SB	WW
0	15.5 (1.88)	25.3 (2.12)
150	18.7 (2.03)	28.2 (1.96)

The effect of tillage on corn N concentration was not significant in 1995 (Table 6.19). During the 1995 season slug damage and high weed population occurred again on NST plots. In addition, high population of barnyard grass was present on ST plots. Therefore, lack of differences in corn N concentration between two tillage systems was most likely a result of high N uptake by weed population on both NST and ST. At seven and nine weeks after corn planting in 1995 greater corn N concentrations were observed on plots with N application than on the control (Table 6.26). By the ninth week after planting corn was N deficient on both fertilized and unfertilized treatments.

Table 6.26. Sweet corn N concentration with two rates of N application at Week 7 and Week 9 in 1995 (standard error of the mean in the brackets).

N application rate (kg ha^{-1})	N concentration (g kg^{-1})	
	Week 7	Week 9
0	27.0 (1.35)	16.4 (0.99)
150	29.7 (1.26)	22.6 (1.21)

Type of cover crop had a significant effect on corn N concentration only at 7 weeks after corn planting in 1995, when corn following winter wheat cover crop had greater N concentration than corn following spring barley (Table 6.27).

Table 6.27. Sweet corn N concentration with two cover crops at Week 7 in 1995 (standard error of the mean in the brackets).

Cover crop	N concentration (g kg^{-1})
SB	26.6 (1.24)
WW	30.1 (1.56)

At nine and 12 weeks after corn planting in 1995 the tillage × cover crop species interaction was significant (Table 6.28). Corn N concentration was higher on ST than on NST with the spring barley cover crop, while the opposite was true with winter wheat at nine weeks after corn planting in 1995. At twelve weeks after planting, corn N concentration was 8.3 g kg^{-1} higher on ST plots than on NST plots with spring barley, while with winter wheat cover crop corn N concentration was just 0.6 g kg^{-1} higher on ST than on NST. Corn plants were N deficient in all tillage and cover cropping treatments, with an exception of corn plants grown in ST with spring barley cover crop at 12 weeks after planting.

Table 6.28. Sweet corn N concentration (g kg^{-1}) with two tillage systems and two cover crops at Week 9 and Week 12 in 1995 (standard error of the mean in the brackets).

Tillage system	Week 9		Week 12	
	Cover crop		Cover crop	
	SB	WW	SB	WW
NST	19.1 (1.25)	24.5 (1.30)	21.1 (1.35)	26.0 (2.07)
ST	19.5 (1.96)	14.9 (1.50)	29.4 (1.58)	26.6 (2.24)

There was no correlation between N concentration in corn plants and any of the three yield parameters on the NST treatment (Table 6.29). Nitrogen concentrations of whole corn plants taken on the ST treatment were well correlated with corn yield, since whole plant N concentration explained 29 to 61% of the variation in corn yield parameters. Better correlation between N concentration of corn plants and corn yield obtained in ST than in NST was related to later stages of corn development on ST plots (V7 to V9) than on NST (V5 to V7) at the time of sampling (Table 3.3). Sampling of corn plants during early stages of corn development is useful in terms of correcting N deficiency in the present crop, since N deficiency detected around V6 stage can be treated by N side-dressing without subsequent yield reduction (Aldrich et al., 1975).

Table 6.29. Correlation coefficients (r) for corn N concentrations and corn yield parameters in two tillage systems[1].

Year	N	Whole biomass		Dry cob		Fresh cob	
	concentration	NST	ST	NST	ST	NST	ST
1993	Corn plants (Week 8)	0.34	0.78**	0.30	0.69**	0.33	0.71**
	Ear leaves (Week 12)	0.52*	0.73**	0.67**	0.69**	0.68**	0.73**
1994	Corn plants (Week 8)	-	-	0.30	0.54*	0.30	0.64**
	Ear leaves (Week 12)	-	-	0.60*	0.65**	0.60*	0.64**
1995	Corn plants (Week 7)	0.03	0.24	0.10	0.27	0.04	0.25
	Corn plants (Week 9)	0.08	0.71**	0.13	0.71**	0.13	0.74**
	Ear leaves (Week 12)	0.67**	0.77**	0.25	0.73**	0.67**	0.75**

*, ** Significant at 0.05 and 0.01 probability levels, respectively. [1]n=16.

At 12 weeks after corn planting strong correlation was observed between N concentration in ear leaves and yield parameters in both tillage systems. In NST 52 to 68% of the variation in corn yield parameters is accounted for by the linear function of the ear leaf N concentration, while in ST the ear leaf N concentration explained 64 to 77% of the variation in corn yield parameters. Similarly, Geraldson and Tyler (1990) reported that sweet corn N concentration obtained at 80% silking stage correlated better with yield than corn N concentration obtained at V8 stage. Plant analysis data obtained at later stages of corn development are useful for confirming the adequacy of present fertilizer management and for determining future fertilizer practices, but have little value in correcting N deficiency for the present crop, since later detection and N application usually do not improve corn yields.

Corn N concentration was affected by tillage only in 1994, when higher corn N concentration was observed with ST than with NST. As expected, application of N fertilizer increased corn N concentration in comparison to the corn plants grown on the control. In 1993 and 1994 corn N concentrations were higher with spring barley than with winter wheat cover crop. In 1995, on the other hand, higher corn N concentration was observed with winter wheat than with spring barely at seven weeks after planting and later in the 1995 growing season there was no difference in corn N between two cover crop treatments.

7. CONCLUSIONS AND FUTURE STUDIES

This study represents the first attempt to introduce a form of conservation tillage, such as NST combined with winter cover crops, into the western Fraser Valley. This region is characterized by an unique combination of humid climate (with more than three quarters of precipitation occurring during October-April period) and relatively poorly drained silty clay loam Gleysols. These soils are not suitable for complete elimination of tillage operations due to poor drainage, unstable structure, and high soil compaction. Therefore in NST treatment all primary tillage operations were performed in the late summer (i.e., before the beginning of heavy rainfall).

Several soil characteristics were used to describe changes in soil conditions caused by NST and cover cropping in comparison to ST and cover cropping. They include (i) physical characteristics, such as ρ_b and ε_a, PR, aggregate stability, soil water content, and soil temperature; (ii) biological characteristics, such as numbers of earthworms and slugs; and (iii) a biochemical characteristic, i.e. availability of soil N during the sweet corn growing season. In addition, sweet corn performance with two tillage systems and two cover crops was also evaluated.

7.1. Soil Physical Characteristics

1. Type of tillage and cover crop did not have a significant effect on ρ_b, ε_a, and aggregate stability probably due to the short duration of this study and relatively low above-ground biomass of the two cover crops. The temporal fluctuations in aggregate stability were quite large and were attributed to soil water content at time of sampling.

2. There were generally no differences in PR between NST and ST before spring tillage. Two to six weeks after spring tillage PR in the upper soil profile in NST was higher than in ST. These PR values in NST were approaching 2000 to 2500 kPa and could be limiting for root growth. As a result of spring discing to a depth of 15 cm and formation of a tillage pan, higher PR was observed in ST than in NST around this depth and could also be restrictive for root growth. The effect of cover crop species on PR was observed either before or after spring tillage, when higher PR was measured under spring barley than under winter wheat.

3. Effects of tillage and cover crop species on soil water content were variable within depths and years. Generally there were no differences in soil water contents between the two tillage systems, with an exception of the 20 cm depth, where lower soil water contents were observed in NST than in ST, during the 1993 and 1995 growing seasons. The combined effect of no crack disruption and crust formation at the soil surface in NST could have resulted in either no difference in soil water contents between NST and ST or in even drier soil conditions observed in NST compared to ST. The effect of cover crop species on soil water content was not consistently observed.

4. Soil temperatures were lower in NST than in ST by 0.4 to 1.0°C, either before spring tillage or during the three to four week period after corn planting. Soil temperatures in NST were above the required minimum for corn emergence, but early corn development could have been slower in NST than in ST due to lower soil

temperatures. Soil temperatures were higher in NST than in ST from three to four weeks after planting to harvest probably due to the lack of canopy closure on NST.

Responses of the soil physical characteristics to two tillage systems following winter cover crops were somewhat different in this study than in other conservation tillage studies carried out in humid, temperate regions. Soil water contents in NST were not higher than in ST, as expected according to the results reported in regions with similar climate. The only soil physical characteristic that might be limiting for corn emergence and root growth in NST is high PR at the top few centimeters of the soil profile, but at the same time NST did not have the tillage pan at approximately 15 cm depth that was observed in ST and which could also reduce root growth and subsequently corn yield.

7.2. Biological Response to Tillage and Cover Cropping

1. Lack of spring tillage during three years resulted in a higher earthworm population in NST than in ST. This effect was evident even two months after late summer tillage, which was applied on both tillage treatments. Higher earthworm population was observed in winter-killed spring barley than in the winter wheat cover crop.

2. The lack of spring tillage combined with mild winter conditions resulted in high slug populations in NST during 1994 and 1995 growing seasons. Slug infestation in NST plots caused significant damage to young corn plants and was one of the main reasons for crop failures in 1994 and 1995. Therefore the only satisfactory sweet corn yield with NST was observed in 1993 when there was no slug damage.

3. Cover crop species, winter wheat vs. spring barley, did not significantly affect sweet corn production, while higher corn yields were achieved with than without N application.

4. Due to the poor sweet corn performance with NST in Exp. 2 it was not possible to determine the optimal N rate for the NST system.

5. In two out of three years N concentration in whole corn plants and in ear leaves was higher with spring barley than with winter wheat cover crop, while tillage generally did not affect corn N concentration. As expected, N application increased corn N concentration relative to the control.

6. Near the end of the 1993 and 1995 growing seasons higher concentrations of soil NO_3 were observed in NST than in ST, while at corn planting in 1994 soil NO_3 was higher in ST than in NST. As expected, application of urea fertilizer increased soil NO_3 concentration in comparison to the unfertilized soil. Higher concentration of soil NO_3 was observed in plots with spring barley cover crop than in plots with winter wheat cover crop throughout the 1993 growing season and at planting in 1994 and 1995.

High sweet corn yields obtained with NST in 1993 indicate that conservation tillage when practiced in crop rotation holds promise for sustainable corn production in this region. Combination of NST and cover cropping practiced in this study needs several modifications in order to be recommended to local farmers. These modifications include (i) crop rotation, (ii) shallow spring tillage or reduced number of spring tillage operations, and (iii) removal of crop residues away from planting rows.

7.3. Need for Future Studies

Even though there was a crop failure in two out of three years of this study valuable experience was gained with NST in the western Fraser Valley.

Complete elimination of spring tillage is not an option for sweet corn production in this region. However, some other form of conservation tillage that involves shallow, spring tillage and fewer number of tillage operations than used at present by local farmers might be successful. Application of shallow, spring tillage would break the soil crust, improve soil-seed contact, and reduce slug populations, especially during growing seasons following mild winters. Therefore it would be useful to further investigate the effects of a reduced number of spring tillage operations on slug occurrence and crop performance.

The no-till drill used on the silty clay loam in the western Fraser Valley left a large number of open drill slits. This created poor conditions for seed emergence and made seeds quite accessible to slugs. In addition, cover crop residues were sometimes pulled into the slits even further preventing their closure. Various types of specialized equipment have been developed for conservation tillage, mainly in the U.S. (Erbach et al., 1983). Since none of the available no-till drill designs work well under all conditions and since there are many relationships among soil, residue, and equipment it is difficult to predict what type of equipment would work under a given condition. Future research in this region should focus on (i) performance of different drill designs, (ii) clearing of residues from the planting rows by using different types of coulters on the drill, and (iii) performance of in-row cultivation.

This study was carried out on the same field for only three years and a larger data base is needed to allow better evaluation of conservation tillage systems in the western Fraser

Valley. It might also be useful to evaluate performance of other crops (e.g., small grains and pea) with conservation tillage, especially when crops are grown in crop rotation.

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APPENDICES

Table A. 1. Methods used for soil analysis by the "Pacific Soil Analysis Inc." laboratory in Richmond, B.C.

Soil characteristic	Method of analysis	Reference
Organic C (g kg^{-1})	Dry combustion	Nelson and Sommers, 1982
Total N (g kg^{-1})	Semi - micro Kjeldahl digestion	Bremner and Mulvaney, 1982
pH (H_2O)	1:1 (v/v) soil:water	McLean, 1982
pH (0.01 *M* $CaCl_2$)	1:2 (v/v) soil:0.01 *M* $CaCl_2$	McLean, 1982
EC (dS m^{-1})	1:2 (v/v) soil:water extract	U.S. Salinity Lab Staff, 1954
CEC ($cmol_c$ kg^{-1})	1 *M* NH_4 acetate extract	Rhoades, 1982
Exch. K, Ca, Mg, Na ($cmol_c$ kg^{-1})	1:5 soil: 1*M* NH_4 acetate extract	Thomas, 1982
Available P (mg kg^{-1})	Bray P-1 extract	Olsen and Sommers, 1982
Avail. Fe, Cu, Zn, Mn, (mg kg^{-1})	1:5 soil:0.1 *M* HCl extract	Baker and Amacher, 1982
Available B (mg kg^{-1})	Hot water extract	Shanina et al., 1967
% sand, silt, clay	Hydrometer method	Gee and Bauder, 1986
Particle density (Mg m^{-3})	Pycnometer method	Blake and Hartge, 1986b

Table A. 2. Basic soil characteristics of Exp. 1.

Soil parameter	Depth (cm)		
	0-15	15-30	30-45
Organic C (g kg^{-1})	24.4	17.9	4.7
Total N (g kg^{-1})	2.4	1.6	0.5
pH (H_2O)	5.7	6.0	5.5
pH ($CaCl_2$)	5.0	5.3	5.3
EC (dS m^{-1})	0.23[1]	0.23[1]	0.21[1]
CEC ($cmol_c$ kg^{-1})	17.9	18.8	11.8
Potassium ($cmol_c$ kg^{-1})	0.86	0.68	0.38
Calcium ($cmol_c$ kg^{-1})	9.74	10.54	6.73
Magnesium ($cmol_c$ kg^{-1})	0.91	1.12	1.81
Sodium ($cmol_c$ kg^{-1})	0.09	0.09	0.08
Phosphorus (mg kg^{-1})	206	134	15
Potassium (mg kg^{-1})	280	245	110
Iron (mg kg^{-1})	226	213	151
Copper (mg kg^{-1})	1.7	2.8	6.3
Zinc (mg kg^{-1})	0.6	0.4	0.5
Boron (mg kg^{-1})	0.5	0.5	0.9
Manganese (mg kg^{-1})	14.0	12.5	6.0
% Sand	13	12	14
% Silt	57	57	65
% Clay	30	31	21
Textural class	silty clay loam	silty clay loam	silt loam
Particle density (Mg m^{-3})	2.66	-	-

[1]Data obtained by multiplying 1:2 (soil :water) extract value by 2.6 to make them comparable with soil paste extracts.

Table A. 3. Soil water contents (kg kg^{-1}) obtained during 1993-1995 growing seasons at the time of penetration resistance (PR) measurements under spring barley.

Depth (cm)	May25, 1993	Jun 24, 1993	Apr 29, 1994	Jun 1, 1994	Apr 23, 1995	May16, 1995	Jun 1, 1995	Average
	Date of sampling							
				(NST)				
0-15	0.30	0.27	0.33	0.31	0.39	0.35	0.30	0.32
15-30	0.35	0.29	0.34	0.32	0.39	0.35	0.32	0.34
30-45	0.34	0.29	0.32	0.34	0.35	0.36	0.33	0.33
45-60	0.34	0.30	0.32	0.35	0.30	0.35	0.34	0.33
Average	0.33	0.29	0.33	0.33	0.36	0.35	0.32	0.33
				(ST)				
0-15	0.30	0.27	0.31	0.31	0.31	0.25	0.26	0.29
15-30	0.33	0.30	0.32	0.32	0.33	0.31	0.32	0.32
30-45	0.34	0.30	0.31	0.32	0.33	0.33	0.32	0.32
45-60	0.34	0.30	0.35	0.31	0.37	0.35	0.35	0.34
Average	0.33	0.29	0.32	0.32	0.34	0.31	0.31	0.32

Table A. 4. Soil water contents (kg kg^{-1}) obtained during 1993-1995 growing seasons at the time of penetration resistance (PR) measurements under winter wheat.

	Date of sampling							
Depth (cm)	May25, 1993	Jun 24, 1993	Apr 29, 1994	Jun 1, 1994	Apr 23, 1995	May16, 1995	Jun 1, 1995	Average
				(NST)				
0-15	0.34	0.28	0.35	0.31	0.38	0.35	0.30	0.33
15-30	0.35	0.30	0.36	0.32	0.38	0.37	0.32	0.34
30-45	0.34	0.30	0.33	0.33	0.30	0.34	0.31	0.32
45-60	0.32	0.29	0.31	0.34	0.32	0.29	0.29	0.31
Average	0.34	0.29	0.34	0.33	0.35	0.34	0.31	0.33
				(ST)				
0-15	0.33	0.26	0.35	0.31	0.37	0.31	0.24	0.31
15-30	0.33	0.30	0.35	0.32	0.38	0.33	0.30	0.33
30-45	0.33	0.29	0.32	0.31	0.34	0.27	0.35	0.32
45-60	0.33	0.29	0.31	0.31	0.30	0.31	0.35	0.31
Average	0.33	0.29	0.33	0.31	0.35	0.31	0.31	0.32

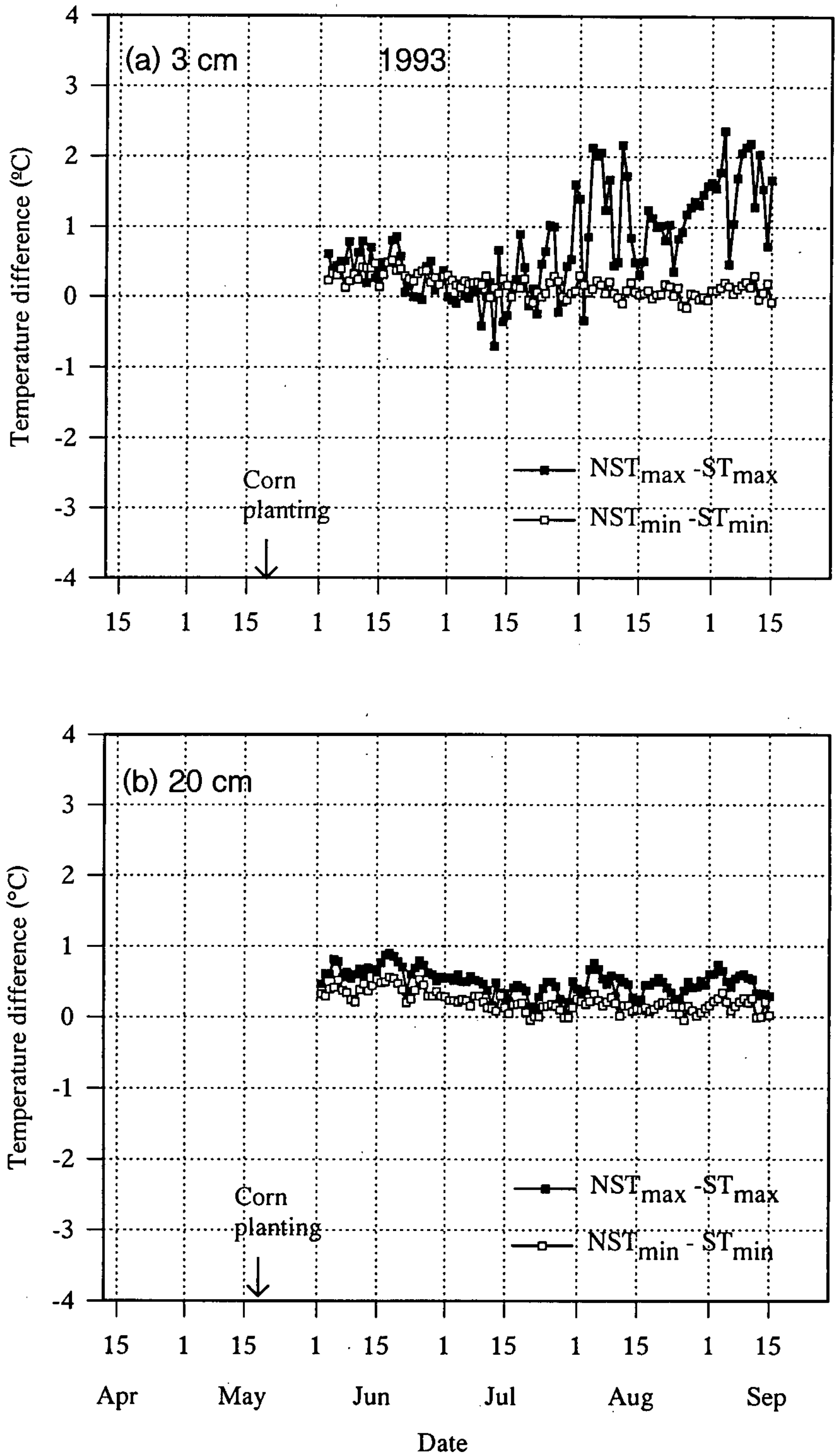


Figure A. 1. Differences in maximum and minimum daily soil temperatures between NST and ST at 3 cm (a) and 20 cm (b) depths under spring barley during 1993 season.

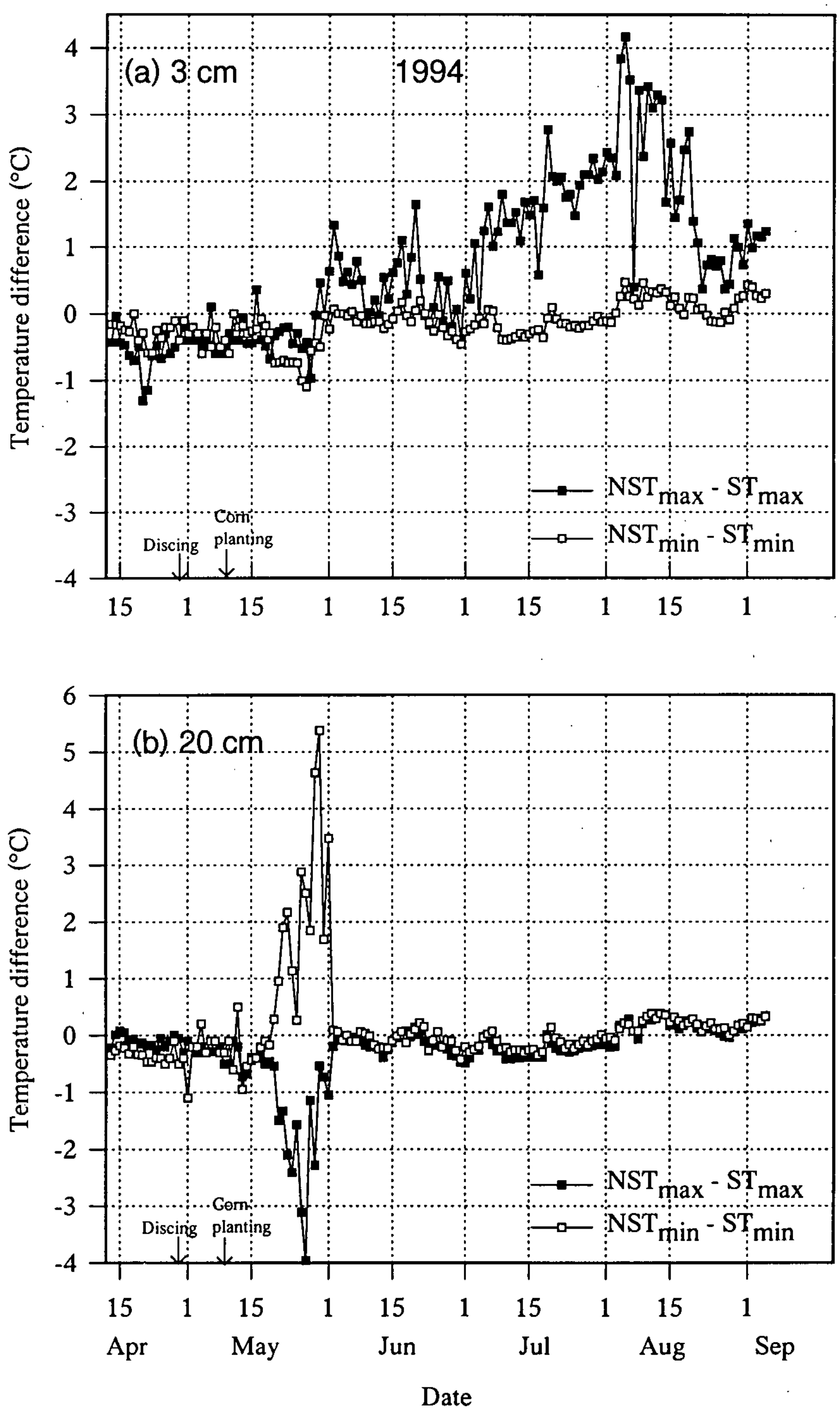


Figure A. 2. Differences in maximum and minimum daily soil temperatures between NST and ST at 3 cm (a) and 20 cm (b) depths under spring barley during 1994 season.

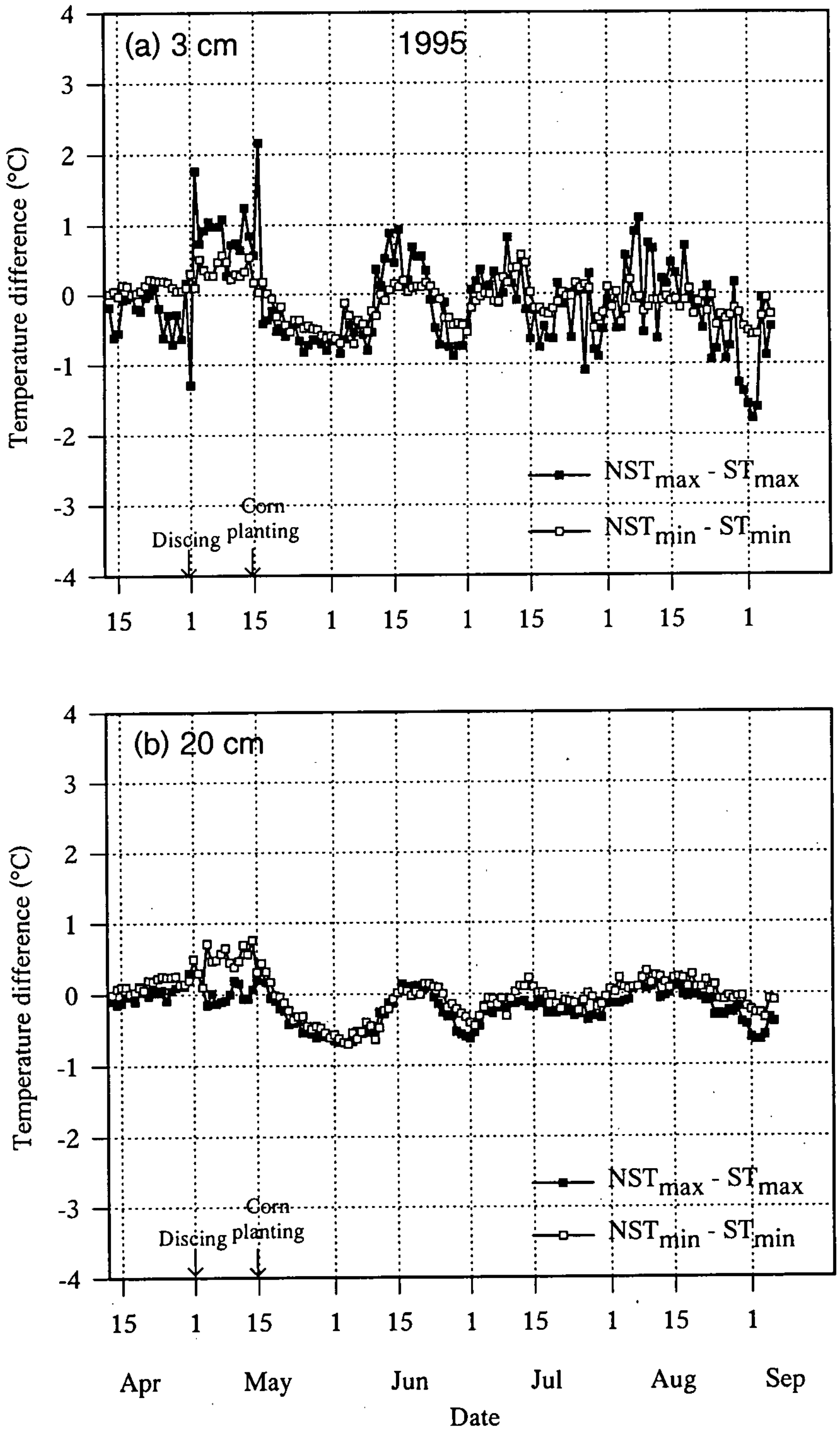


Figure A. 3. Differences in maximum and minimum daily soil temperatures between NST and ST at 3 cm (a) and 20 cm (b) depths under spring barley during 1995 season.

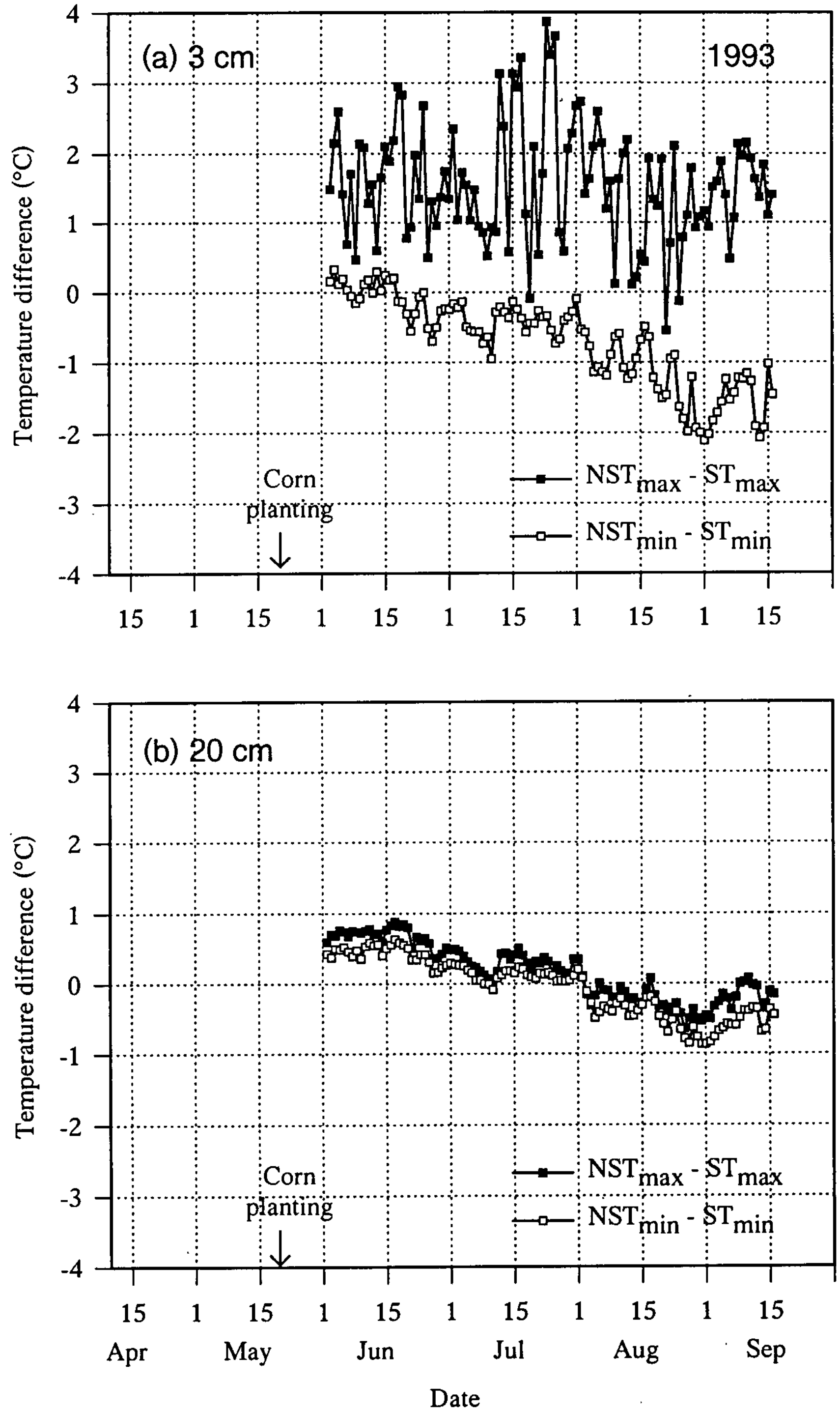


Figure A. 4. Differences in maximum and minimum daily soil temperatures between NST and ST at 3 cm (a) and 20 cm (b) depths under winter wheat during 1993 season.

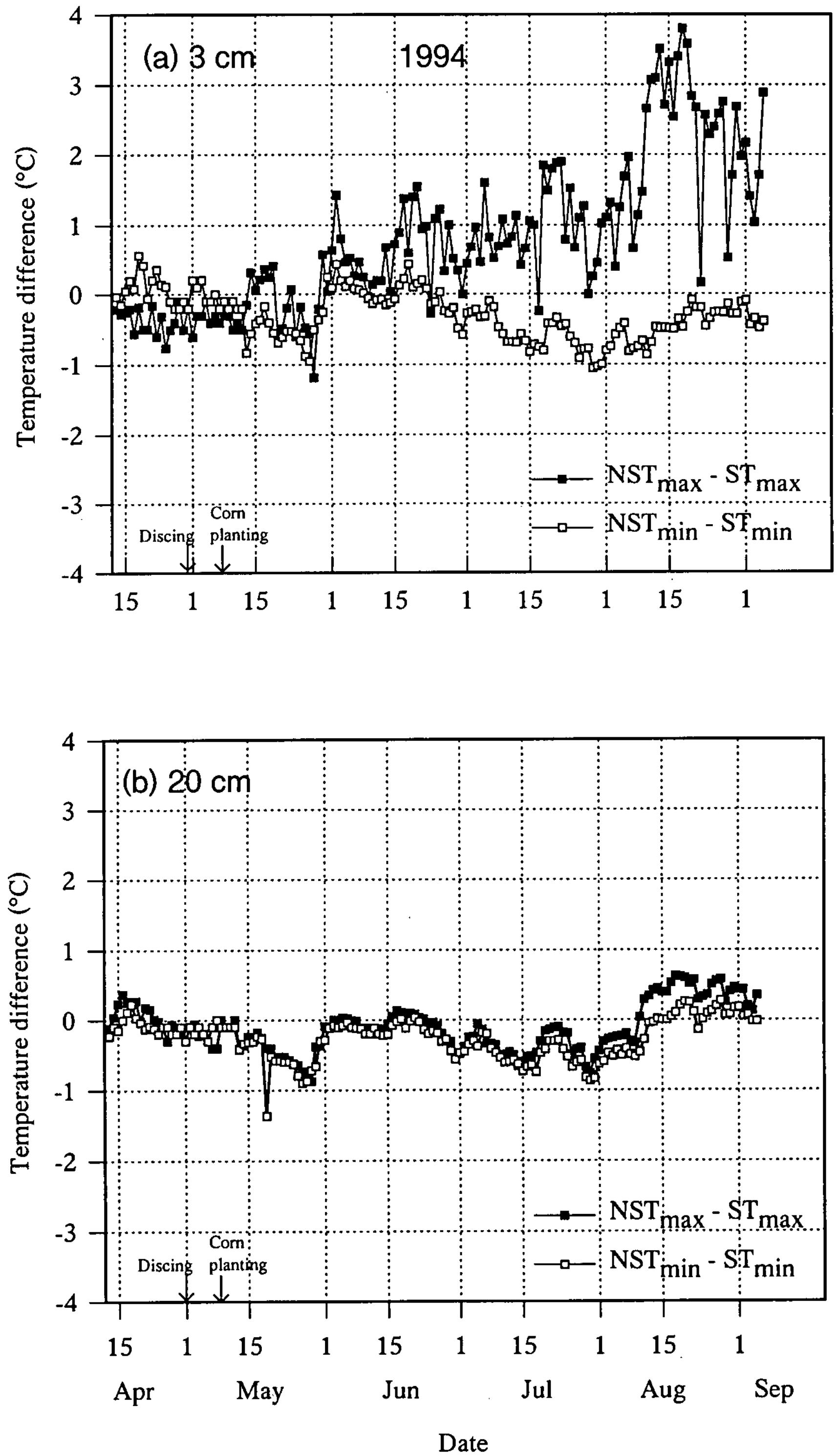
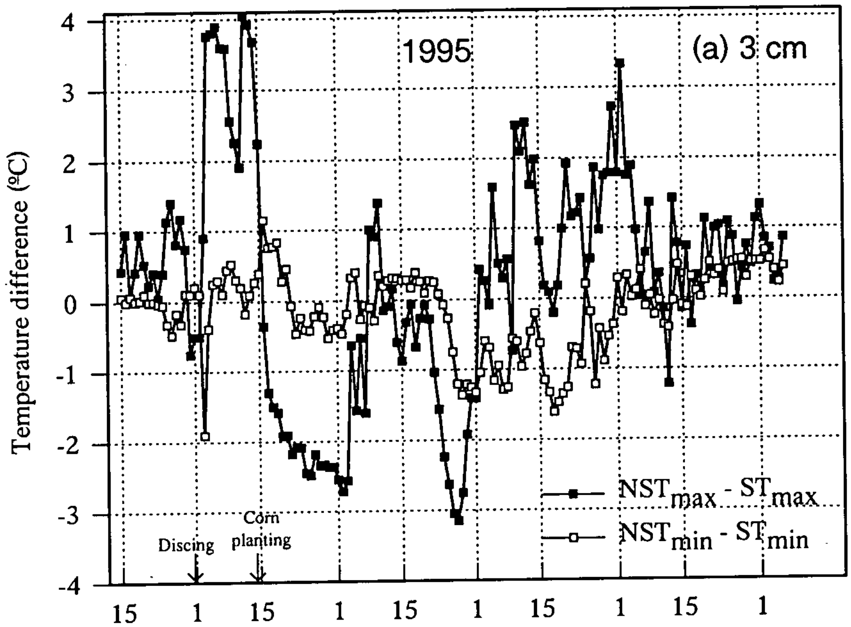


Figure A. 5. Differences in maximum and minimum daily soil temperatures between NST and ST at 3 cm (a) and 20 cm (b) depths under winter wheat during 1994 season.



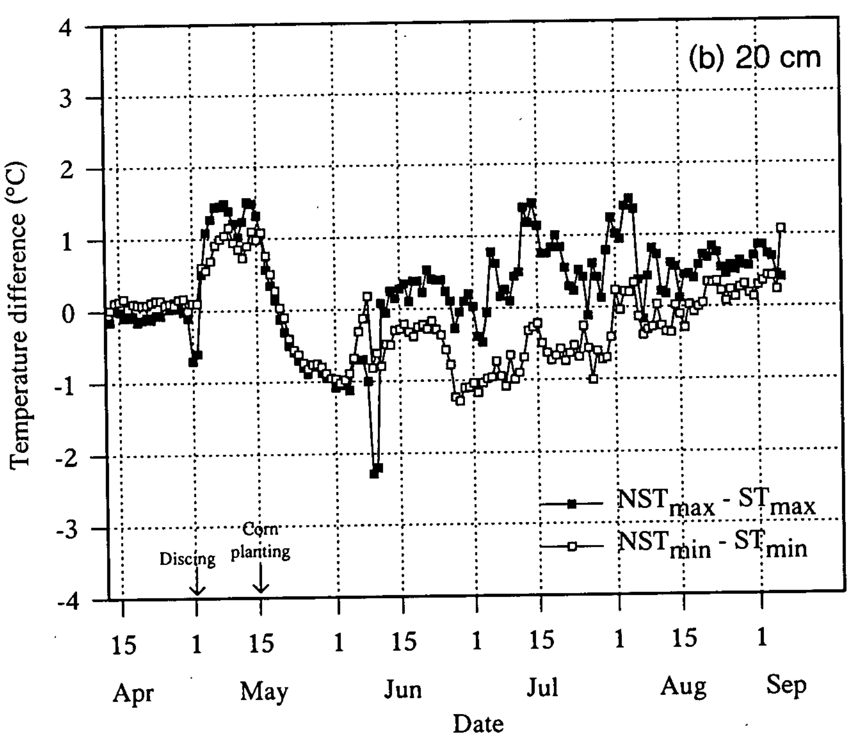


Figure A. 6. Differences in maximum and minimum daily soil temperatures between NST and ST at 3 cm (a) and 20 cm (b) depths under winter wheat during 1995 season.

Table A. 5. Most common weed species observed on no-spring tillage (NST) and spring tillage (ST) treatments during 1994-1995 seasons.

Common name	Scientific name
	Conservation, no-spring tillage (NST)
Common groundsel	*Senecio vulgaris* (L.)
Canada thistle	*Cirsium arvense* (L.) Scop.
Dandelion	*Taraxacum officinale* Weber
Persian darnel	*Lollium persicum* Boiss. & Hoh.
Barnyard grass	*Echinochloa crusgalli* (L.) Beauv.
White clover	*Trifolium repens* (L.)
Shepherd's purse	*Capsella bursa - pastoris* (L.) Medic.
Chickweed	*Stellaria media* (L.) Vill.
Purslane	*Portulaca oleracea* (L.)
Lady's thumb	*Polygonum persicaria* (L.)
Willow herb	*Epilobium parviflorum* (L.)
	Conventional, spring tillage (ST)
Redroot pigweed	*Amaranthus retroflexus* (L.)
Lamb's-quarters	*Chenopodium album* (L.)
Shepherd's purse	*Capsella bursa - pastoris* (L.) Medic.
Barnyard grass	*Echinochloa crusgalli* (L.) Beauv.

Table A. 6. Analysis of variance (F-ratios) for the effects of tillage and N rate on total N concentration in sweet corn on Exp. 2.

Source of variation	df	1994		1995		
		Week 8[2]	Week 12	Week 7[1]	Week 9	Week 12
Till, T	1	1.16	7.55	2.10	31.88*	4.71
N rate, N	4	6.23**	1.77	1.84	0.70	1.43
T × N	4	1.28	0.93	1.52	1.94	1.82

*, ** Significant at the 0.05 and 0.01 probability levels, respectively.
[1] Square root transformation applied prior to analysis. [2] Log_{10} transformation applied prior to analysis.

Table A. 7. Total N concentration in sweet corn at different N application rates at Week 8 in 1994 on Exp. 2.

N application rate ($kg\ ha^{-1}$)	Total N concentration ($g\ kg^{-1}$)
0	29.1c[1]
50	30.5c
100	35.3a
150	33.8ab
200	34.1ab

[1]values with different letters differ within tillage treatment at 0.05 probability level using Duncan's multiple range test.

Table A. 8. Total N concentration in sweet corn under two tillage-planting systems at Week 9 in 1995 on Exp. 2.

Tillage-planting system	Total N concentration ($g\ kg^{-1}$)
NST	20.4
ST	16.9

Table A. 9. Significance of sources of variation from analysis of variance (F-ratios) for soil NH_4 concentration (mg kg^{-1}) by depth during 1993 growing season.

Time of sampling	Depth (cm)	Source of variation						
		Till, T	N rate	T × N	Cover crop, C	T × C	N × C	T × N × C
Planting	0-5[2]	0.44	0.86	0.64	9.31**	2.86	0.02	5.75*
	5-15	0.00	0.19	0.72	0.03	0.05	0.15	2.35
	15-25[2]	1.10	0.15	0.01	5.04*	3.00	1.17	0.16
Week 8	0-5	5.82	58.28**	5.73	1.34	4.03	0.13	8.85*
	5-15	1.81	1.73	1.50	0.06	0.56	1.39	1.65
	15-25	1.19	1.32	1.34	0.68	0.81	0.75	0.92
Week 12	0-5[2]	1.57	0.11	0.04	3.83	0.05	1.24	1.40
	5-15[2]	1.21	0.21	0.89	0.81	0.30	3.13	1.23
	15-25	0.21	0.23	7.23	3.52	3.40	0.08	0.75
Harvest	0-5	0.05	0.47	16.93*	0.83	1.40	0.28	5.66*
	5-15	0.20	1.55	0.48	2.45	0.16	0.02	0.24
	15-25	0.27	1.37	2.10	3.02	1.01	2.32	0.00

*, ** Significant at the 0.05 and 0.01 probability levels, respectively.
[1] Square root transformation applied prior to analysis. [2] Log_{10} transformation applied prior to analysis.

Table A. 10. Significance of sources of variation from analysis of variance (F-ratios) for soil NH_4 concentration (mg kg^{-1}) by depth during 1994 growing season.

Time of sampling	Depth (cm)	Source of variation						
		Till, T	N rate	T × N	Cover crop, C	T × C	N × C	T × N × C
Planting	0-5	3.99	0.90	2.48	0.00	0.01	0.03	0.62
	$5\text{-}15^2$	7.18	1.91	0.36	1.04	0.41	1.29	0.02
	$15\text{-}25^1$	11.15^*	0.00	0.00	0.02	0.00	0.57	0.19
Week 8	$0\text{-}5^2$	0.00	3.59	8.21	0.79	0.26	29.78^{**}	0.82
	$5\text{-}15^2$	21.89^*	0.01	0.01	36.32^{**}	0.17	0.01	0.00
	15-25	8.46	1.67	0.24	25.47^{**}	3.00	0.00	0.80
Week 12	$0\text{-}5^2$	0.91	32.35^*	11.11^*	0.94	4.95^*	0.16	7.40^*
	5-15	2.05	6.87	0.51	0.12	0.21	0.00	0.09
	15-25	4.38	0.97	0.02	0.72	0.36	3.14	1.33
Harvest	$0\text{-}5^2$	6.70	149.11^{**}	8.66	32.54^{**}	21.45^{**}	5.96	3.03
	5-15	10.44^*	0.34	0.12	1.74	0.57	0.13	0.22
	$15\text{-}25^2$	9.18	0.20	0.29	0.73	0.55	0.40	0.78

*, ** Significant at the 0.05 and 0.01 probability levels, respectively.
[1] Square root transformation applied prior to analysis. [2] Log_{10} transformation applied prior to analysis.

Table A. 11. Significance of sources of variation from analysis of variance (F-ratios) for soil NH_4 concentration (mg kg^{-1}) by depth during 1995 growing season.

Time of sampling	Depth (cm)	Source of variation						
		Till, T	N rate	T × N	Cover crop, C	T × C	N × C	T × N × C
Planting	0-5[1]	1.35	0.60	0.20	1.10	0.02	0.07	0.03
	5-15[1]	10.97*	0.03	1.51	0.04	0.92	4.89*	0.22
	15-25	2.02	0.74	0.47	2.06	4.88*	0.00	0.01
Week 7	0-5[2]	1.26	92.81**	18.52*	3.09	21.03**	3.65	3.07
	5-15[2]	0.64	14.33*	0.07	0.58	0.68	4.47	3.59
	15-25	0.04	5.88	0.59	3.38	0.61	0.85	0.36
Week 9	0-5[2]	97.12**	86.58**	22.82*	1.02	15.70**	7.18*	24.96**
	5-15	0.05	0.16	0.03	15.56**	12.16**	0.74	0.06
	15-25[2]	3.80	8.68	0.00	9.06*	0.23	1.82	1.03
Week 12	0-5	2.41	34.39**	1.45	1.75	11.06*	0.31	8.31*
	5-15[1]	0.06	0.25	10.78*	2.05	0.08	3.49	0.63
	15-25[2]	0.31	0.69	0.73	0.90	1.92	0.00	0.36
Harvest	0-5[2]	1088.14**	426.35**	41.04*	65.51**	6.63*	0.60	0.81
	5-15[1]	0.01	0.99	3.29	65.63**	1.25	0.29	8.35*
	15-25	6.24	0.03	2.05	40.25**	5.96*	0.75	0.92

*, ** Significant at the 0.05 and 0.01 probability levels, respectively. [1] Square root transformation applied prior to analysis. [2] Log_{10} transformation applied prior to analysis.

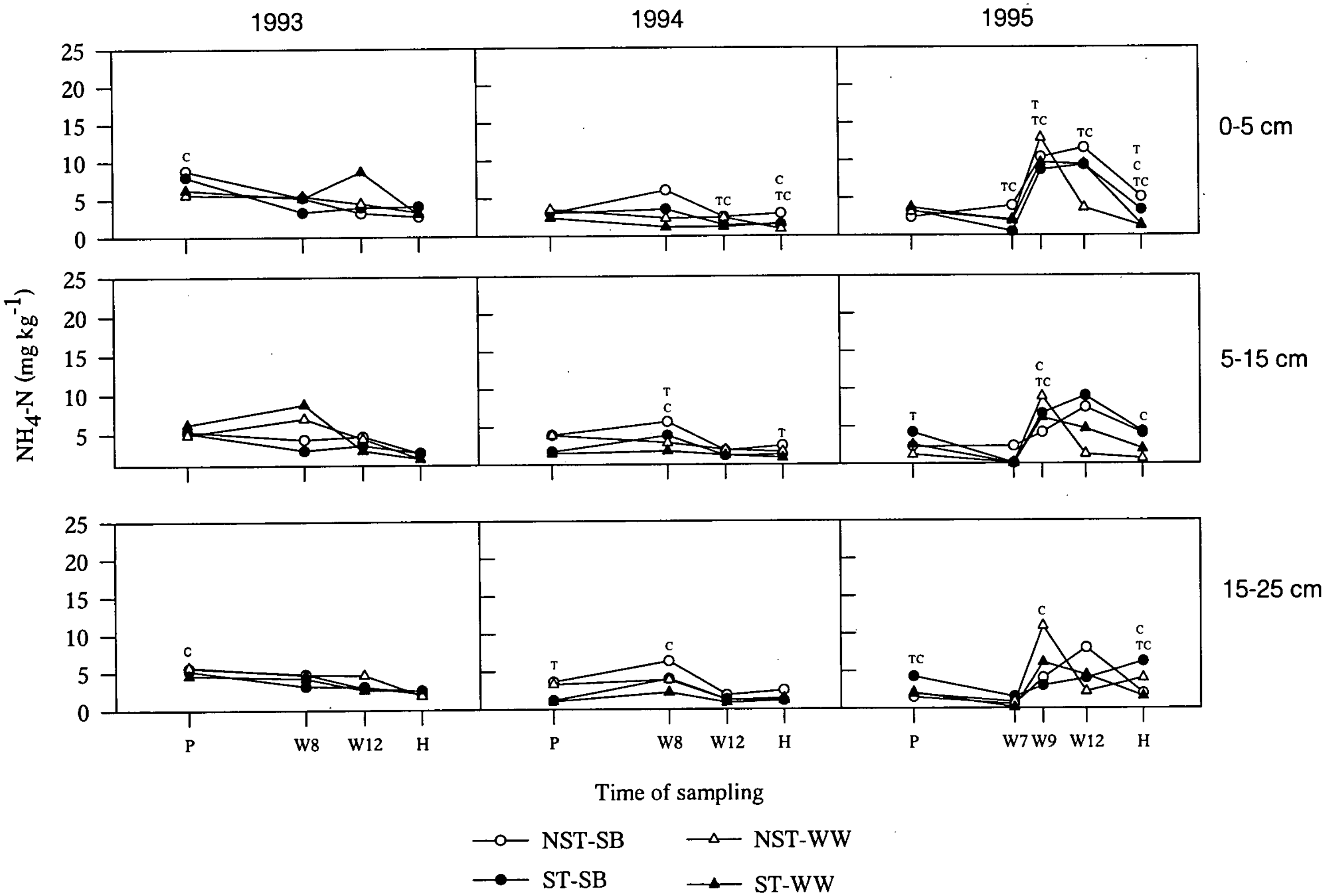


Figure A. 7. Soil NH_4 for two tillage systems under spring barley and winter wheat at varying depths. Data shown are for plots receiving no N fertilizer. (T=effects of tillage significant at 0.05 level; C=cover crop significant at 0.05 level; TC= interaction of tillage and cover crop significant at 0.05 probability level). P=corn planting, W7=week 7, W8=week 8, W9=week 9, W12=week 12, H=harvest.

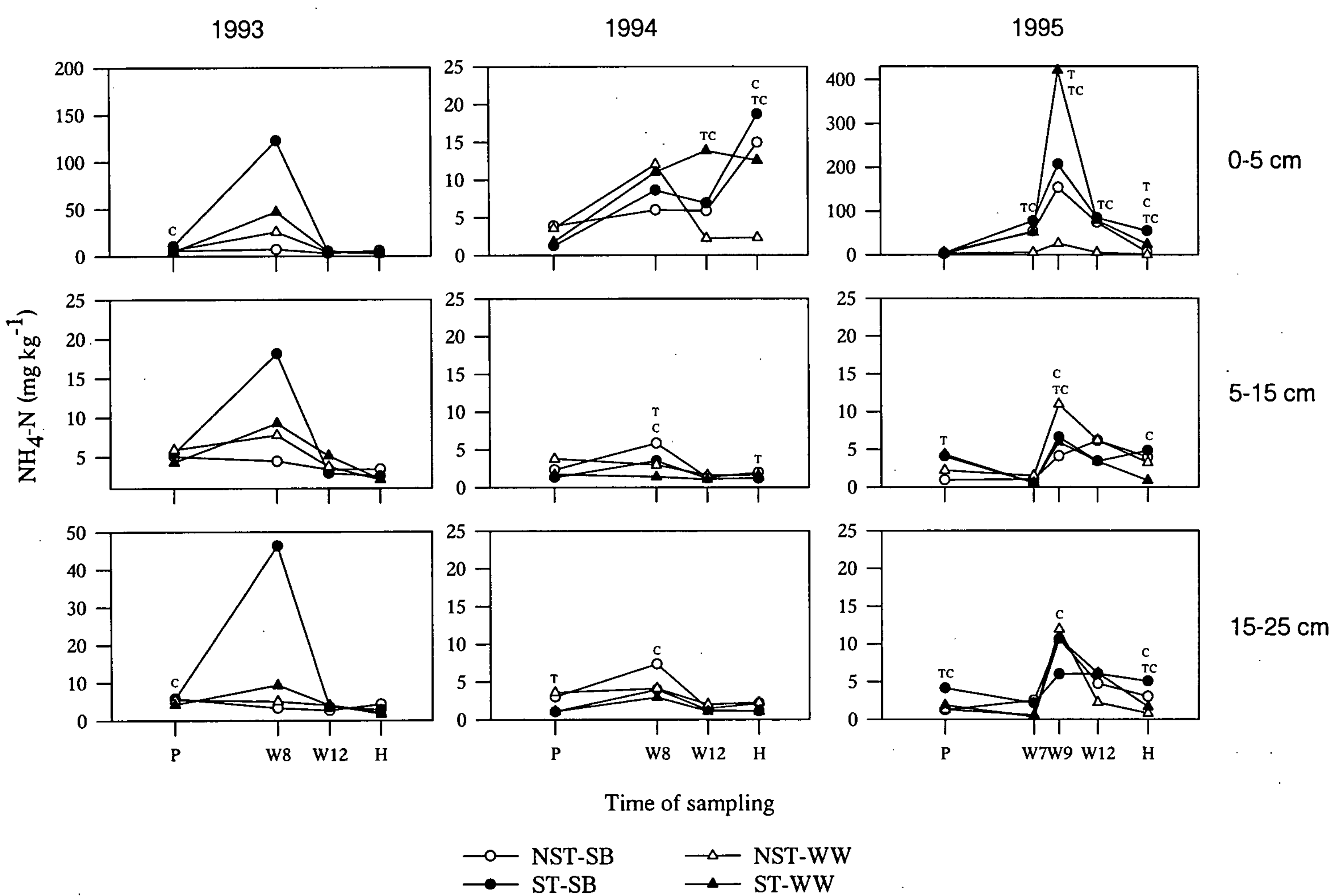


Figure A. 8. Soil NH_4 for two tillage systems under spring barley and winter wheat at varying depths. Data shown are for plots receiving 150 kg N ha^{-1}. (T=effects of tillage significant at 0.05 level; C=cover crop significant at 0.05 level; TC= interaction of tillage and cover crop significant at 0.05 probability level). P=corn planting, W7=week 7, W8=week 8, W9=week 9, W12=week 12, H=harvest.