Soybean Response to Management of Corn Residue through Removal, Tillage, Stalk Chopping, Planter Type, and Nitrogen Application

by

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ABSTRACT

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It is suspected that increasing amounts of corn (*Zea mays* L.) surface residue are resulting in an increasing yield deficit in no-till (NT) relative to conventional till (CT) soybeans (*Glycine max* Merr.). The objective of this research was to test if soybean yield responds to residue management strategies including removal, tillage timing and intensity, stalk chopping, planting equipment, and nitrogen application, and to determine the mechanisms responsible. Four field trials were conducted in the 2700 – 3000 CHU region of Ontario during 2011 and 2012. Yield was responsive to tillage system, planter type, and nitrogen application but these yield trends were not related to residue cover. NT yield was reduced by 11% relative to CT, but only if residue was chopped and soybeans were seeded with a drill. This suggests the increasing frequency of a NT yield deficit is caused by the increasing prevalence of stalk chopping combine heads, and that it can be alleviated by avoiding stalk chopping operations or seeding with a row planter.

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Table of Contents

List of Tables

List of Figures

Introduction

Soybeans are one of the most widely grown oilseed crops globally, due to their broad environmental adaptability and high nutritive value. At 40% protein content by mass and average yields of 2.5 Mg ha^{-1} (FAOSTAT, 2012a), soybeans are a productive protein crop (National Soybean Research Laboratory, 2012). Soy protein is valuable since it is considered a complete protein, containing all essential amino acids which cannot be synthesized by the human body (National Soybean Research Laboratory, 2012). Soybeans are also oil rich, accounting for approximately 20% of the seed weight. The oils are extracted for cooking oil or for biodiesel production, with increasing uses as a replacement for fossil oil. The remaining protein meal is either ground into livestock feed as a protein supplement or is incorporated into food products for human consumption.

As a leguminous crop, soybeans attain between 50-60% of total plant nitrogen (N) on average through a symbiotic relationship with soil rhizobacteria (Di Ciocco et al., 2011; Schipanski et al., 2010; Salvagiotti et al., 2009). Thus soybeans can be grown in soils low in N. In addition, soybean flowering can be either determinate or indeterminate which allows for commercial production to occur over a wide range of day length environments. In 2010, soybeans were grown on over 102 million ha worldwide, with total production amounting to 261.6 million metric tonnes (FAOSTAT, 2012a). Canada ranked 7th highest producing nation, with soybean production of approximately 4.3 million metric tonnes per year (FAOSTAT, 2012b). Ontario produces three quarters of the country's soybeans on just over a million hectares (OMAF statistics, 2013).

It is estimated that 50 – 60% of Ontario soybeans are produced in no-till (NT) conditions and 80% are grown in rotation following corn (Horst Bohner, Soybean Specialist, OMAF, personal communication). Complete provincial adoption of NT practice has not occurred since many farmers claim yield instability with NT relative to conventional tillage (CT, which is aggressive soil disturbance that buries nearly all of crop residue). Yield instability has also been reported in various research trials (Deen unpublished; Dick et al., 1991; Oplinger and Philbrook, 1992; Vyn et al., 1998; West et al., 1996; Yin and Al-Kaisi, 2004). However, the loss in production and revenue of NT has often been offset by the fuel and labour cost savings of fewer field passes (Yin and Al-Kaisi, 2004). From an environmental perspective, CT is detrimental to both farmland and off-site waterways. Tillage reduces aggregate size and fragments soil structure, which augments soil erosion (Seta et al., 1993; Vyn et al., 1998). Productive topsoil is consequently eroded from fields and washed into waterways, resulting in water use impairment from sedimentation, eutrophication, and pesticide contamination (Seta et al., 1993). Erosion potential is drastically reduced with NT since soil structure is maintained and residue cover slows water movement across the soil surface. Seta et al. (1993) reports up to 85% less sediment in surface runoff in NT relative to CT. Additional benefits of NT include reduced greenhouse gas emissions as there is less N_20 released in the growing season than CT (Omonode et al., 2010) and fewer tractor passes lessens fossil fuel consumption and carbon emissions (Yiridoe et al., 2000).

The 50 – 60% of soybean acres currently under no-till represents a significantly reduced percentage relative to five years ago (Horst Bohner, Soybean Specialist, OMAF, personal communication). Exact reasons for the decline in recent years are unknown, but may include greater farm profitability under CT and the financial capability to purchase new conservation tillage tools which are gaining in popularity. These conservation tillage tools are much less aggressive than CT and are designed to leave a minimum of 30% residue coverage on the soil surface (Conservation Technology Information Center, 1997). Other reasons for the decline may be the increasing incidence of glyphosate resistant weeds and the associated rise in financial cost of a chemical burndown prior to planting (Byker et al., 2013; Follings et al., 2013) making NT less affordable. It has also been hypothesized that greater quantities of corn stover on the soil surface are inhibiting planter performance (Bohner et al., 2011), as well as restricting evaporation and soil warming by shading the soil (Mitchell et al., 2012). Excessive soil moisture and cool soil temperature may delay planting and reduce early soybean performance. Quantities of corn residue are rising due to increasing corn yields (OMAF statistics, 2013), growing longer season hybrids resulting in less opportunity for decomposition following grain harvest, reduced N application per unit of grain produced (Cassman et al., 2002), and trends toward earlier planting dates for soybeans (Bohner, 2007b; Conley et al., 2012; Vilamil et al., 2012). Collectively, increasing corn residue biomass quantities and reduced stover decomposition may elevate the frequency and severity of a NT soybean yield deficit. Preliminary field trials have shown that soybean yields were increased by 470 kg ha^{-1} (7 bu ac^{-1}) when corn stover was removed from a NT system (Bohner, 2010). If farmers abandon NT practices and opt for CT to manage residue, they will forego the environmental and long term soil quality benefits of NT production. Thus, there is an impending need to develop corn residue management strategies that minimize the residue impact on soybean performance, yet still achieve the benefits of conservation tillage.

Chapter 1. Literature Review

1.1 Causes of increasing corn residue quantity

1.1.1 Higher corn yield

Corn residue quantities present at the time of soybean planting are largely a function of stover biomass at fall harvest and the amount of decomposition which occurs prior to seeding. Stover biomass production is closely associated with grain yield in corn (Leask and Daynard, 1973; Tollenaar and Lee, 2006). The relationship of stover biomass relative to yield is indirectly provided through the harvest index measurement (proportion of dry matter in the grain relative to the above ground plant dry matter). Tollenaar and Lee (2006) demonstrate that the harvest index has consistently remained around 50% in corn hybrids since the 1930s, even as average grain yields have increased. Therefore, an increase in corn yield will simultaneously result in a proportional increase in the quantity of stover. Johnson et al. (2006) describe that corn yield, and thus stover biomass, in the United States has been increasing at a rate of 108 kg ha^{-1} yr^{-1}. Ontario statistics also demonstrate increasing grain corn yield, of approximately 90 kg ha^{-1} yr^{-1} between 1981 and 2000 (Figure 1). However, since 2000, the rate of yield improvement has risen to approximately 280 kg ha^{-1} yr^{-1}, indicating the potential quantity of residue biomass at soybean planting is rapidly increasing.

Improvement in grain yield and stover biomass may be attributed to plant breeding and better agronomic practices. Seventy-five percent of this realized gain since the 1930s is attributed to advances through plant breeding for greater stress tolerance, higher leaf area indices and delayed leaf senescence (Tollenaar and Lee, 2006; Valentinuz and Tollenaar, 2004). In addition, secondary breeding efforts, such as the development of insect resistance (*Bacillus thuringienesis, [Bt]* corn) and reductions in stalk lodging, have concurrently protected crop yield. The other 25%

of yield enhancement may be accounted from improved agronomic practices (Tollenaar and Lee, 2006) such as early planting, advances in agricultural machinery, seed treatments, synchronizing fertilizer application with crop uptake (Cassman et al., 2002), fungicide applications, and growing hybrids that mature late in the season to capture more sunlight.

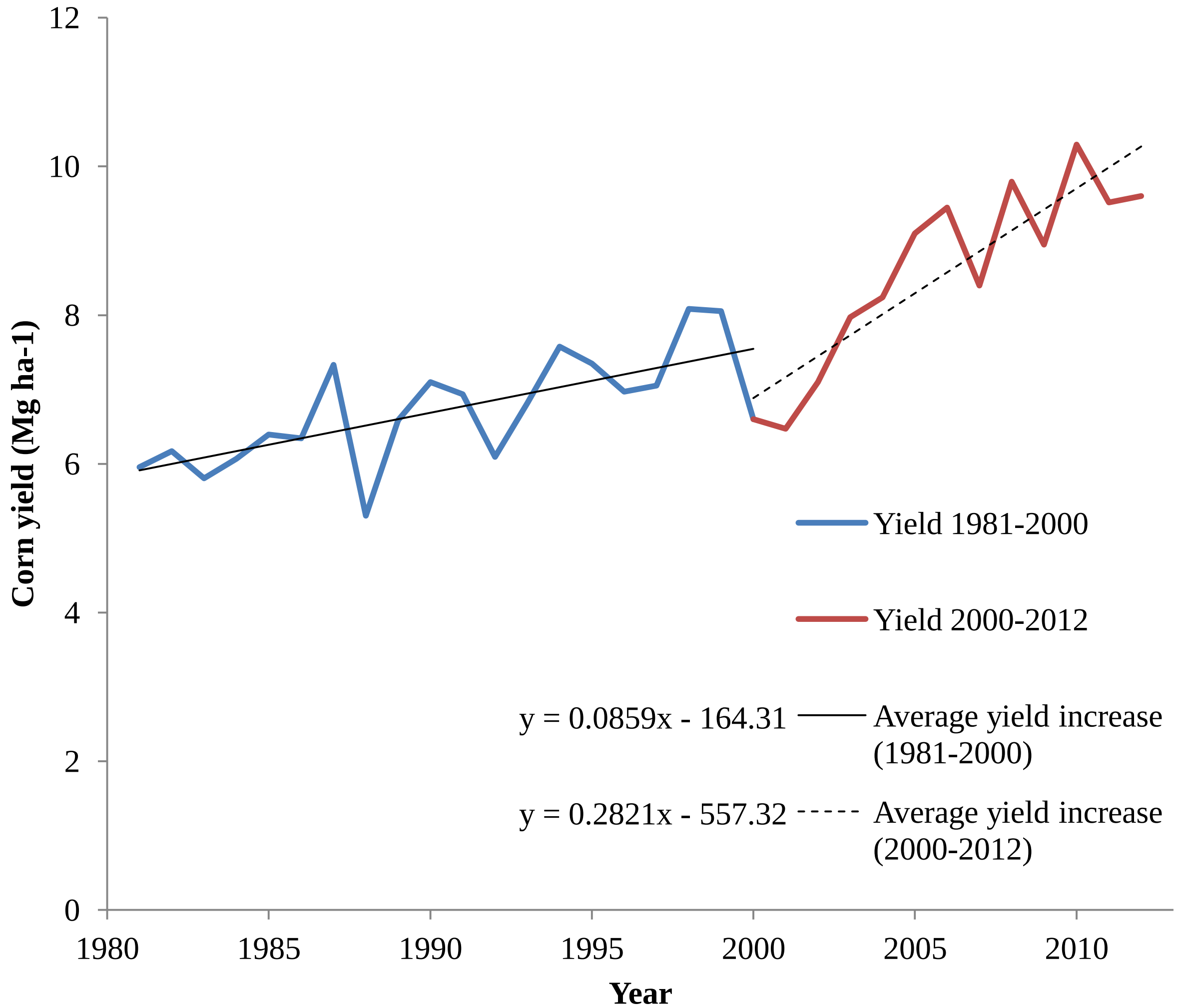

Figure 1-1. Provincial average corn yields in Ontario between 1981 and 2012. (Source: OMAF statistics, 2013)

1.1.2 Reduced residue decomposition prior to soybean planting

Although improved corn yield is desired by all farmers, it is possible that some of the agronomic mechanisms implemented to attain these higher yields are also negatively influencing the short term dynamics of residue decomposition. The most probable influencers include late maturing hybrids, or the ‘stay green’ effect and *Bt* corn. Possibly to a lesser extent, fungicide applications, selection of disease tolerant varieties, and stalk robustness may limit decomposition as well.

The duration and rate of decomposition of corn stover depends primarily on biological processes involving the breakdown of dead plant tissue by invertebrates and microorganisms (Satchell, 1974). In general tissue desiccation occurs when nutrients and energy are no longer transported throughout plant tissue and it represents the initiation of decomposition. Organisms immediately invade and consume plant material. The rate of degradation is influenced by factors affecting biological activity including the digestibility of the food source (also referred to as litter quality), availability of soil provided nutrients such as N, and environmental conditions such as temperature, moisture, and oxygen concentration (Satchell, 1974; Wildung et al., 1975). Plant decay continues until all plant tissue is consumed. However, soybeans are planted much before the bulk of the original corn stover has been decomposed and are consequently affected by remaining residue on the soil surface.

It has been suggested that the amount of residue decomposition that occurs prior to soybean planting has been decreasing because corn harvest has been trending later with full-season hybrids, and soybean planting has been trending earlier to maximize yield potentials. Clearly, farmers strive for higher yields and are consequently pushing growing season limits in both corn and soybean crops. Crop biomass is influenced by duration and efficiency of canopy light interception (Dohleman and Long, 2009). Lengthening the season through earlier planting and growing full-season cultivars, increases accumulated light capture and biomass yield potential for both corn and soybean. Delayed leaf senescence in modern hybrids extends the duration of maximal light capture, effectively enhancing the yield potential compared to older hybrids with earlier canopy senescence (He et al., 2001; Valentinuz and Tollenaar, 2004). Similarly, growing full-season cultivars maximizes the yield potential with longer durations of biomass accumulation. Fungal infection and severity have been reduced up to 89% accredited to disease tolerant hybrids (Welz and Geiger, 2000) and from the use of foliar fungicide applications (Munkvold et al., 2001; Paul et al. 2011) which may delay tissue necrosis and decomposition of residues. This condenses the time available for tissue decay. This delay could significantly limit the reduction in residue biomass prior to soybean planting. Zwahlen et al. (2007) observed in Switzerland that nearly 50% of corn leaf tissue is decomposed in October, when air temperature is above freezing; yet negligible changes in residue biomass occurred over winter due to low soil temperature. Since freezing temperatures occur over the winter months in Ontario, it is expected that decomposition rates would also be very low. Similarly, Al-Kaisi and Guzman (2013) recorded only 11 – 22% of above ground corn residue decayed over the winter months since harvest. Delayed tissue desiccation would minimize the duration and rate of decomposition which drastically limits the quantity of residue decayed prior to soybean planting.

The time interval for decomposition is also being compressed by the increased practice of early soybean planting. This management strategy has been shown to consistently increase grain yield (Bidegain et al., 2007; Conley et al., 2012; Hopper et al., 1979; Pedersen and Lauer, 2003; Vilamil et al., 2012) and is being rapidly adopted by Ontario soybean growers (Bohner, 2007b). Earlier soybean planting (i.e. approximately a month earlier than 20 years ago) has been possible through improved seed vigour of modern soybean cultivars, and through the use of seed treatments for controlling insects and diseases in stressful conditions, which may occur more frequently with earlier planting (Bohner and Earl, 2010; Hammon et al., 2002). This new technology provides the opportunity for soybeans to: i. develop a large photosynthetic capacity prior to reproduction, ii. flower early during cooler conditions and extend the duration of reproductive growth, iii. lengthen the duration of photosynthesis (Cooper, 2003; DeBruin and Pedersen, 2008), and iv. enhance stand establishment (Hammon et al., 2002). Through this strategy to improve soybean yield, planting early has reduced the window for corn residue decomposition. However, considering the low quantity of stover decay that occurs in the early spring (ie. less than 10% as reported by Zwahlen et al. [2007]), the actual implication of early soybean planting compressing the duration of residue decomposition may be quite minimal. Nevertheless, late corn tissue desiccation and early soybean planting may collectively reduce the quantity of residue decay to exacerbate soybean seeding issues and delayed early plant development.

The rate of corn stover decay may also be impeded by N supply limitations. The optimum carbon to N ratio for decomposition is 30:1, and corn stover with a carbon to N ratio of 57:1 (USDA, 2011), only provides half the required N to sustain maximum decomposition rates (Green et al., 1995). Decomposing microbes must therefore draw upon inorganic N in the soil. Increasing corn stover biomass hinders decomposition rates as the available soil N cannot meet the increased demand by decomposers (Chantigny et al., 1999). Additionally, Cassman et al. (2002) identified that the rise in average corn yield since the 1980s occurred while N fertilizer rates remained the same; indicating an increase in corn N use efficiency. Tollenaar and Lee (2006) also suggest that N use efficiency may be improved through advancements in genetic potential of modern hybrids. In effect, there has been an increase in the proportion of carbon relative to the quantity of available N in the ecosystem for decomposition. Thus, increasing stover biomass further impedes residue decay. Nitrogen fertilization has been shown to accelerate tissue degradation in controlled lab settings (Green et al., 1995; Kochsiek and Knops, 2013); however, limited success has been observed in the field (Bundy and Andraski, 2002; Kochsiek and Knops, 2013). Bundy and Andraski (2002) comment that corn stover decay is not responsive to fall N application since decomposition is reduced more by low temperature as opposed to N deficiency. By spring, the fall applied N may be lost from the soil. This suggests that spring applied N may accelerate decomposition rates more than fall applied, since soil temperature is above freezing and environmental losses would be minimized.

The *Bt* hybrids have been indicated to be responsible for greater residue quantities at the time of soybean planting. The argument is that *Bt* hybrids have altered the chemical composition of corn stover, mainly increased lignin content, such that litter quality is reduced and residue is more difficult to decompose. It is well documented that lignin content is indeed negatively related to decomposition rates due to low enzymatic digestibility (Satchell, 1974; Heal et al., 1997; Sewalt et al., 1997; Tovar-Gomez et al., 1997). Many studies confirm higher lignin content in *Bt* hybrids than closely related non-*Bt* isolines (Al-Kaisi and Guzman, 2013; Flores et al., 2005; Martin et al., 2004; Saxena and Stotzky, 2001). However this is a point of contention as other labs indicate this is false (Rossi et al., 2003; Jung and Shaeffer, 2004; Mungai et al., 2005; Yanni et al., 2011). Regardless, much of the literature demonstrates indifferent decomposition rates between *Bt* and non-*Bt* hybrids (Al-Kaisi and Guzman, 2013; Lehman et al., 2010; Sewalt et al., 1997; Zwahlen et al., 2007). In light of this evidence, many farmers continue to maintain the notion that residues of *Bt* hybrids are still more robust in the spring than non-*Bt* hybrids. One possible explanation could be that similar amounts of easily digestible, non-structural carbohydrates are decomposed in both hybrids over winter; however *Bt* hybrids often comprise a higher lignin content. Since lignin is a less digestible plant material relative to other chemical components, *Bt* hybrids would appear more robust in the spring. Another possible explanation may be that the majority of *Bt* decomposition studies cut and bury the residue, biasing decomposition measures toward incorporated conditions. Decomposition on the surface can be reduced by as much as 30% relative to buried residue (Gregorich and Ellert, 1994; Kochsiek and Knops, 2013; Parker, 1962). If there are differences in lignin content between *Bt* and non-*Bt* hybrids, there may be potential for differences in decomposition when the residue remains on the surface. Contrary to this theory, Al-Kaisi and Guzman (2013) observed similar decay between *Bt* and non-*Bt* residue whether incorporated or not. In addition, decomposition response to N application was unaffected by transgenic traits, despite higher lignin content in the *Bt* hybrid (Al-Kaisi and Guzman, 2013). However, the study was conducted by placing residue into mesh bags biasing decomposition towards horizontal residue conditions. *Bt* hybrids may exemplify reduced lodging relative to non-*Bt* hybrids due to greater lignin content (if it exists) or less insect feeding and crop damage. In effect, standing residue may not decompose as rapidly as horizontal residue due to less surface contact with decomposing microbes (Satchell, 1974; Stemmer et al., 1990). Regardless of whether *Bt* hybrids influence residue composition, soybean production has likely been affected more by increasing residue quantities. Thus residue management practices must be investigated to determine the effects on soybean performance.

1.2 Residue effects on soil properties

Crop residue has been shown to restrict soil water loss and delay soil warming (Horton et al., 1996; Klocke et al., 2009; Mitchell et al., 2012; Vyn et al., 1998). Reducing residue coverage on the soil surface, both through incorporation or removal, can reduce soil moisture content and increase soil temperature at soybean planting (Fortin, 1993; Vyn et al., 1998; Wilhelm et al., 1986). Residue cover is therefore identified as the leading cause of the soil moisture and temperature differential between NT and CT (Horton et al., 1996; Vyn et al., 1998; Wilhelm et al., 1986). Specifically, Vyn et al. (1998) reported that volumetric water content at planting was up to two times greater in NT than fall tilled systems. In that study, removal of previous crop residue (i.e., a bare NT soil) frequently eliminated soil moisture differences between tilled and NT soil. In Ontario, retention of soil moisture in NT is problematic as it delays soil warming and may delay planting date relative to CT.

Mitchell et al. (2012) explains that evaporation from saturated soils is energy driven, from energy sources such as wind currents or solar radiation. Extrapolating this observation to tillage systems, soil water content is higher in NT than CT because surface residue obstructs energy from contacting the soil surface. Reflective properties of lightly coloured crop residue reflect shortwave radiation, inhibiting energy absorption by the soil (Bussiere and Cellier, 1994; Horton et al., 1996; Tanner and Shen, 1990). This shading effect reduces air temperature at the soil surface and reduces evaporation potential (Blevins et al., 1983; Klocke et al., 2009; Mitchell et al., 2012). In nearly complete surface residue covered fields, Klocke et al. (2009) found that evaporative water loss was reduced by 50 – 65% compared to bare soil.

It is suggested that soil drying can be further slowed if residue biomass increases. However, the degree to which evaporation is limited depends upon the percent coverage, orientation, and distribution of surface residue. Increasing residue cover on the soil surface corresponds to increased reflected solar radiation (Horton et al., 1996; Mitchell et al., 2012). This would indicate that the orientation of the residue could influence evaporative water loss. If residue orientation is vertical (above the soil surface) as opposed to horizontal (on the soil surface), the amount of soil cover would be reduced. This exposes more bare soil to solar radiation. In theory, flattening residue with light tillage, wide depth gauge wheels on a narrow row spaced seed drill, or stalk chopping heads on combines may delay soil drying. Bristow (1988) confirms that greater evaporation potential is possible with vertical residue because the bare sections of soil are absorbing radiation when it is most intense and perpendicular to the soil surface. In effect, soils under vertical residue were found to be 3˚C warmer than soil under horizontal residue. However the former soil was still 7˚C cooler than a bare soil (Bristow, 1988). Although vertical residue does not eliminate soil moisture and temperature differences between CT and NT, the temperature difference between CT and NT can be exacerbated when residue is stalk chopped and not managed properly thereafter.

Similar to Bristow (1988), Aase and Siddoway (1980) observed temperature differentials with residue orientation but credited an increase in air turbulence across the soil surface with vertical residue orientation. Air movement augments diffusive water loss, allowing the soil to dry and warm more rapidly than residue covered soil. When residue is flat on the soil surface, thickness and reduced porosity of surface residue limit evaporation through restrictions in air movement and radiation transmittance. Increasing the thickness of the residue layer further reduces radiation transmittance (Tanner and Shen, 1990) along with air movement across the soil surface (Aase and Siddoway, 1980). If the residue is chopped into fine pieces or compacted, pore space is compressed which minimizes air movement. Ultimately restrictions to air movement and light transmittance diminish evaporative potential (Aase and Siddoway, 1980; Horton et al., 1996). Because increasing residue biomass likely results in amplified soil coverage and residue thickness, it would seem that greater residue biomass does not influence evaporation directly, but rather through these secondary effects (Mitchell et al., 2012; Tanner and Shen, 1990). In effect, rising corn yields and residue biomass will accentuate the soil moisture and temperature differential between NT and CT.

1.3 Increasing residue effects on planter type performance

The importance of planter configuration has been demonstrated in corn. Emergence uniformity, emergence speed, consistent plant-to-plant spacing and grain yield are improved with well maintained and well equipped seeding equipment particularly in NT conditions (Liu et al., 2004). Similarly, seeding soybeans in NT demands more advanced planting equipment than in conventional systems. Surface residue along with greater soil penetration resistance in NT (Gantzer and Blake, 1978) limits the ability of a conventional drill to slice through surface residue and to penetrate the soil for uniform seeding depth. No-till drills have improved performance in these adverse conditions, as the seed openers have greater down pressure for improved penetration of both residue cover and compacted soil. Some NT drills are equipped with a coulter ahead of the seed opener for improving seed placement and seedbed preparation. However, NT drills continue to lack the seed spacing and depth uniformity abilities of a row-unit planter (Bohner and Earl, 2010; Bertram and Pedersen, 2004). The importance of seed spacing in soybean has not been extensively demonstrated. It is assumed that minor variability of within-row seed spacing is inconsequential in regards to yield. The vegetative and reproductive plasticity of individual soybean plants compensate for spaces between neighbouring plants or for plants which are less productive (Andrade and Abbate, 2005; Carpenter and Board, 1997; Egli, 1993; Vega et al., 2000). Yet Moore (1991) reported that full compensatory growth is not always attainable. In that study, soybean seed yield increased by up to 257 kg ha^{-1} when plants were equidistantly spaced as opposed to non-equidistantly spaced plants. Therefore potential yield loss associated with uneven seed spacing can be minimized if seeded with a row-unit planter.

Seeding depth uniformity is thought to be of greater concern than seed spacing in comparing yield performance of seed drills to row-unit planters. Non-uniform seeding depth results in uneven access to moisture, variable germination, and seedling emergence (Staton, 2013). Seeding depth >0.06 m delays emergence and increases plant mortality due to increased exposure to seedling stresses such as infection by soil borne diseases, cold soils, or crusting (Banks and Gilmour, 1979). In contrast, shallow seed placement (i.e., <0.02 m) can reduce seedling survival as moisture may be insufficient for germination or to support seedling growth. Seed access to moisture may be variable with drill-type planters with uneven seed placement, poor seed to soil contact, and failure to close the seed trench (Wagner-Riddle et al., 1994). Increased seedling mortality can theoretically limit yield potential through suboptimal plant stands. Better seed placement with row-unit planters has been shown to increase stands by 4 – 17% compared to drills when planted at a similar seeding rate (Bohner, 2010; Staggenbord et al., 2004).

Increasing residue quantities and stalk robustness exacerbate non-uniformity in NT drill performance. Residue interferes with planting equipment by creating uneven surface conditions, reducing disc penetration, and hair-pinning of the seed (Wagner-Riddle et al., 1994). This results in inconsistent seeding depth, and ultimately reduced populations (Siemens et al., 2004). Modern row-unit planters overcome these limitations through: i. the inclusion of a coulter, designed to cut through residue ahead of the row openers (Kulkarni, n.d.) ii. utilization of double disc openers, which have been shown to have less seed placement spatial distribution than single disc openers, as found on drills (Karayel and Ozmerzi, 2007), iii. greater vertical movement of individual seeding units to manage uneven terrain (Grisso et al., 2001), and iv. regulation of individual row-unit down pressure to maintain uniform seeding depth across variable field conditions (Anonymous, 2013). Some planters also are equipped with row cleaners, which remove residue away from the seed row. Most of these options are unavailable on drills as the features are not conducive to narrow row spacing. The combination of some, or all of these features would suggest row-unit planters can attain greater seedling survival and yield than NT drills (Bohner, 2010; Staggenbord et al., 2004; Wagner-Riddle et al., 1994), particularly where high amounts of residue are present on the soil surface. However, row planter vs. drill response to different tillage systems and across variable levels of residue cover has not been thoroughly investigated. Therefore, further research must be conducted to determine if limitations of the NT drill can be overcome with some minimal tillage ahead of soybean planting, with the removal of residue, or even with the use of a row-unit planter.

1.4 Increasing corn residue effects on soil nitrogen and soybean performance

Soybeans form symbiotic relationships with rhizobia, but on average only 50 – 60% of total plant N is derived from N fixation (Di Ciocco et al., 2011; Schipanski et al., 2010; Salvagiotti et al., 2009). The remaining demand is acquired from inorganic N pools in the soil. During early vegetative development, seed reserves and root uptake are solely responsible for increases in total plant N content, and depletion in soil mineral N would effectively restrict soybean N accumulation at this time (Rufty et al., 1984). Since N stimulates early growth in soybeans (Starling, 1998; Osborne and Riedell, 2011) a low soil N supply when soybean plants are most dependent upon root absorption may hinder early season biomass accumulation. Restrictions in early season soybean growth have been shown to reduce grain yield up to 52% (Meese et al., 1991; Oplinger and Philbrook, 1992; Osborne and Riedell, 2006; Vyn et al., 1998).

Consequently, increasing corn stover may increase microbial demand for soil mineral N and lower soybean grain yield. Therefore, soybeans may benefit from an early season N fertilizer application when available soil N is low. This is particularly true in NT conditions as surface residue may also hinder soil warming and delay N mineralization (Andraski and Bundy, 2008; Green et al., 1995).

Supplemental N applications may temporarily restore mineral N pools and accelerate the decomposition of crop residues in the short term (Green et al., 1995). However, soybean response to N fertilizer in fields with high corn residue biomass is still unclear. Much of the literature supports the notion that N fertilizer inhibits nodule formation and activity, as the intricate relationship between rhizobia and soybean is easily influenced by changes in soil NH_4^+ and NO_3^- concentrations (Osborne and Riedell, 2011; Salvagiotti et al., 2008; Salvagiotti et al., 2009; Beard and Hoover, 1991). In many instances the yield response to N fertilizer is negligible since the increase in N uptake is usually offset by the reduction in N fixation (Mehmet, 2008; Salvagiotti et al., 2008). Contrastingly, other researchers have found positive yield responses to N application. Salvagiotti et al. (2009) found a 5% yield increase to in-season N fertilizer application. They maintain that the yield response is more pronounced in high yielding environments since the proportion of nodule N contributions to total plant N is reduced in these conditions. Other scientists contend that soybeans would more likely respond to N application in low yielding environments or in cool soils where N mineralization is reduced and nodulation is delayed (Osborne and Riedell, 2011; Sij et al., 1979, Hardy et al., 1971). For instance, Osborne and Riedell (2006) found a 6% yield increase to small amounts of N applied at planting (i.e., less than 16 kg N ha^{-1}). They attributed this response to accelerated dry matter accumulation prior to the R4 growth stage. Although a minor decline in early nodule activity was observed, it was more than offset by the increase in root N uptake (Osborne and Riedell, 2011). Similarly, Beard and Hoover (1991) explain that nodule number is relatively unaffected if N application rates are kept below 56 kg N ha^{-1}. However, the threshold fertilizer rate likely depends on existing soil N concentration. Comparatively, positive yield responses to N are also dependent upon soil nitrate levels. For instance, Scharf and Wiebold (2003) obtained a 67 kg ha^{-1} yield advantage to N application if soil tests were below 50 kg NO_3 ha^{-1} in the top 0.9 m measured at planting. Lamb et al. (1990) observed even greater yield responses to N (up to 538 kg ha^{-1}) with soils below 90 kg NO_3 ha^{-1} in the top 0.6 m. Scharf and Wiebold (2003) suggest it may be possible that accelerated early season growth from N application is more influential in shorter growing seasons as it accelerates early season growth. However, since the literature indicates soybeans respond to N application in low NO_3 environments, it would appear that soybeans would also benefit from a small N application at planting in high amounts of surface residue. Decomposition of large quantities of corn residue immobilizes mineral N and reduces soil nitrate concentration. However further research is required to determine if there is a response to N fertilizer in different levels of surface residue attained through various tillage systems, residue removal levels or some combination of the two.

1.5 Tillage effects on corn residue, soybean yield, and yield influencers

Surface residue restrictions on soil drying and warming is widely blamed for the deficit in NT soybean yield in northern growing regions such as Ontario (DeFelice et al., 2006; Toliver et al., 2012; Vasilas et al., 1988; Vyn et al., 1998). Pre-plant differences in soil moisture and temperature between NT and CT may extend into the early growing season and affect plant growth and development (DeFelice et al., 2006; Johnson and Lowery, 1985; Vyn et al., 1998; Yusuf et al., 1999). Differences in speed of emergence, plant density, growth, development, and nodulation may be detected. These early season canopy differences could potentially impose a yield deficit to NT soybeans. The following sections describe the response of early plant growth parameters to soil temperature and extrapolate these responses to observations in tillage systems.

1.5.1 Emergence and plant density

Delayed seedling emergence prolongs the exposure to stresses, such as disease, soil crusting, and crop injury (Hammon et al., 2002; Meese et al., 1991; Nyvall, 1999; Vyn et al., 1998). It may also increase the risk for plant mortality which can result in yield loss (Bohner and Earl, 2010; De Bruin and Pedersen, 2008; Elmore, 1991). Therefore, expedient hypocotyl elongation and emergence may be important for maintaining plant stands and maximizing yield. Optimal soil temperature for rapid hypocotyl elongation and seedling emergence is identified to be in the range of 25 – 30˚C (Hatfield and Egli, 1974; Hopper et al., 1979; Tyagi and Tripahti, 1983). Weber and Miller (1972) demonstrate less time is necessary to reach 50% emergence as soil temperature is increased. Specifically, emergence required six days at 15˚C, four days at 20˚C, and three days at 25˚C when planted at the same seeding depth (the actual planting depth was not reported). These results demonstrate that the days to emergence were reduced more significantly with a temperature change from 15˚C to 20˚C compared to 20˚C to 25˚C. Similar trends were also exhibited by Hatfield and Egli (1974) and Hopper et al. (1979). Exponential change in enzyme activity to small temperature fluxes at low temperatures may be partially responsible (Duke et al., 1979); however, Hopper et al. (1979) also explain that impedance to hypocotyl elongation is exaggerated by mechanical resistance at low soil temperatures.

Soil temperature below 10˚C adversely affects germination and emergence, particularly if experienced by seeds during imbibition. This situation is referred to as imbibitional chilling or cold injury, and may result in cracked cotyledons, reduced hypocotyl growth rate, and decreased plant density (Hobbs and Obendorf, 1972; Jones and Gamble, 1993). Hobbs and Obendorf (1972) report a 28% reduction in seedling survival when imbibition temperatures were dropped from 12˚C to 5˚C. Jones and Gamble (1993) similarly report only 44% of the seeds emerged when planted into 3˚C soil as opposed to 58% survival in 10˚C soil (a 24% population reduction over 7˚C). The probability of experiencing imbibitional chilling and subsequently reduced population is elevated with early planting (i.e. in April), due to greater risk of cold temperatures. Given that yield is positively correlated with plant density, especially at low densities (De Bruin and Pedersen, 2008; Elmore, 1991), significant population decline will reduce seed yield.

Slower emergence and thinner plant stands may be observed in NT relative to CT as soil temperature is generally 2 – 3˚C lower in NT (DeFelice et al., 2006; Johnson and Lowery, 1985; Yusuf et al., 1999). Vyn et al. (1998) found that NT emergence was consistently delayed by 1.3-1.6 days, and populations were reduced anywhere from 17 – 80% compared to CT, depending on the site and year. Meese et al. (1991) also observed delayed emergence with NT (approximately three days difference), but found equal stand densities early in the season. Interestingly however, population at crop maturity in NT was 8% lower than CT in that experiment. Regardless, both studies incurred yield losses of 8 – 57% in normal to wet growing season environments with NT (Meese et al., 1991; Vyn et al., 1998). Oplinger and Philbrook (1992) similarly report reductions of population and yield in NT relative to the moldboard plow by 15% and 11%, respectively. Elmore (1991) also observed that population and yield were reduced by 27% and 17%, respectively, with NT in 1987, but contrastingly reported no differences relative to a disced treatment in 1986. Other research in Iowa and Wisconsin did not incur differences in population nor emergence amongst tillage systems (Kiszonas, 2010; Pedersen and Lauer, 2004; and Turnman et al., 1995). Variability in emergence speed and stand density in response to tillage indicate environmental conditions influence plant response. However, there is greater risk for imbibitional chilling and differences in emergence and plant densities between NT and CT during early planting, particularly with large amounts of corn residue on the soil surface.

1.5.2 Crop growth and development

Crop growth and development is also influenced by soil temperature; gaining biomass and developing more rapidly as temperature increases (Duke et al., 1979; Meese et al., 1991; Weber and Miller, 1972). In a change of soil temperature from 13˚C to 20˚C, soybean photosynthetic rates can increase three-fold, effectively expediting biomass accumulation (Duke et al., 1979; Lindemann and Ham, 1979). Likewise, Weber and Miller (1972) demonstrate vegetative development is accelerated through increasing soil temperature. The time intervals from planting to the V1 growth stage (first trifoliate unfolded, Fehr et al., 1971) were 23, 17, and 15 days at 15˚C, 20˚C, and 25˚C respectively. Delayed vegetative biomass accrual and canopy fill may reduce yield as light interception is reduced, and flowering may occur premature to when the soybean plant can simultaneously support reproductive and vegetative growth (Board and Hall, 1984; Egli and Leggett, 1973). However, a season delay in the initiation of reproductive development may also reduce yield since a condensed period of reproductive growth diminishes yield potential (Egli et al., 1978). In low soil temperatures, the number of days to reach the R1 growth stage (first flower, Fehr et al., 1971) is lengthened, which effectively reduces the duration of growing season available for pod and seed growth. Weber and Miller (1972) report that it took 78 days in 15˚C, 69 days in 20˚C, and 67 days in 25˚C to reach the R1 growth stage. Similar to the studies on speed of emergence, this research reveals greater divergence in developmental progress across a 2 – 3˚C range below 20˚C than above 20˚C. Since the risk for low soil temperature is increased early in an Ontario growing season, minor soil temperature differences can have drastic effects on growth and development. This theory suggests that soybean plants in NT would be smaller and less developed than those grown in CT, as soil temperature is a few degrees warmer in CT (DeFelice et al., 2006; Johnson and Lowery, 1985; Yusuf et al., 1999). Yusuf et al. (1999) confirms that prior to the R5 growth stage (beginning seed fill, Fehr et al., 1971) total plant biomass was 15 – 20% greater in CT soybeans compared to NT in Illinois. Contrasting evidence from Kiszonas (2010) in Iowa reveals similar growth and development between NT and CT soybeans. Pedersen and Lauer (2004b) also did not detect vegetative growth differences between tillage systems in Wisconsin. These differences are likely attributed to differing environmental conditions early in the growing season.

Occasionally retarded early plant growth and development is observed in NT relative to CT, but it does not translate into a yield deficit. The phenomenon is referred to as compensatory growth. Webber et al. (1987) and Yusuf et al. (1999) observed 15 – 23% more vegetative biomass by R1 in CT over NT, yet the final yield difference was insignificant. Greater leaf area in CT than NT supported a higher crop growth rate early in the season, while after R5 crop growth rate in NT exceeded that of CT due to greater net assimilation (Yusuf et al., 1999). Pedersen and Lauer (2004b) also found that biomass accumulation was greater in NT than CT after R4 (late pod set, Fehr et al., 1971). This ability allows NT soybeans to compensate in final grain yield. Board and Harville (1994) also defend the idea of compensatory growth in soybeans, commenting that optimal light interception during vegetative and early reproductive growth was not required to maximize soybean yield.

1.5.3 Nodulation

Nodules contribute a substantial portion of total plant N through biological fixation, and assist in producing an economical soybean crop. Limitations in N fixation may negatively affect soybean performance since the crop may be N deficient. Nitrogen is known to accelerate growth and can enhance crop yield (Salvagiotti et al., 2009; Osborne and Riedell, 2011; Thibodeau and Jaworski, 1975). Delayed nodulation, reduced nodule number and nodule activity constrains the supply of N and may reduce plant growth and yield. Delayed nodule formation has been observed with decreasing root zone temperature due to slowed plant development (Zhang and Smith, 1994). In that study, N fixation was delayed at a rate of two days for every 1˚C decrease in soil temperature from 25˚C to 17.5˚C. Low soil temperature also reduced the success of rhizobia infection, resulting in fewer nodules per plant than soybean plants grown in warm soil temperatures (Duke et al., 1979; Weber and Miller, 1972; Zhang and Smith, 1994). Weber and Miller (1972) observe that there was an average of 18.8 and 96.5 nodules $plant^{-1}$, 42 days after planting in 15˚C and 25˚C soil respectively. Zhang and Smith (1994) report similar disparity in nodule number across root zone temperatures. While neither of the aforementioned studies obtained grain yields, Hume and Blair (1992) demonstrate that yield is positively correlated with nodule number under field conditions. Compounding the effect of fewer nodules, low soil temperature has also shown to inhibit Nitrogenase activity (Duke et al., 1979; Lindemann and Ham, 1979), effectively reducing ammonia synthesis and the plant's N supply. Collectively, low root zone temperature can have a significant, negative impact on total fixed N and grain yield. Therefore, lower soil temperature observed in NT relative to CT may result in minor reductions in nodule number, activity, and formation in NT (Hardy et al., 1971).

Contrary to this theory, it appears that early season nodule number may be actually greater in NT than CT (Lindemann et al., 1982; Mendes et al., 2003; Wagner-Riddle et al., 1994). However, nodule weight and activity per plant were indifferent between tillage systems (Lindemann et al., 1982). Van Kessel and Hartley (2000) support greater nodulation and N fixation under NT conditions and attribute the response to delayed mineralization. Since nodulation is reduced with increasing soil N concentration, greater N mineralization experienced in higher soil temperatures (i.e. CT) moderated nodule formation. Yet, in light of recent increases in corn residue biomass and the potential for an accentuated soil temperature differential between tillage systems, there is concern that soybean development and the onset of nodulation will be delayed in NT relative to CT. If N fixation is delayed under high surface residue scenarios, soybeans may be briefly limited in N, impeding growth. Applying a small amount of N fertilizer, particularly prior to nodule formation, may alleviate this temporary deficiency, accelerate crop growth, and potentially improve seed yield.

1.5.4 Soybean yield

Soybean response to tillage system is dependent upon many variables, and early season plant growth differences do not always result in yield differences. In fact the success of NT is thought to be influenced by soil type, duration in NT production, and growing season conditions. Soil drainage is another conduit for water loss. Whether naturally or artificially drained, well drained soils can minimize the soil moisture content disparity between NT and CT. Differences in drainage across soil types are partially responsible for the variable success of NT production, with well drained fields being more responsive to NT in Ontario. In general, yield in NT is similar to CT on coarse textured soils but is more variable on fine textured soils (DeFelice et al., 2006; Roland, 1992; Vyn et al., 1994). Yin and Al-Kaisi (2004) contend that a yield lag with NT can still occur on well drained soil; but mentioned that the occurrence is less frequent (4 out of 15 years, 26%) relative to poorly drained soils (5 out of 13 years, 38%). Yin and Al-Kaisi (2004) also observed the magnitude of yield differential between NT and CT was greater on poorly drained soils than well drained, at 8.2% and 5.4% respectively. Supporting research on fine textured soils indicate an 8% (West et al., 1996) and 13% (Vyn et al., 1994) yield loss with NT vs. the moldboard plow. Similarly, Lueschen (1992) found 5% yield improvement with disced soil relative to NT on a clay loam soil. Fine textured soils rely upon evaporation for water loss and since surface residue impedes this pathway, there is a tendency for NT to be disadvantageous on poorly drained soils.

Advocates of NT claim that even on poorly drained soils, potential yield reductions can be minimized through continuous, long-term NT practices (Dick et al., 1991; Yin and Al-Kaisi, 2004; Toliver et al., 2012). Over time, established macropore continuity aids in the filtration and drainage of excess soil moisture (Seta et al., 1993; VandenBygaart et al., 1999). Although duration in NT production may improve NT soybean yield in some soils, this may not always be the case (Toliver et al., 2012). Yin and Al-Kaisi (2004) found that the magnitude of the yield deficit to NT was actually increased from 7.4% to 10.8% over 10 years of NT production in poorly drained soils. Johnson (1994) also noted that comparative yield between NT and CT was not improved over 18 years of NT production. Similarly, long-term tillage research in Elora, Ontario has shown that the incidence of a NT yield deficit remains evident in certain years even after 34 years of NT production (Deen unpublished). Therefore, it appears that yield response to NT is more dependent upon year as opposed to the duration of NT practices.

Seasonal growing conditions can have a profound effect on soil warming, drying and success of NT soybeans. Review articles illustrate that moisture conservation effects of surface residue actually boost NT soybean yield above CT in arid environments (DeFelice et al., 2006; Toliver et al., 2012). Comparatively, temperate environments, such as the northern Corn Belt and Ontario, may be prone to NT yield deficits because of delayed soil drying and warming. Even within Ontario, a gradient of increasing magnitude and frequency of a NT yield deficit is observed as growing seasons are shortened. Long term tillage research in Elora, Ontario (a well drained, loam soil, 2700 CHU) demonstrated that in two out of the past 10 years, NT yielded significantly less than the Moldboard Plow (Deen, unpublished). The yield loss was 16.3% and 43.3% in 2003 and 2009 respectively. Similar long term tillage trials from Ridgetown, ON (well drained, Brookston clay loam soil, 3400 CHU) revealed equal yields to an advantage of 9.5% with NT (Hooker, unpublished). The shorter growing season may be more prone to a NT yield deficit because of: i. delayed soil warming delays planting and further compresses the growing season, ii. delayed emergence and early crop growth affect yield more (Kladivko et al., 1986), and iii. a compressed growing season limits the opportunity for late season compensatory growth.

Inconsistent yield trends of NT relative to CT from year to year within a location indicate that seasonal weather trends are responsible. In the research from Elora, it was noted that NT yields were less than CT when the seasonal average air temperature was below average and rainfall was above average (Environment Canada, 2013). Other studies support this finding as they also observed a NT yield reduction in cool and wet growing seasons (Dick et al., 1991; Toliver et al., 2012). It is believed that soil temperature and moisture differences between NT and CT are intensified and prolonged into the growing season under cool and wet conditions (Herbek et al., 1986). Therefore, obtaining consistent results in tillage research is challenging as variable environmental conditions strongly influence the outcome. Research must be conducted across multiple years at different locations in order to truly decipher soybean response to tillage.

1.6 Minimum tillage systems

Although differences in emergence, plant density, crop growth and development were compared primarily between CT and NT, it is important to address the influence of minimum tillage on these parameters of soybean yield determination. Minimum tillage is a term used to describe an implement that works the soil less aggressively than CT and would be categorized as a conservation tillage system, maintaining a minimum of 30% residue cover (Conservation Technology Information Center, 1997). The objective is to attain the benefits of both CT (soil drying, warming, and mechanical weed control) and NT (reduced labour requirements, fuel consumption, and erosion protection). Implements categorized as minimum till may include vertical tillage tools, zone-tillage, Discs, and Disc Rippers.

Since minimum tillage generally increases soil temperature above NT, but not to the extent of CT (Griffith et al., 1977; Kladivko et al., 1986; Sindelar et al., 2013), theory dictates that minimum till effects on the aforementioned canopy measures would fall between that of NT and CT. Oplinger and Philbrook (1992) support this theory demonstrating that increasing plant density was observed from NT (34.3 plants m^{-2}) to minimum till (para plow – leaving 66% residue cover [35.3 plants m^{-2}]) to the moldboard plow (39.5 plants m^{-2}). Similar trends were also reported with emergence and grain yield. However, comparable to the differences between NT and CT, inconsistent response patterns are also observed with reduced tillage throughout the literature. Vyn et al. (1998) observed that soybeans seeded in fall disc, chisel plow, and zone-till treatments have the capacity to emerge just as rapidly as CT and maintain equal plant populations. Both canopy measures in minimum till were greater than NT. Comparatively, emergence, population, and yield may be indifferent between NT, CT, and various types of minimum tillage systems (Kiszonas, 2010; Lueschen et al., 1992; Perez-Bidegain et al., 2007; Turnman et al., 1995). Factors such as percent residue cover, residue orientation, seasonal timing of tillage, type of tillage implement, and environmental conditions may be potential causes for this variable response. Vyn et al. (1998) demonstrate that population and emergence speed were reduced in NT relative to tilled systems; but removing the residue abolished those differences. As corn stover biomass increases, there is potential for more distinct differences in soil temperature across tillage systems, and possibly with plant growth parameters as well. Therefore it is imperative to re-evaluate soybean performance across a range of tillage systems and across multiple residue management strategies, especially as the quantity of corn residue is increasing and becomes more problematic.

1.7 Residue removal

Residue removal may potentially create a short-term yield improvement opportunity in NT fields in Ontario, or fields with high surface biomass. Numerous studies have demonstrated decreasing surface coverage corresponds to drier and warmer soil (Andraski and Bundy, 2008; Doran et al., 1984; Horton et al., 1996; Klocke et al., 2009; Mitchell et al., 2012; Sindelar et al., 2013; Toliver et al., 2013; Vyn et al., 1998; Wagner-Riddle et al., 1994; Wilhelm et al., 1986). As just illustrated, warmer soil temperature accelerates speed of emergence (Hatfield and Egli, 1974; Hopper et al., 1979) and plant development (Weber and Miller, 1972), increases seedling survival (Meese et al., 1991; Oplinger and Philbrook, 1992), and plant growth (Weber and Miller, 1972; Yusuf et al., 1999). Individually and combined these responses increase yield potential. Residue removal studies in Ontario have generally revealed a positive soybean yield response to increased residue removal in NT conditions. Vyn et al. (1998) consistently demonstrated at two locations over three years that residue cover in a NT system decreased soybean yield. Specifically, treatments with residue retained yielded 40 – 90% of those in the bare NT soil. Similarly, preliminary results in Bohner (2010) revealed a 0.47 Mg ha^{-1} (7 bu ac^{-1}) advantage to removing residue in a NT production system. However, research on soybean response to residue removal in Ontario is limited and needs to be explored further; especially across different tillage systems. The objective is not to evaluate the long term consequences on soil productivity attributed to residue removal, but rather the short term benefit to soybean production.

1.8 Research opportunities

Soybean grain yield response to tillage is fairly well understood throughout the literature. Moisture tends to be the driving factor and in general, the success of NT follows an inverse relationship with soil moisture. Clay soils, short growing seasons, and years with cool wet springs tend to exacerbate the yield differential between NT and CT. Residue from the previous crop interferes with soil drying and warming (Doran et al., 1984; Toliver et al., 2012; Wilhelm et al., 1986) which is associated with slower early season plant growth and development. Although not always the case, these early season plant differences have translated into yield reductions. Soil moisture and temperature divergence between NT and CT are suspected to increase as residue biomass on the soil surface rises. NT may reduce soybean emergence, development, population, and nodulation compared to CT. However, the literature fails to address the effect on early season canopy measures and yield in different residue management systems, particularly in fields with high amounts of corn stover on the soil surface. The primary hypothesis of this research is that residue management strategies, such as minimal tillage, stalk chopping, residue removal, planter configuration, or nitrogen application can be used to alleviate the yield deficit observed with NT. Sub-hypotheses related to this overall hypothesis include i. reduced population and nodulation, and delayed emergence and development induced by tillage or residue removal treatments will result in lower yield ii. a row planter will achieve greater plant density than the drill, particularly in treatments with high surface residue coverage, and will thus yield higher in those treatments, and iii. treatments with high proportions of surface coverage will respond positively to N fertilizer. The objectives are to i. evaluate soybean yield in different residue management systems (tillage and residue removal) to determine if high quantities of surface biomass limit productivity ii. study early season soil and plant responses to residue management systems to dissect which variables are responsible for potential yield differences, iii. evaluate early and late season plant responses to planter type across a range of residue management systems, and iv. compare the effects of N fertilizer on soybean performance across multiple combinations of tillage and residue removal levels.

Chapter 2. Materials and Methods

2.1 Site descriptions

Field trials were conducted at two locations in 2011 as well as 2012, for a total of four site-years. Locations had corn as the previous crop with yield similar to or above the provincial average, and were level in topography. In 2012, sites were located in regions with a relatively short growing season (i.e. below 2900 CHU). In 2011, the trial locations were near Lucan, ON (43˚20'N, 81˚38'W, 3000 CHU, imperfectly drained Huron silty clay loam, 3.3% organic matter) and Moorefield, ON (43˚45'N, 80˚44'W, 2800 CHU zone, Perth loam with 3.3% organic matter). A field beside the 2011 Moorefield location was used in 2012, along with a second location 8 km North-West of Arthur, ON (43˚83'N, 80˚53W, 2600 CHU, imperfectly drained silt loam, 3.8% organic matter). Henceforth, the names of the locations will be referred to as Lucan11, Moore11, Arthur12, and Moore12 to distinguish locations and identify the year of study. Further descriptions of each field can be found in Appendix A.

2.2 Experimental design

At each location, ten 'tillage' treatments were established in a randomized complete block design with three replications. The treatments used in the study reflect customary tillage practices in Ontario, and were selected to attain different levels of residue cover of the soil. Treatments varied in either the timing of incorporation (fall and/or spring), type of implement, and residue chopping. All tillage operations were performed travelling parallel with the corn rows to make 6.1-m wide by 45.7-m long plots. The stalk chop treatments were produced with a flail mower in the fall. The mower was operated as close to the ground as possible (0.10 m above the soil surface). Border strips of 1.5 m width were used to separate tillage systems. The tillage systems implemented in this study include:

1. ***No-till*** (NT)

2. ***Stalk chop followed by No-till*** (SC + NT)

3. ****Stalk chop with fall and spring Residue Tillage Specialist*** *(RTS, Salford, Osceola, IA;* SC + Fall & Spring RTS) - one pass of the RTS in both the fall and the spring at 0.05 – 0.08 m depth. The implement consists of 2 sets of 0.55 m diameter fluted coulters followed by finger harrows then rolling harrows.

4. ***Fall & Spring RTS*** - one pass of the RTS in both the fall and the spring at 0.05 – 0.08 m depth.

5. ****Spring RTS*** - two passes of the RTS in at 0.05 – 0.08 m depth, on the day of, or before planting.

6. ***Fall RTS*** - two passes of the RTS in the fall at 0.05 – 0.08 m depth.

7. ***Fall Disc & Spring Cultivate*** - one pass of a tandem disc in the fall (0.07 - 0.10 m deep) followed by one pass of secondary tillage in the spring with the RTS (0.05 – 0.08 m deep).

8. ***Fall Disc & Cultivate*** - one pass of the tandem disc (0.07 - 0.10 m deep) and one pass of the RTS (0.05 m deep); both occurring in the fall.

9. ****Disc Ripper*** - one pass in the fall using a Disc Ripper (Salford, Osceola, IA) succeeded by secondary tillage in the spring with the RTS (0.05 – 0.08 m deep). The Disc Ripper possesses a front gang of straight blade discs (0.6 m diameter) followed by chisel shanks, operated at approximately 0.10 m and 0.25 - 0.30 m depth respectively. Rolling harrows are positioned on the rear.

10. ***Moldboard plow*** - a three, 0.36 m furrow Kverneland (Kverneland, Norway) roll-over plow was used in the fall (0.15 m deep). A field cultivator or RTS was used for secondary tillage in the spring.

*Treatments evaluating the starter N fertilizer treatments

Residue removal treatments were imposed as split-block treatments and were established in 15.4 m wide strips perpendicular to the direction of tillage whole plots. Three rates of residue removal were targeted and named No Removal, Nearly Complete Removal, and Intermediate Removal. Residue removal was performed prior to tillage operations but subsequent to any stalk chopping activities. The level of Intermediate Removal was achieved by visually estimating removal of 50% of residue biomass. Typically, the leaves and top half of the stalk were removed. Residue removal was accomplished travelling perpendicular to corn rows using a rotary hay rake in the Arthur12 and Moorefield locations, and using a tined wheel, angled side delivery rake at the Lucan11 site. Actual residue levels achieved were estimated through a variety of residue measures, as described in the succeeding section.

Planter type was evaluated as a split-split plot treatment on seven of the ten tillage treatments (NT, SC + NT, Fall & Spring RTS, Fall RTS, Fall Disc & Spring Cultivate, Fall Disc & Cultivate, and Moldboard Plow) and all residue removal levels. Planter types consisted of either a traditional NT seed drill (John Deere 1560) or a row-unit planter (no-till Kearney planter [Thamesville, ON]). Enhanced features of the row planter over the drill include vacuum seed singulation, double disc seed trench openers, wavy tillage coulters mounted in front of each seed row (operated at a depth of 0.03 – 0.05 m), a '20/20 Air force' row-unit pressure regulator by Precision Planting (to provide uniform down pressure and seed spacing), and a Valmar vacuum fertilizer spreader connected to 2 X 2 side banded disc openers. For the planter type treatments no fertilizer was applied (in either the drill or the row planter); however, the fertilizer discs were engaged while planting with the row planter. Both planter types seeded on row widths of 0.38 m centers. This was achieved in the drill by alternately blocking seed cups. In both planting units, eight rows were sown per plot to achieve split-split plot dimensions of 3.0 m x 15.4 m.

Starter N was evaluated as a split-split plot treatment on three of the ten tillage treatments (Spring RTS, SC + Fall & Spring RTS, and Disc Ripper). Starter N split plot treatments involved the comparison of no fertilizer (0 kg ha^{-1}) relative to the application of 56 kg N ha^{-1} (122 kg Urea ha^{-1} [46-0-0]). This is the same N rate used by Scharf and Wiebold (2002) and represents the lowest broadcast rate for commercial fertilizer equipment. Both N treatments were applied using the row planter. Drop tubes from the fertilizer hopper on the planter were disconnected from the side banding discs to broadcast the fertilizer on the soil surface.

See Figure 2 for a detailed visual of the experimental design.

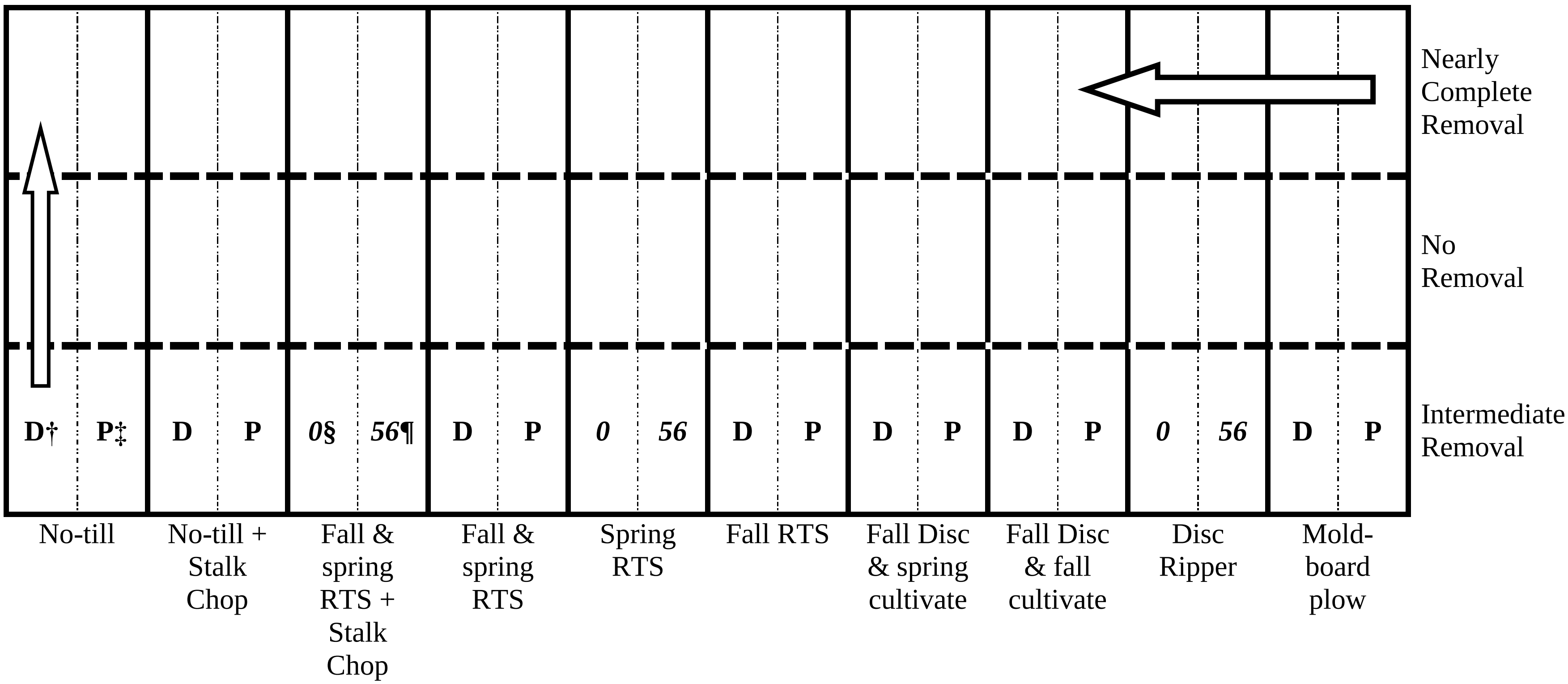

Figure 2-1. Example layout of a single replication of the experimental design.

Whole plots (tillage system) are outlined in the solid black line, residue removal split-plots are across tillage treatments and outlined by the thick dashed line, and planter type or nitrogen split, split-plots are outlined by the thin dashed line.

† **D** = Drill seeded on 0.38 m centers, no nitrogen

‡ **P** = Row planter seeded on 0.38 m centers, no nitrogen

§ ***0*** = 0 kg N ha^{-1} seeded with the row planter (same treatment as P)

¶ ***56*** = 56 kg N ha^{-1} applied at planting, seeded with the row planter

2.3 Cultural practices

Residue removal, stalk chopping, and fall tillage were conducted on November 9, 2010 for the Lucan11 site and on November 10, 2010 for the Moore11 site. Coincidentally, fall field operations were completed on November 9, 2011 for both the Arthur12 and Moore12 locations. Spring tillage procedures occurred the day of planting, except for Moore11 when it occurred a day prior. In 2011, planting was delayed to June 3rd due to wet weather conditions in the spring at both the Lucan11 and Moore11 sites. Comparatively, warm and dry conditions in 2012 allowed for early planting. At Arthur12 soybeans were planted on April 19th, while Moore12 was seeded on May 14th, which is the desired time for planting in the region. Pioneer cultivar 90M40 (DuPont Pioneer, Mississauga, ON) was planted at Arthur12 and both Moorefield locations, but cultivar 91M41 was sown at Lucan11 to better match the cultivar with the slightly longer growing season. Planting depth was set for 0.038 – 0.045 m and targeted seeding rates ranged between 444,600 – 494,000 seeds ha^{-1}. Actual seeding rates at each site depended on the population sown by the drill; and they were 518,700 seeds ha^{-1}, 439,600 seeds ha^{-1}, 496,500 seeds ha^{-1}, and 489,000 seeds ha^{-1} at the Lucan11, Moore11, Arthur12, and Moore12 sites, respectively. All of the seed was treated with Cruiser Maxx® (thiamethoxam, mefenoxam, and fludioxonil; Syngenta, Basel, Switzerland) fungicide and insecticide seed treatment. Soil fertility levels (see Appendix A) were sufficient for growing soybeans based on locally recommended fertilizer rates (OMAFRA, 2009); thus fertilizer was not applied at any of the sites (other than the N treatments). Weeds were controlled through application of glyphosate [N-(phosphonomethyl) glycine] at a rate of 890 g a.i. ha^{-1} when substantial weed pressure was observed. Two applications were performed if necessary. The tractor and sprayer were driven in the buffer zone between tillage treatments.

2.4 Data collection

Note: Unless otherwise stated, all measurements were obtained on the individual split-split plot level.

2.4.1 Residue analysis

Residue quantity and distribution were evaluated through two different measurements. Biomass was collected to determine residue mass within each replication and verify the residue mass differences in the removal treatments. A visual assessment, including the line transect method (Sloneker and Moldenhauer, 1977) was used to generate a soil surface coverage value in the split plot level.

2.4.1 a) Residue biomass

Corn residue was collected for biomass determination only in the spring after planting for the 2011 crop year, but for the 2012 season, residues were collected in both the preceding fall (2011) and the spring (2012). Additionally, biomass samples were only collected from the NT (without stalk chopping) treatments in 2011, whereas the 2012 season also had samples gathered from the Fall RTS after tillage operations. Within the tillage systems measured, surface residue was gathered from a 0.5 m^2 area in the fall and two 0.5 m^2 sections in the spring from each of the three levels of residue removal. Samples were collected from within a 2.0 m buffer zone between planter type or nitrogen split-split plots to avoid extracting residue from the area designated for grain harvest. Soil was washed from the residue, and then oven dried at 80˚C for a minimum of three days.

2.4.1 b) Line transect

Soil residue cover was measured twice in every tillage x removal split-plot using the line transect method (Sloneker and Moldenhauer, 1977), once in the fall after tillage operations and the second in the spring after planting. Markings spaced every 0.15 m on a 3.8 m rope were inspected for the presence or absence of residue per tillage x residue removal split-plot. In 2011 only one rope length was used but three lengths in the 2012 season.

2.4.2 Soil moisture and temperature

Instantaneous measures of soil moisture and temperature were recorded periodically from planting through to 28 days after planting. A Fieldscout TDR 300 soil moisture meter (Spectrum Technologies Inc, Plainfield, IL) was used to measure the average volumetric water content of the top 0.12 m of soil through time-domain reflectometry (TDR). Soil temperature was measured with a thermometer probe (Spectrum Technologies Inc, Plainfield, IL) to a depth of 0.05 m. Measurements were acquired 0, 3, 7, 14 and 28 days after planting (DAP) in both 2011 and 2012. Three to four subsamples were obtained randomly from each split-split plot from within the seed rows. In 2011 the subsample values were recorded, but 2012 data consists of only the plot averages. In both years, plot averages were utilized in the statistical analyses.

2.4.3 Emergence

The number of days from planting to 50% soybean emergence was only recorded in the 2012 growing season. At Arthur12, 50% emergence was estimated when 185,000 plants ha^{-1} emerged vs. 244,000 plants ha^{-1} at Moore12. Emergence was recognized when the cotyledons extended above the soil surface. Percent emergence of each split-split plot was estimated every two days when seedlings began to emerge. Days to 50% emergence could then be calculated using the emergence estimates for the days surrounding 50%. For the few select experimental units which did not achieve 50% emergence by the last rating day, those plots were designated an emergence timing 0.5 days longer than the latest rating day.

2.4.4 Development

In 2011, plant development was measured at the VC and V3 development stages (unifoliate and three trifoliate, Fehr et al., 1971). The rating technique at VC consisted of visually estimating the proportion of plants at the VC stage with the remainder of plants assumed to be at the VE stage (cotyledon, Fehr et al., 1971). Conversely, the V3 timing involved counting the number of plants within their respective stages of development in two 0.5 m^2 subsamples in each experimental unit. The average developmental stage was utilized in the statistical analysis.

The VC and V3 development measures were also obtained in 2012. The technique for the VC was similar to the V3 method used in 2011. Plants within a single 1.5 m by 1.14 m rectangle (three rows wide x 1.5 m long) were counted according to stage of development. The V3 development evaluation in 2012 was consistent with 2011 measures.

In 2012, additional measures of plant development were performed. Measures during reproductive development were also targeted at R7 (early crop maturity, Fehr et al., 1971). The average stage of development was estimated from five consecutive plants in two adjacent rows (total of 10 plants) in two randomly chosen locations in the plot.

2.4.5 Population

Plant population was measured at the V3 and R8 growth stages (crop maturity, Fehr et al., 1971). Plant density at the V3 timing was determined by counting plants in two 0.5 m^2 squares in each split-split plot. The pre-harvest population assessment was performed by counting the plants within a 0.91 m diameter hoop. Counts were conducted in three random sub-samples within each split-split plot.

2.4.6 Nodule number, soil nitrate, and ammonium concentration

Nodulation measurement timing was targeted for the initiation of visible nodule formation, around the V2 (two trifoliate, Fehr et al., 1971) – V3 growth stage. Five random plants were collected from each contrasting tillage and residue removal treatments: NT, SC + NT, Spring RTS, Fall RTS, and Moldboard Plow, in No Removal and Nearly Complete Removal residue levels. Samples were collected only from the row planter treatments without N fertilizer to obtain consistent comparisons. The plants were placed in plastic freezer bags and stored in freezers at -5˚C until analyzed. Soil was gently removed from the roots of three of the five plants with the least amount of root pruning from collection, transport, and storage. Growth stages of the selected plants were recorded and all of the nodules were separated from the roots and counted. Soil samples were collected on the same day as plant collections for nodule assessment for determination of nitrate and ammonium concentrations. Samples were only collected from the same treatments as those used for nodulation assessment. From each plot, five, 0.30 m deep soil cores were combined and mixed. The samples were immediately placed on ice in coolers and were transported to a lab for analysis.

2.4.7 Yield components

Prior to harvest, the yield components were determined including pod number plant^{-1}, seed number plant^{-1} and seed weight plant^{-1}. Contrasting tillage treatments (SC + NT, Spring RTS and Moldboard Plow) and residue removal levels (Nearly Complete Removal and No Removal) were selected from the zero-N, row-unit planted plots. In 2011, five samples of six consecutive plants were collected and combined, whereas 2012 consisted of five consecutive plants from four random samples within the plot. The length of row harvested was assumed to be equal across all tillage systems and residue removal levels. Pods containing seed were counted on each plant to determine pods plant^{-1}. Plants of the same treatment and replication were then threshed together with the seeds subsequently counted and weighed. Average seed number and weight per plant was then calculated.

2.4.8 Grain yield

Harvest occurred mid-October at the Moore11 and Lucan11 sites and mid-September at Arthur12 and Moore12. A Wintersteiger (Innkreis, Austria) small plot combine was used to harvest three of the centre four rows of each plot. Harvested grain from individual plots was collected in cloth bags then weighed for yield and a subsample for moisture determination. Plot area was calculated using the width of three soybean rows and the recorded length from each individual plot.

2.5 Statistical Analysis

Statistical analyses were all computed using the MIXED procedure in SAS version 9.3 (SAS Institute, Cary, NC). The analysis was conducted as a split-split block design with three replications. Tillage system (Tillage) was evaluated as the main effect, residue removal level (Removal) as the split-plot effect and planter type (Planter) or N application (Nitrogen) as the split-split block effects. Other fixed effects include location (Location) and measurement timing (Stage [used when appropriate]). Replication nested in site (Block [Location]) was the random, main effect evaluated. In the measurements where data were collected from all tertiary experimental units, including soil moisture, soil temperature, emergence, plant development, plant density and yield; three separate models were analyzed. The models include i. the Nitrogen Model (response of measured variables to N fertilizer and interactions in the three tillage systems dedicated to N comparisons) ii. The Planter Type Model (response of measured variables to planter type and interactions in the seven tillage systems dedicated to planter type comparisons), and iii. The Tillage x Removal Model (response of measured variables to tillage and residue removal across all tillage systems - only plots sown with the row planter with 0 kg N ha^{-1} were included for analysis). The remaining measurements, including residue assessment, nodule number, soil nitrate/ammonium, and yield components were only evaluated with the Tillage x Removal Model.

Response variables with multiple measurement timings, including residue weight, line transect, soil moisture, soil temperature, plant development, and plant population, were evaluated with the REPEATED statement included in the model. The subject imposed was Tillage*Removal*[Planter or Nitrogen or neither]*Block(Location) and Stage was the repeated effect. Covariance structures implemented varied depending on the response variable. Spatial power was used for soil moisture, soil temperature and plant density analyses. Development was analyzed under the autoregressive order (1) structure and residue assessment measures (line transect and weight) were analyzed under unstructured covariance structures. Models with heterogeneous variance were corrected by grouping the heterogeneous effect in the REPEATED statement. If non-convergence was observed then grouping the effect in a RANDOM intercept model was attempted. If non-convergence persisted, then the highest order fixed interactions, with non-significance according to a REPEATED model with adjusted covariance parameter estimates, were removed from the model. The model was then re-evaluated under the default parameter assumptions.

Residuals of each model were tested through PROC UNIVARIATE and PROC PLOT to determine if error assumption criteria were achieved. Normal distribution of the residuals was evaluated with the Shapiro-Wilk statistic and a histogram of residual values. Examination for patterns of a residual by predicted scatter plot was used to verify random distribution. Finally, variance homogeneity was tested by evaluating uniformity of the range of residual data points across each level of the fixed effects. Outliers were detected using Lund's test of outliers with a Type I error rate of 0.05 (Lund, 1975).

Least squared means were generated and compared using a Type I error rate of 0.05. Due to the complex nature of a 3-way factorial design, means were not adjusted by any multiple means comparison tests.

Relationships between soybean seed yield, tillage system, and average soil moisture contents were also modeled using soil moisture as a covariate. Briefly, the average soil moisture content was used as a covariate, and the covariate was tested for differences across tillage systems, similar to the approach used by Vyn and Hooker (2002). In other words, the relationship between soybean yield and soil moisture may depend on the tillage system. The effects of location, year, replication and their interactions were treated as random factors because inferences were made across location and years. Soil moisture was included as a continuous variable (covariate) and the tillage system was the fixed effect. Interaction between the soil moisture and tillage indicates that seed yield depends on both soil moisture and tillage system. A model for testing the relationship among soil moisture and tillage system was produced in SAS PROC MIXED version 9.2 (reference). A modified Shapiro-Wilk W-test using Royston's algorithm tested for normality to determine if transformations were necessary. No transformations were necessary. If the testing model produced significant tillage*soil moisture interactions, soil moisture relationships were produced for each tillage system. Parameter estimates for each response relationship were produced in PROC MIXED, as outlined by Vyn and Hooker (2002).

2.6 Validation of residue removal differences

The residue biomass was different for the residue removal levels at most locations (Table 2-1). The exception is Lucan11, where residue biomass in the Nearly Complete Removal treatment was identical to Intermediate Removal. At this location, an older style, tined wheel, side angle delivery rake was used to remove stover, which was ineffective at moving residue close to the soil surface and resulted in equal biomass in Nearly Complete Removal and Intermediate Removal. However, the line transect analysis showed that the Nearly Complete Removal treatment had 7.2% lower residue cover compared to that in the Intermediate Removal treatment ($P=0.0016$). Therefore each residue removal level was distinctly different from other removal levels at the same location.

Table 2-1. Corn stover weight and percent soil surface coverage by corn residue in the spring in each residue removal level† at Lucan, ON, and Moorefield, ON in 2011 and Arthur, ON and Moorefield, ON in 2012.

	Lucan		**Moore11**		**Arthur**		**Moore12**	
Residue Removal level	Mass (g m^{-2})	Percent coverage (%)	Mass (g m^{-2})	Percent coverage (%)	Mass (g m^{-2})	Percent coverage (%)	Mass (g m^{-2})	Percent coverage (%)
NR	672 a‡	61 a	653 a	57a	453 a	61 a	569 a	61 a
IR	484 b	50 b	473 b	42 b	306 ab	54 b	328 b	46 b
NCR	484 b	43 c	29 c	23 c	139 b	38 c	129 c	26 c

† Residue removal levels consist of no removal (NR), nearly complete removal (NCR), and intermediate removal (IR)

‡ Means with the same letter in the same location and type of residue measurement are not significantly different according to Fischer's Protected LSD at P=0.05

Chapter 3. Results and Discussion

Contrasting environmental conditions were experienced in 2011 and 2012. Frequent spring rains resulted in late planting in 2011 (June 3rd for Lucan11 and Moore11), but precipitation events and ambient temperature for the remainder of the season were favourable for soybean growth. In contrast, the 2012 spring was drier than average, which allowed for early planting (April 19th for Arthur12 and May 14th for Moore12). After planting at Arthur, air temperatures were below average for three to four weeks; and several high rainfall events shortly after planting caused soil crusting and emergence issues. After emergence at both 2012 locations, rainfall was significantly below average and a severe drought occurred. Detailed weather data including accumulative seasonal precipitation and daily temperature are provided in Appendix 2.

3.1 Soybeans planted with a NT drill - Yield response to tillage system, stalk chopping, and residue removal

The response of soybean yield to tillage system depended on the planter type, which resulted in a planter type x tillage system interaction (P=0.0002; Table 3-1). Both drill and row planter performance varied in response to tillage system. When seeded with the drill, soybean yield averaged across residue removal levels was negatively affected by NT when corn residue was cut with a flail mower (Table 3-2). The SC + NT treatment reduced soybean yields by 0.32 Mg ha^{-1} (P=0.0024) compared to the Moldboard Plow treatment. Contrasts reveal this response was only observed in 2011, with similar yields in 2012 (i.e., approximately 0.10 Mg ha^{-1}, P>0.60). Comparatively, the yield of NT without stalk chopping trended 0.11 Mg ha^{-1} (3.6%) lower than the Moldboard Plow, but the difference was not significant (P=0.2550). A similar but statistically significant NT yield deficit, of 0.11 Mg ha^{-1} was reported by Lueschen et al. (1992).

Environmental conditions through the growing season may partially explain the absence of a significant NT yield deficit (without stalk chopping). NT yield reductions predominately exist in cool and wet growing seasons and it is relatively nonexistent in warm and dry seasons (Dick et al., 1991; Guy and Oplinger, 1989; Meese et al., 1991; and Toliver et al., 2012; Webber et al., 1987). DeFelice et al. (2006) demonstrated yield in NT is competitive or better than CT in climates in North America with limited precipitation. Water retention in NT reduces drought severity and the associated yield loss. In the current study, soils were dry in 2012 since precipitation between April and August was approximately 50 – 55% of the 30 year seasonal average (Environment Canada, 2013). Contrastingly, frequent rainfall events in the spring of 2011 delayed planting to June 3. Although precipitation and temperature were near-average after planting in 2011 (Environment Canada, 2013), weather conditions were favourable for growth, contributing to minor yield disparity between tillage systems. Consequently, only NT environments with fragmented surface residue (i.e., SC + NT) exemplified a yield deficit. Variable year-to-year weather conditions aside, these yield results indicate that the increasing occurrence of a NT yield deficit may be caused by the growing prevalence of chopping residue as opposed to strictly increased corn residue in a NT production system.

Of all the tillage systems seeded with the drill, yield improvement above SC + NT only occurred in NT (7.4% greater, P=0.0464, contrast not shown) and the Moldboard Plow. All other tillage systems yielded between SC + NT and NT, yet were not statistically greater than SC + NT. This indicates that minimum tillage did not enhance yield above those produced with NT alone. Previous studies have suggested that minimum tillage systems do increase yield above NT and may result in equivalent yields to CT (Lueschen et al., 1992; Oplinger and Philbrook, 1992;

Vyn et al., 1998). It could be that late planting in 2011 and dry weather in 2012 masked any yield response to minimum till.

Decreased yield due to stalk chopping in NT reveals residue orientation, distribution, and size affected the performance of the NT drill. Residue removal contrasts in SC + NT reveals Nearly Complete Removal in SC + NT improved yield above No Removal by 0.26 Mg ha^{-1} (10%, P=0.0059, contrasts not shown). However, Nearly Complete Removal of chopped residue still yielded approximately 0.18 Mg ha^{-1} (6%) lower than the Moldboard Plow averaged across all removal levels. Comparatively, removing corn residue in NT alone (without stalk chopping) did not increase yield, nor in most other tillage systems (data not shown).

Considering the NT drill is the most popular seeding equipment used in Ontario for soybean, and the prevalence of chopper combine heads is increasing (Peter Johnson, OMAF cereal specialist, on the Nov 20th, 2013 edition of the Cropline), this research clearly indicates why NT growers claim to be increasingly experiencing yield deficits compared to their CT neighbours. The stalk chopping treatment did not accurately mimic all combine chopper heads commercially available (there are many various designs and degrees of stover fragmentation), but the objective of the treatment was to alter the size shape, and distribution of residue. Therefore, this research suggests that if intensively stalk chopped residue is left unmanaged it can result in significant yield decline. Avoiding intensive stalk chopping operations or removing residue from the soil surface would reduce the severity of the yield deficit, while the effect of tillage following stalk chopping was not investigated with the drill.

Although not investigated in this study, it can be hypothesized that tillage following stalk chopping could be a strategy to improve yields above NT when drill seeded. Drill performance was compromised in SC + NT conditions in part due to reduced ability of the drill to perform with a thick layer of fragmented residue pieces on the soil surface. Effectively, soil moisture was increased with stalk chopping (discussed in section 3.3). Minimum tillage (Fall & Spring RTS) following stalk chopping reduced residue cover by 12% compared to stalk chopping without tillage ($P<0.0001$), and it is possible that soil surface conditions may be more favourable for drill performance if chopped residue pieces are incorporated vs. left on the surface.

Table 3-1. Analysis of variance for measured soil and plant characteristics in response to planter type in seven different tillage systems and three levels of residue removal in Lucan, ON and Moorefield, ON in 2011 and Arthur, ON and Moorefield, ON in 2012.

Source of variation	df	Soil moisture	Soil temperature	df	Emergence	df	Plant development	Plant density	Yield
		-----------------	-----------------		----------		----------------	----------------	----------------
Location (L)	3	<.0001	<.0001	1	<.0001	3	0.0089	<.0001	<.0001
Tillage (T)	6	<.0001	<.0001	6	<.0001	6	<.0001	0.3608	0.2619
Residue Removal (R)	2	0.9856	0.0001	2	0.1064	2	<.0001	0.3949	0.0015
Planter type (P)	1	<.0001	0.003	1	0.0023	1	0.0419	<.0001	0.0004
Stage (S)	4	<.0001	<.0001			1	<.0001	<.0001	
T × R	12	0.0002	0.0025	12	0.7348	12	0.9445	0.2539	0.1420
P × T	6	0.1561	0.9881	6	0.0094	6	0.5300	0.5085	0.0002
P × R	2	0.5928	0.9069	2	0.5805	2	0.9854	0.4154	0.6622
L × T	18	0.6076	0.0097	6	0.0011	18	<.0001	0.3107	0.7964
L × R	6	0.1318	0.6958	2	0.0898	6	0.0055	0.0345	0.0321
L × P	3	0.0801	0.0314	1	0.002	3	0.0306	<.0001	0.0080
T × S	24	0.0002	0.0006	-	-	6	<.0001	0.3916	-
R × S	8	0.4663	0.0241	-	-	2	<.0001	0.363	-
P × S	4	0.6871	0.4069	-	-	1	0.2616	0.0119	-
L × S	12	<.0001	<.0001	-	-	3	<.0001	0.0413	-
P × T × R	12	0.7173	0.8877	12	0.8037	12	0.8904	0.4633	0.9909
L × T × R	36	<.0001	0.2039	12	0.7099	36	0.0724	0.712	0.2205
L × P × T	18	0.0953	0.8141	6	0.0352	18	0.1627	0.5841	0.3450
L × P × R	6	0.8225	0.964	2	0.9596	6	0.6496	0.5733	0.7587
T × R × S	48	0.9874	-	-	-	12	0.5508	0.7715	-
P × T × S	24	0.929	1	-	-	6	0.8393	0.3577	-
P × T × S	24	0.929	1	-	-	6	0.8393	0.3577	-
L × T × S	72	0.6252	0.9842	-	-	18	0.0382	0.819	-
P × R × S	8	0.6961	0.9994	-	-	2	0.8892	0.0714	-
L × R × S	24	0.0653	0.3591	-	-	6	0.0034	0.4183	-
L × P × S	12	0.6729	0.8452	-	-	3	0.8478	0.0209	-
L × P × T × R	-	-	-	12	0.9352	36	-	0.4012	0.4487
P × T × R × S	-	-	-	-	-	12	-	0.4408	-
L × T × R × S	-	-	-	-	-	36	-	0.4877	-
L × P × T × S	-	-	-	-	-	18	-	0.9562	-
L × P × R × S	-	-	-	-	-	6	-	0.823	-
L × P × T × R × S	-	-	-	-	-	36	-	0.9369	-

Table 3-2. Soybean yield† in seven tillage systems seeded with the row planter and seed drill at Lucan, ON and Moorefield, ON in 2011 and Arthur, ON and Moorefield, ON in 2012.

Tillage system	Grain yield		
	Planter type		Advantage to row planter
	Seed drill	Row planter	
	Mg ha^{-1}		
No-till (NT)	2.94 ab‡	3.03 ab	0.09
Stalk Chop + NT	2.74 c	3.08 a	0.34 ***
Fall & Spring Residue Tillage Specialist (RTS)	2.79 bc	2.86 bc	0.07
Fall RTS	2.89 abc	2.98 abc	0.09
Fall Disc, Spring Cultivate	2.82 bc	2.80 c	-0.02
Fall Disc & Cultivate	2.85 bc	3.02 a	0.17 *
Moldboard Plow	3.06 a	2.94 abc	-0.12

† Soybean yield is averaged across locations and residue removal levels

‡ Means followed by the same letter within the same planter type are not statistically different according to Fischer's Protected LSD Test (at p=0.05).

*, ***Indicates significantly different from zero at P=0.05 and P=0.0001, respectively.

3.2 Soybeans planted with a row planter – Yield response to tillage system, stalk chopping, and residue removal

The interaction of planter type x tillage system reveals yield in a specific tillage system was affected by the planter type. The row planter resulted in enhanced yield relative to the drill in the SC + NT and Fall Disc & Cultivate treatments. Specifically in SC + NT, yield was improved by 0.34 Mg ha^{-1} (12.4%) when seeding with the row planter vs. the NT drill ($P<0.0001$). However, Table 3-2 illustrates a tendency for positive yield increases with the row planter over the drill in other systems as well. Additionally, means comparisons of a significant planter type x location interaction (Table 3-1) reveals that the row planter outperformed the drill at specific locations.

Location or more specifically the environmental conditions at a location, critical influenced the outcome of planter type performance. Yield of the row planter was improved over the drill at two of four locations ($P<0.05$): 0.1 Mg ha^{-1} (2.4%) at Lucan11 and 0.22 Mg ha^{-1} (7.3%) at Moore11. At Moore12, yield trended 0.05 Mg ha^{-1} higher than the drill but was not significantly different ($P=0.2624$). Yields at Arthur12 were similar between planter types ($P=0.7863$). Thus, significant yield gains with the row planter only occurred in the first year of the study. Inconsistent yield responses to planter type also occur throughout the literature. Bohner and Earl (2010) observed 0.12 Mg ha^{-1} (3.7%) greater yield with a row planter. Bertram and Pedersen (2004) reported a 0.21 Mg ha^{-1} (4.7%) advantage to a row planter; but it was only present under NT conditions following corn and not in CT. Similar to the current research, Pedersen and Lauer (2003) also observed variable year to year differences. Conversely, Cox and Cherney (2011) reported a 7% yield advantage to the drill; however, this was confounded by row spacing differences between the planter types. The apparent causes for yield discrepancies vary throughout the literature. Inconsistencies observed in the current research appear to be affected by soil water content, plant establishment, and vegetative development (discussed later).

Soybean yield when sown with the row planter: Soybean yield was significantly affected by tillage (P=0.0146, Table 3-3). Yield did not respond to residue removal (P=0.0739); despite significant differences in residue cover (P<0.0001), soil temperature (P=0.0002), plant development (P=0.0002), and nodule number (P=0.0430). Residue removal did affect yield in certain tillage systems, but only significantly at the Moorefield locations (P=0.0118 and P=0.0328 for Moore11 and Moore12 respectively). Immediate discussion will pertain to results of the tillage main effect, while deviations in residue removal treatments at Moorefield will be addressed later in this section.

Although yield responded to tillage, the eight tilled treatments failed to elevate yield above either of the two NT systems (Table 3-4). Rather NT yielded statistically equivalent to 0.28 Mg ha^{-1} (10%, P=0.0028) higher than tilled systems. Therefore, residue management using tillage did not increase yields above NT. Comparable yields between tilled and NT is consistent with other tillage studies that seeded with a row planter (Bohner, 2010; Kiszonas, 2010; Pedersen and Lauer, 2003b; Perez-Bidegain et al., 2007; Yusuf et al., 1999).

Despite the observation of NT success, the data from this study can still be used to explore other questions surrounding residue management and minimum tillage. The yield of treatments with spring tillage trended lower than NT and systems with only fall tillage. For example, soybeans grown in Fall Disc & Fall Cultivate yielded 7.9% more (P=0.0167) than soybeans with Fall Disc & Spring Cultivate (Table 3-4). Fall Disc & Spring Cultivate was also numerically the lowest yielding tillage system. Yields were not different among other systems that deployed spring tillage, including Fall & Spring RTS (with and without stalk chopping), Spring RTS, and Moldboard plow. All other systems yielded significantly higher than the lowest yielding tillage treatment and did not contain spring tillage (except for the Disc Ripper). This demonstrates spring tillage was generally detrimental to crop yield. These results are inconsistent with Yiridoe et al. (2000) who reported similar yields between discing in the fall and spring. Differing conclusions regarding the effect of spring tillage are likely attributed to differing environmental conditions experienced in each study such as soil type, seedbed characteristics (including aggregate size, seed to soil contact, etc), length of growing season, and weather patterns. Weather patterns in particular will be discussed in a later section.

In contrast to the NT drill results, row planter performance was unaffected by stalk chopping residue (Table 3-4). Yields were similar between stalk chopped and non stalk chopped environments in both NT (P=0.5579) and Fall & Spring RTS (P=0.8442). When tillage followed stalk chopping, yield was decreased by 0.23 Mg ha^{-1} (7.6%, P=0.0116) relative to NT. However this effect was a result of spring tillage, as discussed above, since a similar yield reduction was observed when stalk chopping did not occur.

The main effect of residue removal did not affect soybean yield; nor did yield respond to residue removal in specific tillage systems averaged across locations (Table 3-3). However, investigation of yield results at individual locations reveals a significant yield response to residue removal in certain tillage systems. Specifically this only occurred at Moore11 and Moore12 (P=0.0118 and P=0.0328 respectively). At the Moore11 location, yield responded to residue removal in the SC + NT, SC + Fall & Spring RTS, Spring RTS, Fall RTS, and Moldboard Plow systems (Table 3-5). At Moore12, the NT, SC + NT, and Spring RTS systems were affected by residue removal (Table 3-5). The remaining tillage systems in Moorefield in both 2011 and 2012 yielded similarly across all removal levels.

In every tillage system that responded to residue removal at Moore11 and Moore12, Intermediate Removal was the lowest yielding, or equal to the lowest yielding. Contrastingly, Nearly Complete Removal was always the highest yielding residue removal level. Yield associated with No Removal depended on the tillage system and location. Specifically, No Removal significantly outperformed Intermediate Removal in only Moore11 in the Fall RTS and Moldboard Plow systems by 14% (P=0.0288) and 17% (P=0.0091) respectively. No Removal and Intermediate Removal were statistically equivalent in the remaining tillage systems; even though yield of stalk chopped treatments at Moore11 (with and without tillage) and NT at Moore12 were elevated enough to equate to Nearly Complete Removal.

Tillage systems that responded to residue removal at both Moore11 and Moore12 were SC + NT and Spring RTS; however only the Spring RTS had a consistent yield response across both locations. In Spring RTS, Nearly Complete Removal yielded 14 – 23% greater than No Removal and Intermediate Removal (P=0.0468 – P=0.0004). Yield response to residue removal varied between locations in the SC + NT system. In Moore12, Nearly Complete Removal improved yield by 0.43 Mg ha^{-1} relative to No Removal (P=0.0238). A similar yield response was observed by Bohner (2010) in NT conditions without stalk chopping, who speculated the outcome was driven by early planting. Moore12 was also seeded in an early to average time frame for the region. Perhaps if seeded earlier, a yield difference between No Removal and Nearly Complete Removal may have been observed in NT (without stalk chopping). In Moore11, the yield of Intermediate Removal in SC + NT was actually the lowest yielding residue removal level. Nearly Complete Removal was shown to improve yield above Intermediate

Removal, but was not required to achieve top yield in this system as it was similar to No Removal.

The yield response to residue removal was inconsistent with the row planter. Only certain tillage systems at the Moorefield locations responded to removal. This contrasts with Vyn et al. (1998) who reported complete removal of wheat straw in NT conditions consistently improved yield of the following soybean crop. One discrepancy between studies is that Lucan11 and Arthur12 may have been unresponsive to residue removal due to shortcomings of removal treatments. The hay rake used at Lucan11 inadequately removed stover in Nearly Complete Removal, leaving 4.84 Mg ha^{-1} or 72% of the mass in No Removal. Comparatively, residue biomass of Nearly Complete Removal at Morre11 and Moore12 ranged between 4% and 22% of mass still present in the No Removal treatments. Although well defined residue removal categories existed at Arthur12, post-harvest stover weight was 21% lower than that of the next lowest location. This was caused by differences in grain yield of the previous corn crop as stover biomass is proportional to yield (Tollenaar and Lee, 2006). Arthur12 corn grain yield was only 9.4 Mg ha^{-1} compared to the Moorefield and Lucan11 sites which had corn grain yields ranging from 10.7 – 12.5 Mg ha^{-1}. Initial residue quantities at Arthur12 may have been insufficient to impose a significant yield effect.

Table 3-3. Analysis of variance for volumetric soil water content (VSWC), soil temperature (Soil Temp.), residue cover, soybean development, density, and seed yield in response to tillage system, residue removal, and timing of measurement when soybeans were seeded with the row planter at Lucan, ON and Moorefield, ON in 2011, and Arthur, ON and Moorefield, ON in 2012.

Source of variation		VSWC	Soil Temp.		Residue cover	Develop-ment	Plant density	Yield
	df	------- P>F ------		df	------------------ P>F ---------------			
Location (L)	3	<.0001	<.0001	3	0.0208	0.0052	<.0001	<.0001
Tillage (T)	9	<.0001	<.0001	9	<.0001	0.0001	0.2571	0.0146
Residue Removal (R)	2	0.5328	0.0002	2	<.0001	0.0002	0.1022	0.0739
Stage (S)†	4	<.0001	<.0001	1	<.0001	<.0001	<.0001	-
T × R	18	0.0526	0.5498	18	<.0001	0.9987	0.0581	0.2429
L × T	27	0.2693	0.0631	27	<.0001	0.0168	0.8026	0.8141
L × R	6	0.407	0.5459	6	<.0001	0.0175	0.0312	0.3470
L × S	12	<.0001	<.0001	3	<.0001	<.0001	0.8691	-
T × S	36	0.0366	0.6544	9	<.0001	<.0001	0.8559	-
R × S	8	0.1468	0.1986	2	0.1149	<.0001	0.7965	-
L × T × R	54	0.6442	0.9988	54	<.0001	0.9998	0.4219	0.0451
T × R × S	72	0.9904	1	18	0.1304	0.9910	0.9577	-
L × T × S	108	0.8032	1	27	<.0001	0.1067	0.8159	-
L × R × S	24	0.731	0.674	6	0.7603	0.0157	0.4860	-
L × T × R × S	216	0.9999	-‡	54	-	1	0.0924	-

† Stage is the timing of measurement, which varies depending on the variable in question. VWSC and Soil Temp. were taken 0, 3, 7, 14, and 28 DAP. Residue cover measurements occurred after fall tillage and after planting. Development measurements occurred at the VC and V3 growth stages, and plant density was taken at the V3 and R8 growth stages.

‡Missing values occur because the response variable is not a repeated measure or because the statistical model failed to calculate with the inclusion of that term.

Table 3-4. Soybean yield, number of leaves plant^{-1}, and volumetric soil water content (VSWC) on different days in response to tillage averaged across residue removal levels when soybeans were seeded with the row planter at Lucan, ON and Moorefield, ON in 2011, and Arthur, ON and Moorefield, ON in 2012.

Tillage system	Yield	VSWC					Development	
		0 DAP†	3 DAP	7 DAP	14 DAP	28 DAP	VC	V3
	Mg ha^{-1}	m^3 m^{-3}					Number of leaves plant^{-1}	
No-till (NT)	3.03 ab‡	27.6 a	28.8 a	30.5 a	34.4 a	29.9 a	0.81 a	3.66 c
Stalk Chop + NT	3.08 a	26.9 a	28.3 a	29.6 ab	33.6 ab	29.1 ab	0.80 a	3.73 c
Stalk Chop + Fall & Spring RTS	2.85 cd	23.2 bc	25.2 bc	28.1 bcd	31.0 cde	26.7 cd	0.73 bcd	3.80 bc
Fall & Spring RTS	2.86 bcd	23.2 bc	25.3 bc	26.5 de	30.7 cde	26.4 cd	0.71 cd	3.78 bc
Spring RTS (2x)	2.90 bcd	23.3 b	25.4 bc	27.7 bcd	31.1 cde	27.4 bcd	0.77 abc	3.73 c
Fall RTS (2x)	2.98 abc	26.3 a	27.0 ab	28.5 bc	31.9 bcd	28.3 abc	0.80 a	3.76 bc
Fall Disc & Spring Cultivate	2.80 d	21.6 bcd	25.0 c	27.1 cde	30.0 de	25.6 de	0.69 d	3.73 c
Fall Disc & Cultivate	3.02 abc	25.4 a	26.9 ab	28.9 abc	32.3 bc	27.9 bc	0.79 ab	3.80 bc
Disc Ripper	3.09 a	21.3 cd	24.1 c	26.4 de	30.3 de	25.5 de	0.77 abc	3.91 b
Moldboard Plow	2.94 abcd	20.6 d	23.7 c	25.4 e	29.8 e	24.7 e	0.79 ab	4.09 a

† DAP=Days after planting

‡ Means followed by the same letter within the same variable and time of measurement are not statistically different according to Fischer's Protected LSD Test at P=0.05.

Table 3-5. Soybean yield when seeded with the row planter in response to tillage and stalk chop systems across residue removal levels in Moorefield, ON in 2011 and 2012.

Tillage and stalk chop (SC) system	Moorefield, 2011			Moorefield, 2012		
	NR†	IR	NCR	NR	IR	NCR
			Mg ha^{-1}			
No-till (NT)	3.55 a‡	3.38 a	3.42 a	2.99 ab	2.75 b	3.25 a
SC + NT	2.97 ab	2.89 b	3.30 a	3.00 b	3.12 ab	3.43 a
SC + Fall & Spring RTS	3.20 ab	2.83 b	3.30 a	2.95 a	3.04 a	2.72 a
Fall & Spring RTS	3.21 a	3.22 a	3.32 a	2.78 a	2.79 a	2.90 a
Spring RTS	3.23 b	2.95 b	3.64 a	2.78 b	2.61 b	3.16 a
Fall RTS	3.35 a	2.94 b	3.46 a	3.07 a	3.03 a	3.06 a
Fall Disc & Spring Cultivate	3.13 a	3.22 a	3.06 a	2.61 a	2.71 a	2.80 a
Fall Disc & Cultivate	3.50 a	3.14 a	3.41 a	3.20 a	3.04 a	3.16 a
Disc Ripper	3.45 a	3.52 a	3.36 a	3.09 a	3.27 a	3.00 a
Moldboard Plow	3.35 a	2.85 b	3.15 ab	2.76 a	3.13 a	3.10 a

† Residue removal levels include: No Removal (NR), Nearly Complete Removal (NCR), and Intermediate Removal (IR)

‡ Means followed by the same letter within the same tillage treatment at a particular location are not statistically different according to Fischer’s Protected LSD Test at P=0.05

3.3 Effects of planter type on soil and canopy parameters

3.3.1 Soil parameters

Soil moisture in the Planter Type Model: Planter type significantly affected soil moisture measured in the row (Table 3-1). Compared to the drill, the row planter, across all tillage systems, consistently reduced volumetric soil water content (Table 3.6) with an average reduction of 0.009 $m^3 m^{-3}$ (3%, P>0.0001). This difference between planter types persisted for at least 28 days after planting. The degree of soil moisture disparity between planter types did not differ across locations (P=0.0801), but there were some trends detected. Larger differences were observed in the 2012 season vs. 2011, but at each location soil moisture with the row planter was always lower than the drill. Whether the reduction in soil moisture due to the row planter contributed to a yield improvement appeared to be dependent on precipitation amount after planting. In 2011, cumulative growing season rainfall was 91% of the 30 year average, whereas 2012 was only 50 – 55% (Environment Canada, 2013). The low amount of rainfall in 2012 may explain the trend for greater moisture differential observed between planter types in that year. Additionally, it may explain the absence of a yield response as lower water content associated with the row planter further limited seasonal water availability. Contrastingly, water availability was not a major yield limiting factor in 2011 so seed row moisture reductions enhanced yield.

Despite a statistically insignificant soil moisture interaction of planter type x tillage system (P=0.1561), soil moisture trends between planter types in different tillage systems coincided with yield measurements. Other studies have also demonstrated soil moisture influences soybean response to tillage (DeFelice et al., 2006; Toliver et al., 2012; Yin and Al-Kaisi, 2004). In the present study, decreases in soil water content particularly in NT systems were associated with a trend for increased soybean yield. The row planter lowered volumetric soil water content by 0.0166 $m^3 m^{-3}$ (5%, Table 3-6) relative to the drill in the SC + NT system ($P<0.0001$). This moisture differential persisted throughout the period of data collection (up to 28 days after planting) as the interaction of planter type x tillage x stage was insignificant ($P=0.9290$).

Moisture loss with the row planter relative to the drill in the NT system was less extreme than SC + NT, at only 0.0033 $m^3 m^{-3}$ ($P=0.3434$). Chopping the residue into a thick layer of small pieces on the soil surface, probably reduced drill performance for adequate seed-soil contact. Residue cover was similar between NT and SC + NT across seed rows, but it is suspected that stalk chopping resulted in greater residue cover over the row which blocked solar radiation and impeded soil drying (Horton et al., 1996; Klocke et al., 2009; and Mitchell et al., 2012). It is also possible that the closely spaced depth gauge wheels on the drill depressed chopped residue into the soil more than they would in standing, uncut residue. This further restricted air movement across the soil surface and resulted in greater soil moisture. These effects would have led to greater yield separation between planting implements in SC + NT than in NT (Table 3-2). Thus, NT success was improved when soil moisture was reduced which agrees with the findings of a meta-analysis of tillage experiments by DeFelice et al. (2006).

For both the row planter and the drill, minimum tillage reduced soil moistures to those below NT (Table 3.6); however, tillage never translated into statistically higher yields from NT. In fact, compared to NT, minimum tillage was often detrimental to yield. Other studies indicate tillage is disadvantageous in years and locations where moisture is limited (DeFelice et al., 2006; Dick and VanDoren, 1985; Pedersen and Lauer, 2003a; Toliver et al., 2012; Webber et al., 1987; Yin and Al-Kaisi, 2004). Seasonal precipitation was considerably below average in 2012 and it is possible that tillage limited total seasonal plant available water and consequently compromised yield. The exception to the trend is the Moldboard Plow, where soil moisture was reduced the most, yet soybean yield was similar to the highest yielding treatments. Reduced moisture in the Moldboard Plow may have allowed for proliferated root exploration which increased access to water (Hoogenboom et al., 1987), enhanced seedbed uniformity, or improved stand establishment (Barzegar et al., 2004; Lueschen et al., 1992; Vyn et al., 1998), all of which may enhance yields. Alterations in other soil properties induced by CT, such as reduced bulk density and increased soil porosity (Mielke et al., 1986) may have also promoted root growth (Hallmark and Barber, 1981; Hooker, 2000) and consequently increased water uptake. Perhaps this helped compensate for reduced soil moisture in the top 0.12 m of soil. Additionally, enhanced root growth may inadvertently increase uptake of phosphorus and potassium, which may improve plant growth and seed yields.

A separate statistical analysis, using moisture as a covariate, revealed soybean seed yield depended on the mean soil water content within each tillage system. The seed yield response to soil moisture was best described as quadratic relationships across tillage systems. Using contrasts, the soil moisture relationships were similar among Fall RTS, Fall & Spring RTS, SC + NT, and Disc systems ($P>0.50$); therefore, data across these tillage systems were combined and a reduced model was produced using NT, the Moldboard Plow, and the combined tillage systems. The resulting ANOVA of the reduced model produced the P-vales for the following factors: tillage system ($P=0.0083$), average soil moisture linear ($P=0.0004$), average soil moisture quadratic ($P=0.0019$), average soil moisture linear x tillage interaction ($P=0.0085$), and average soil moisture quadratic x tillage interaction ($P=0.0139$). The soil moisture and tillage interactions indicate that the relationship between seed yield and soil moisture depends on the tillage system.

Parameter estimates of relationships between seed yield and soil moisture were produced for each of the three tillage systems (Table 3-7). The relationships depicted in Figure 3-1 support previous arguments regarding moisture effect on yield. Namely, moisture reductions in NT improved yield. What is different is that this observation was only true in a certain range of soil water content values. Below 0.32 m^3 m^{-3}, soil moisture reductions actually decreased yield in NT. Additionally, NT yield was very responsive to soil moisture as small changes in soil water content considerably affected yield. This resulted in a narrow range in soil water content for attainment of peak yield and may possibly be a contributing cause for NT yield instability observed in Ontario from year to year. Comparatively, yield in the Moldboard Plow and the combined tillage group was much more stable across soil moisture levels. Yield potential increased with increasing soil water content but began to plateau around 0.40 m^3 m^{-3}. The main difference between the Moldboard Plow and the combined tillage group relationships is that the rate of yield gain per unit increase in soil water content was greater with the Moldboard Plow, resulting in higher yield potential. A possible mechanism for this observation may be that CT reduced bulk density and aggregate size which promoted root growth (Hallmark and Barber, 1981; Hooker, 2000). As soil moisture was increased, a larger root system had the ability to access more plant available water which reduced water limitations.

The most probable cause for the difference in in-row soil moisture between planter types is attributed to the configuration, type and number of disc blades per seeding implement. The row planter opened the seed trench with two disc blades, effectively disturbing more soil than the single blade on the drill. In addition the 2 x 2 fertilizer banding disc was engaged on the row planter even though fertilizer was not applied. A wavy edged coulter was also operated preceding the row openers to cut residue, open, and aerate the soil. Comparatively the drill possessed only a single disc blade to open the seed row. More soil disturbance with the row planter likely created a microenvironment of increased soil pore space and improved vapour flow which lowered soil moisture (Braunack and Dexter, 1989). Furthermore, 0.11-m-wide depth gauge wheels on the drill were also spaced 0.19-m apart. These wheels pressed residue into the soil which imposed a greater aeration and drying barrier than vertical residue (Aase and Siddoway, 1980; Bristow, 1988; Sindelar et al., 2013). The combination of these factors likely contributed to lower soil water content with the row planter than the drill.

It should be noted that configuration of commercially available row planters may vary and, as a result, the magnitude of impact on soil water content of a row planter vs. a drill may also vary. The specific arrangement of discs on the row planter vs. the drill used in the study did result in a significant difference in moisture. However, if the configuration was altered (i.e., attachment of row cleaners, or removal of tillage coulter and side band fertilizer discs) the moisture differential could change or moisture levels across planter types may be similar.

Tillage effects on volumetric soil moisture in the Tillage x Removal Model: Tillage significantly affected surface residue coverage (Table 3-3), as tillage intensity decreased (Moldboard Plow > Disc Ripper > Disc & Cultivate > RTS > NT) residue coverage was increased. Consequently, variable levels of tillage intensity affected magnitude of moisture loss relative to NT. Volumetric soil water content was reduced with spring tillage anywhere from 0.043 m^3 m^{-3} (16%) with the Spring RTS (P=<0.0001) to 0.07 m^3 m^{-3} (25%) in the Moldboard Plow system (P=<0.0001). These results were observed on the day of planting. Mitchell et al. (2012) report similar results, confirming volumetric soil water content can be reduced by 0.08 m^3 m^{-3} in a CT system with a spring tillage pass. Other studies similarly demonstrate that magnitude of water loss increases as tillage intensity increases due to lower residue cover on the soil surface (Blevins et al., 1983; Hooker, 2000; Vyn et al., 1998). However, absolute soil water content values were not indicative of yield trends in the current research since yield differences between tillage implements were inconsistent with trends in soil water content. For example the Disc Ripper and Fall Disc & Spring Cultivate treatments maintained equal volumetric soil water contents throughout all evaluation timings, yet the yield of the Disc Ripper was 9.7% (P=0.0019) greater than Fall Disc and Spring Cultivate. Compared to NT, soil water content was 0.04 – 0.06 $m^3 m^{-3}$ (12 – 23%) lower in the Disc Ripper treatments but the yields were similar (P=0.4774). Similarly the Moldboard Plow consistently resulted in reduced soil water content by at least 0.05 $m^3 m^{-3}$ (17%) below NT; and while the yield of NT trended 3% greater, it was statistically insignificant (P=0.3268). Therefore soil moisture is not the sole influential yield factor with respect to tillage.

As suggested in the previous section, soil parameters not measured may also be responsible. Tillage reduces bulk density and soil strength, and increases the proportion of fine aggregates (Hallmark and Barber, 1981; Hooker, 2000; Janovicek et al., 2006; Mielke et al., 1986; Vyn et al., 1994). Hooker (2000) suggests that these soil changes are also responsible for improved early shoot growth and final seed yield in soybean. Hallmark and Barber (1981) also illustrate a considerable increase in root and shoot growth with decreasing bulk density which was caused by tillage. Thus it is inappropriate to solely attribute soybean yield to a single soil parameter, such as absolute soil water content values, as there are numerous other soil physical properties affected by tillage that may impact soybean performance.

As discussed in section 3.2, where the complete list of tillage systems were compared using the row planter, soybean yield was responsive to tillage timing, suggesting that soil properties may be differentially impacted by spring vs. fall timing. The timing of incorporation within a certain type of implement resulted in insignificant differences in residue cover when measured using the line transect method (data not shown). Similar trends in residue cover across tillage timing are also reported by Hooker (2000). Therefore, residue cover did not influence the yield response to tillage timing. Similarly, soil temperatures were similar across tillage timings. Rather the interaction involving tillage x stage (timing of measurement) affected soil water content (Table 3-3) in a way that influenced yield. Spring tillage consistently reduced soil water relative to NT, from the day of planting to 28 DAP (Table 3-4). Moisture in systems tilled only in the fall did not differ from NT on the day of planting; yet as time passed fall tilled soils became drier than NT. This supports observations in Janovicek et al. (2006) which reported 2 – 4% higher soil water content in NT systems than fall tilled, four to six weeks after planting.

Soil moisture profiles were similar among the four RTS based systems with a single exception. On the day of planting, Fall RTS was 0.031 – 0.032 m^3 m^{-3} (13%) wetter than the other RTS systems (which all contained at least one pass in the spring, P=0.0019 – 0.0014 respectively). This difference was soon negated, as measurements from three days after planting indicate that soil water contents were similar among all RTS systems. Although differences were insignificant, the trend indicates slightly drier soil with a spring RTS pass. A similar trend is observed with soybean yield response to timing of the RTS pass. Both yield and soil moisture differences were not statistically different but there was a tendency for lower yield and moisture content if spring tillage occurred.

Similar to the RTS, Fall Disc & Fall Cultivation resulted in 0.03 m^3 m^{-3} (18%) higher soil water content than Fall Disc & Spring Cultivation on the day of planting averaged across all locations (P=0.0002). The distinction from the RTS systems is that the moisture disparity was maintained until the final measurements were collected 28 days after planting (0.023 m^3 m^{-3}, 9% difference, P=0.0220). Yield in the Fall Disc & Spring Cultivation system was 0.22 Mg ha^{-1} (7.9%) lower than Fall Disc & Fall Cultivation (P=0.0167). These results illustrate the continual presence of reduced soil moisture with spring cultivation, from 0 days to 28 days after planting, may have significantly limited soybean yield in the disc tillage system. The same trend occurs in the stalk chopped treatments. Fall & Spring RTS reduced soil water content by 0.037 m^3 m^{-3} (14%, P=0.0002) relative to NT in both stalk chopped treatments. The moisture differential persisted for up to 28 days after planting when soil moisture was 0.024 m^3 m^{-3} (8%) lower in the RTS system (P=0.0211). Soybean yield was reduced by 7.6% compared to SC + NT (P=0.0187). Thus, spring tillage dried the soil and reduced total plant available water which may have caused the yield reduction. Many other studies illustrate yield is decreased when soil moisture is reduced, but it typically occurs in climatic regions where precipitation is limited (DeFelice et al., 2006; Doran et al., 1984; Elmore, 1990; Pedersen and Lauer, 2004a) such as 2012.

Within the row planter, reductions in volumetric soil water content, associated with tillage timing, seemed to reduce yields. This contrasts with the observation that greater yield is associated with the row planter which has lower soil water content than the drill. A differentiating factor between these two conclusions is the spatial distribution of water loss. The row planter decreased soil water content specifically in the seed row whereas tillage also reduced soil water in the inter-row space. In effect, water volume loss per square metre soil surface was greater when tilled. Evidently a localized area of water loss was beneficial to yield while a widespread moisture reduction was detrimental. This was likely accentuated in 2012, which experienced below average growing season precipitation and moisture retention was critical for success.

Residue removal impacts on soil moisture: Although the literature suggests potential for improved yields in Ontario from residue removal due to decreasing soil moisture with declining surface biomass (Doran et al., 1984; Sindelar et al., 2013; Toliver et al., 2013; Vyn et al., 1998; Wilhelm et al., 1986), in the current study, removing crop residue had negligible impacts on reducing soil moisture in NT systems, regardless of planter type and tillage system (Table 3-1). Consequently, yields in each planter type treatment were relatively unaffected by residue removal (P=0.6622). Even in the SC + NT system, residue removal did not affect soil water content. While residue removal in a SC + NT system may increase yield (see Section 3.1), it appears the mechanism is related to planter performance as opposed to a soil moisture effect. Causes for current moisture discrepancy with the literature may be that the environmental conditions during each year did not provide an opportunity for moisture differences to exist across residue removal. For example, 2011 was a late-seeded year. Warm weather and intense solar radiation at the time of planting quickly dried the soil, whether or not it was covered with residue. Comparatively 2012 was a dry year, even early in the season. Consequently water content in the top 0.12 m of soil was similar for all residue removal levels at the time of planting and for the following 28 days.

Planter type and tillage effect on soil temperature: Soil drying accelerates warming, and corresponding effects of higher temperatures on plant growth and development can improve yield (Elmore, 1991; Jones and Gamble, 1993; Hobbs and Obendorf, 1972; Hatfield and Egli, 1972; Perez-Bidegain et al., 2007; Vyn et al., 1998). Although in-row soil moisture differences were observed between planter types and across tillage systems, temperature differences were minor and rarely related to moisture trends.

Planter type significantly affected soil moisture and grain yield at two locations (Lucan11 and Moore11), but a significant planter type effect on soil temperature only occurred at a single and different site (Moore12). At Moore12, soil temperature was 0.5˚C warmer with the row planter (Table 3-8, $P<0.0001$). Therefore, in the current study, soil temperature was not related to soil moisture, and yield enhancement from the row planter at Lucan11 and Moore11 was not caused by a temperature increase.

In the Tillage x Removal model, tillage system altered soil temperature ($P<0.0001$, Table 3-3). Differences in soil temperature between each tillage system remained consistent across residue removal levels, locations and days of measurement. Mean soil temperature was slightly elevated with the Moldboard Plow and more aggressive conservation tillage systems, including the Disc and Disc Ripper, while there were insignificant differences in temperature between all NT and RTS systems (data not shown). The Moldboard plow was the tillage system with the highest numerical soil temperature, and only the Fall Disc & Cultivate did not differ from it. Compared to NT, the Moldboard Plow was 0.75˚C warmer ($P<0.0001$). Aside from the Moldboard Plow, Fall Disc & Cultivate was the only other system to significantly warm the soil greater than NT, specifically by 0.46˚C ($P=0.0098$). The remaining systems were all equivalent in temperature to NT (data not shown).

Elmore (1990) also observed minor soil temperature differences between tillage systems, of only 1˚C. However, the majority of studies demonstrate 2 – 3˚C warmer soil with CT relative to NT (DeFelice et al., 2006; Hooker, 2000; Johnson and Lowery, 1985; Yusuf et al., 1999). Lack of soil temperature differences among NT and reduced till systems in this study is consistent with those reported by Hooker (2000), who showed similar soil temperatures between NT and minimum till systems.

Although increases in soil temperature with Fall Disc & Cultivation and Moldboard Plow were statistically significant, the biological significance is questionable. Acceleration in soybean growth and development is very minimal with a temperature increase less than 1˚C (Hatfield and Egli, 1974; Hopper et al., 1979; Weber and Miller, 1972). Therefore, it is unlikely that temperature affected the tillage yield response.

Table 3-6. Volumetric soil water content (VSWC)† in seven tillage systems seeded with the row planter and seed drill at Lucan, ON and Moorefield, ON in 2011, and Arthur, ON and Moorefield, ON in 2012.

Tillage system	VSWC		
	Planter type		Moisture reduction with the row planter
	Seed drill	Row planter	
		m^3 m^{-3}	
No-till (NT)	30.6	30.2	0.4
Stalk Chop + NT	31.2	29.5	1.5 ***
Fall & Spring RTS	27.2	26.4	0.8 *
Fall RTS	29.0	28.4	0.6
Fall Disc, Spring Cultivate	26.8	25.9	0.9 *
Fall Disc & Cultivate	29.0	28.3	0.7 *
Moldboard Plow	26.0	24.8	1.2 **
Average	28.5 a	27.6 b	0.9 ***

† VSWC measurements were obtained through Time Domain Reflectometry at a depth of 0.12 m in the seed row and is averaged across locations and residue removal levels (No Removal, Intermediate Removal, and Nearly Complete Removal)

*, **, *** Indicates significantly different from zero at P=0.05, P=0.001, and P=0.0001, respectively

Table 3-7. Parameter estimates of equations that describe the relationship between average soil moisture content (mc %) and tillage system on soybean seed yield.

Equation Component	Tillage	Coefficient	SE	df	P>F
Intercept	NT	-6.28	2.61	58	0.0193
	Combined Group	2.03	0.57	58	0.0008
	MP	1.45	1.15	58	0.21
Linear (A)	NT	0.575	0.17	641	0.0008
	Combined Group	0.047	0.029	641	0.10
	MP	0.085	0.078	641	0.28
Quadratic (B)	NT	-0.0088	0.003	641	0.0018
	Combined Group	-0.0005	0.0004	641	0.25
	MP	-0.0009	0.0014	641	0.51

Yield (Mg ha^{-1}) = Intercept + A(mc) + $B(mc)^2$

Tillage systems include No-till (NT), Combined Group (Fall RTS, Fall & Spring RTS, SC + NT, and Disc tilled systems – both spring and fall cultivation), and the Moldboard Plow (MP)

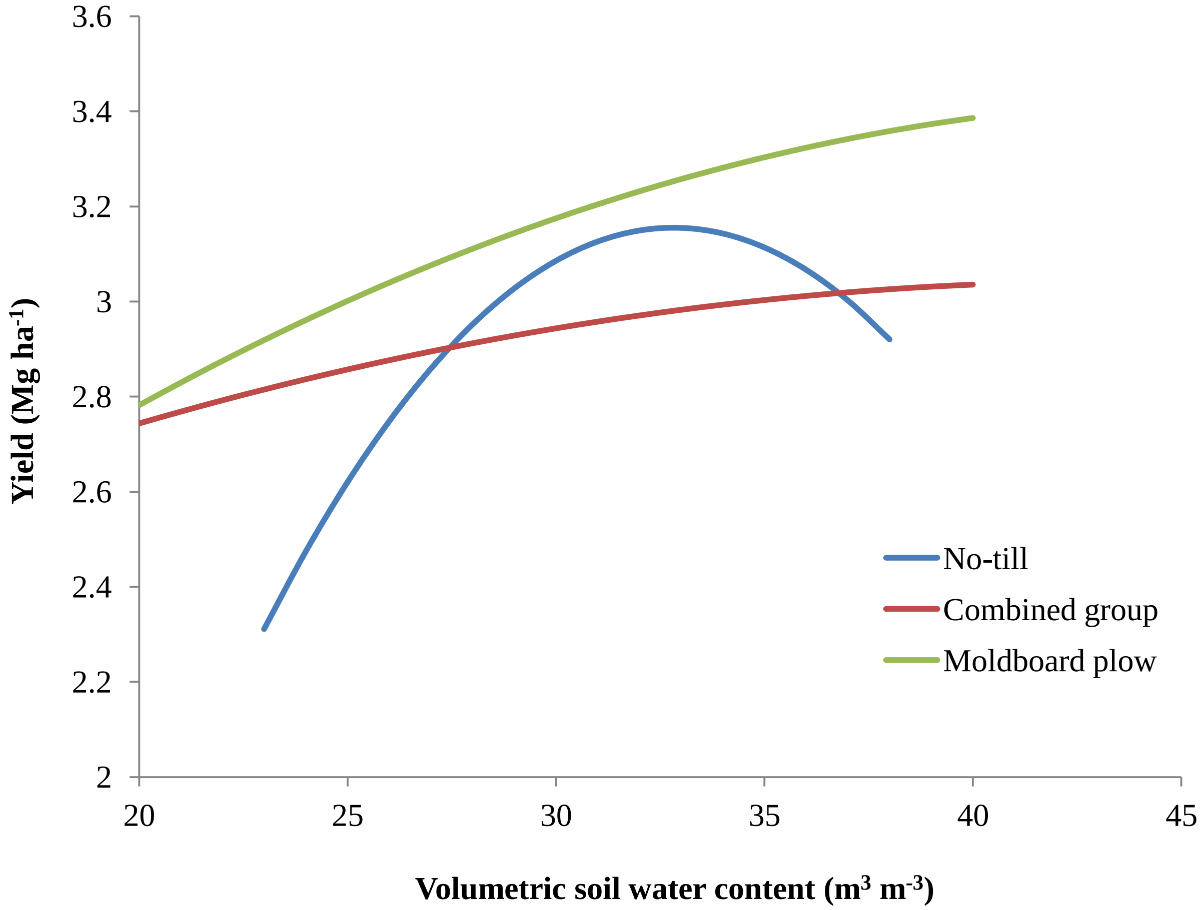

Figure 3-1. Soybean yield response to volumetric soil water content in No-Till, Moldboard Plow, and a combined group† of reduced tillage systems averaged across Lucan, ON and Moorefield, ON in 2011 and Arthur, ON and Moorefield, ON in 2012.

†Combined group refers to Fall RTS, Fall & Spring RTS, Stalk chop + No-till, and Disc tilled systems – both spring and fall cultivation

Table 3-8. Means comparison of grain yield, volumetric soil water content† (VSWC), soil temperature‡, days to 50% emerged§ plants ha^{-1}, plant density, and number of leaves $plant^{-1}$¶ averaged across tillage system and residue removal levels between the drill and row planter at Lucan, ON and Moorefield, ON in 2011, and Arthur, ON and Moorefield, ON in 2012.

Measured variable	Lucan11		Moore11		Arthur12		Moore12	
	Drill	Row planter	Drill	Row planter	Drill	Row planter	Drill	Row planter
Yield (Mg ha^{-1})	3.67 b#	3.77a	3.01 b	3.23 a	1.86 a	1.85 a	2.93 a	2.99 a
VSWC (m^3 m^{-3})	34.5	33.9	28.8	28.2	27.1	26.1	23.8	22.5
Soil Temperature (˚C)	23.1 a	23.2 a	20.2 a	20.3 a	10.6 a	10.5 a	20.1 b	20.7 a
Days to 50% emerged plants ha^{-1} (days)	-	-	-	-	34.7 b	35.4 a	10.2 a	10.2 a
Plant development (number of leaves)	2.21 a	2.19 a	2.24 a	2.26 a	2.30 a	2.19 b	2.51 a	2.49 a
Plant density (plants m^{-2})								
Third trifoliate	31.9 b	39.2 a	24.6 c	36.2 a	30.1 a	29.4 a	42.1 b	45.4 a
Pre-harvest	28.8 c	34.0 b	23.6 c	31.3 b	26.5 b	25.4 b	36.6 c	40.6 b

† VSWC measurements were obtained through Time Domain Reflectometry at a depth of 0.12 m in the seed row

‡ Soil temperature was measured three times per plot at the 0.05 m depth in the seed row

§ Emergence was recognized when the cotyledons extended above the soil surface and estimations of emergence were conducted in the days surrounding plant emergence.

¶ Represents the number of leaves $plant^{-1}$ averaged between measurements obtained at cotyledon staging and the third trifoliate.

Means followed by the same letter within a measured variable at a single location are not statistically different according to Fisher's Protected LSD Test at P=0.05. No letters indicate the interaction was not significant.

3.3.2 Soybean canopy response to tillage system, stalk chopping, and residue removal

Nodulation and yield components did not respond to tillage system or planter type. Therefore, they did not contribute to explanation of yield differences, and consequently will not be discussed at length in this section. Emergence and plant density were significantly affected in the Planter Type Model while only measures of plant development, including emergence, were shown to respond to tillage in the Tillage x Removal Model.

Planter type effects on soybean emergence: Plant emergence was significantly affected by the three-way interaction involving planter type x tillage system x location (Table 3-1). Emergence mean comparisons of the significant three-way interaction are illustrated in Table 3-9. Yield differences observed among planter types and tillage systems show no clear relationship with days to emergence. For example, at Arthur12, emergence with the row planter was 0.63 days slower in the SC + NT system (P=0.1068); yet the yield was greater with this seeding equipment. An emergence delay does not necessarily translate into a yield reduction as yield can also be determined by weather conditions post emergence (Meese et al., 1991; Yusuf et al., 1999). In contrast, at Moore12, emergence trended 0.58 days faster with the row planter compared to the drill in SC + NT (P=0.1396) and yield was 11% greater with the planter. While a half day emergence delay associated with the drill is unlikely to fully explain the 11% yield reduction, this result is consistent with other reports in the literature. Rapid emergence is generally associated with greater yield (Lueschen et al., 1992; Vyn et al., 1998; Wagner-Riddle et al., 1994), possibly due to shortened exposure to pre-emergence stresses and improved plant stands (Hammon et al., 2002; Nyvall, 1999). At both locations, the days to emergence of the NT and SC + NT systems with the drill did not differ from each other and were both significantly slower than emergence in the Moldboard Plow. This result could partially explain the yield deficit of SC + NT relative to the Moldboard Plow with the drill since emergence was delayed by 0.9 – 2.4 days; however, it does not address similar yields between NT and the Moldboard Plow. Vyn et al. (1998) displayed that a 1.5 day delay in emergence with NT contributed to an 18% yield loss relative to CT. However the yield response was not entirely an emergence related issue since other yield influencers such as soil temperature, soil moisture, crop growth, and plant density were also affected by tillage.

Tillage effects on soybean emergence in the Tillage x Removal Model: Seedling emergence did not reflect yield results well between planter type x tillage. However, more similarities exist between emergence and yield in the Tillage x Removal Model, despite that the data were only collected in 2012. Emergence was significantly affected by the tillage main effect (P=0.0086, Table 3-10); however the interaction with location (P=0.0169) reveals the differences occurred predominately at Arthur12. Emergence at Arthur12 was impeded due to soil crusting and cold soil temperature experienced post-planting. Select tillage systems created a more stressful environment than others; hence emergence differences were observed. Moore12 experienced optimal growing conditions immediately following planting; thus emergence speed was relatively uniform across treatments.

The fastest emerging tillage treatments at the Arthur12 location were the most aggressively tilled systems (the Moldboard Plow and Disc Ripper), the fall tilled systems (RTS and Disc & Fall Cultivation) and NT (with and without stalk chop, Figure 3-2). On average seedlings in these systems required 35 days to achieve 185,000 emerged plants ha^{-1}. The other tillage treatments, which were all forms of minimum till involving a pass in the spring, experienced a day delay in emergence. Thus, spring tillage in minimal till was detrimental to speed of emergence. Specifically within the disced treatments, emergence was delayed by 1.74 days with spring cultivation (P=<0.0001). The Spring RTS was also delayed relative to Fall RTS, but only by 0.88 days (P=0.0247).

When seeded at the same depth, the number of days for soybeans to emerge is largely dependent on the soil temperature (Hatfield and Egli 1974; Hopper et al., 1979; Tyagi and Tripahti, 1983; Weber and Miller, 1972). However, soil temperature did not relate to any of the observed emergence differences across tillage system at Arthur12. For example, the maximum temperature difference at Arthur12 averaged across measurement timings, of 0.7˚C, occurred between the Moldboard Plow and Disc Ripper (P=0.0388). This was not a sufficient difference to biologically impose an emergence delay, nor was an emergence difference observed between those two tillage systems. Therefore it likely that soil temperature did not result in emergence differences. Rather soil moisture recordings averaged across locations were inversely analogous to emergence results at Arthur12. Tillage systems with lower soil moisture tended to result in delayed emergence, excluding the Moldboard Plow and Disc Ripper. Although emergence and moisture trends mostly coincide, it is unlikely that soil moisture reductions imposed significant germination delays. The literature indicates severe moisture limitations (i.e., volumetric soil water content of approximately 0.09 m^3 m^{-3}) can delay seedling development and reduce seedling survivability (Helms et al., 1996; Helms et al., 1997). These studies report that at this moisture content there is sufficient water for imbibition but not for hypocotyl and radicle elongation. When moisture content was increased to 0.11 m^3 m^{-3} soil water was not limiting seedling emergence (Helms et al., 1996; Helms et al., 1997). Considering the average volumetric soil water content at Arthur12 was between 0.21 – 0.31 m^3 m^{-3} in the weeks following planting, seedlings had access to sufficient water quantities for germination and growth. More likely is that spring tillage accentuated the risk for soil crusting. Heavy rains following planting at Arthur12 resulted in soil crusting and it is possible that minimum till systems with a spring pass were most affected. Uson and Poch (2000) confirm that reduced tillage caused thicker and more complex crust layers compared to CT and NT. However, this contrasts with much of the literature which indicates residue cover protects the soil from crusting (Cassel et al., 1995; Neave and Rayburg, 2007; Wagger and Denton, 1992).

Interpreting emergence results at Arthur12 to describe the yield response averaged across all sites may be inappropriate because results at one site may not be consistent with other locations. Moore12 for instance did not exemplify significant differences in emergence. However, some emergence trends revealed through the stressful conditions in Arthur12 share similar responses to location-averaged yield results (the tillage x location yield interaction was insignificant). For example, tillage systems which were statistically the most rapid emerging systems at Arthur12 were also statistically highest yielding averaged across all locations. Emergence and yield trends between spring vs. fall only tillage are also comparable. Early season stress in Arthur12 may have exacerbated true emergence differences that might have been present at the other locations; but were hidden by either rapid emergence or the absence of data collection.

Although delayed emergence may result in plant mortality (Adee et al., 1994; Dick and van Doren, 1985; Hammon et al., 2002; Meese et al., 1991 Nyvall, 1999; Vyn et al., 1998), in this study population was unaffected by tillage when seeded with the row planter (P=0.2571, Table 3-3). Even at Arthur12 which exhibited significant emergence delays in specific tillage treatments, plant densities were similar. Therefore, delayed emergence did not hinder yield through a population reduction, but likely through delayed plant development (see below).

Soybean plant population: Population was significantly affected by the three-way interaction of planter type x location x stage (Table 3-1). Locations with greater differences in plant density between planter types also demonstrated greater yield differences. Arthur12 was the only location where mean soybean yields of row planter and NT drill did not differ (Table 3-8). Arthur12 was also the only location that had similar populations between planter types from the third trifoliate to harvest. While other studies have indicated equal to greater populations and yield with the drill than the row planter (Cox and Cherney, 2011; Oplinger and Philbrook, 1992), the results were confounded by row width effects. This may have masked true population and yield differences attributed to planting equipment. Janovicek et al. (2006) observed that plant stand success was improved with the drill as row width narrowed; even from 0.38 m to 0.19 m. However the majority of research, especially in Northern soybean growing regions, report better plant stands with a row planter compared to drilled beans as long as row spacing does not exceed 0.38 m (Bertram and Pedersen, 2004; Bohner, 2007a; Bohner and Earl, 2010; Staggenbord et al., 2004; VanKoughnet, unpublished). At Arthur12, seeding rates of both planters were similar. It was expected that plant population of the drill would have been lower due to greater mortality often associated with the drill vs. the planter, assuming equal seeding rates (Bertram and Pedersen, 2004; Bohner and Earl, 2010; VanKoughnet, unpublished). At Arthur12, similar plant populations and yield between planter types may have been caused by soil crusting. The tillage associated with the row planter may have reduced bulk density in the seed row making the soil more susceptible to crusting. This may explain the emergence delay with the row planter at

Arthur12. Alternatively, the seeding rate and depth of soil covering the seed at the time of planting was set to be similar between the drill and planter, but it was noted that loosened soil with the row planter washed into the seed row following a heavy rainfall event (which occurred 14 days after planting). In effect, the seed depth of the row planter was increased, which delayed emergence and reduced plant establishment. This observation is supported by the significant planter type x location interaction in the development model (P=0.0306). Soybean plants in the drill treatment were 13% more developed than plants in the row planter treatment at the VC growth stage at Arthur12 (P<0.0001). If seeds were at similar depths there would not have been a developmental difference at this early stage of development. The other sites displayed equal development between planter types (Table 3-8) and therefore seeds were at similar depths.

The greatest yield and population differences between row planter and drill occurred at Moore11. At V3 there was 27% greater plant survival with the row planter over the drill. At pre-harvest, this difference was reduced to 17.5% mainly because of minimal seasonal stand loss occurring with the drill while 10% stand loss occurred with the row planter. Bohner (2007a) and VanKoughnet (unpublished) support this observation as they reported less post-emergent stand loss with diminishing initial plant population. Plant populations at Lucan11 and Moore12 were also lower in the drill-seeded treatments than the row planter, but to a lesser extent than Moore11. Drilled populations at Lucan11 were 10 – 14% lower than the row planter depending on the time of measurement, and 6 – 8% lower at Moore12. It is recognized in the literature that drilled soybeans can suffer greater seedling mortality than the row planter due to variable seed placement, which is a suggested cause for yield disparity between planter implements (Bertram and Pedersen, 2004; Bohner and Earl, 2010; VanKoughnet, unpublished). Increasing seeding rate is often implemented to compensate for reduced plant establishment with the drill in order to attain final plant densities equal to the row planter (Bertram and Pederson, 2004; Bohner, 2007a; Devlin et al., 1995; Oplinger and Albaugh, 1996).

Observed plant survival with the drill was much lower than reported in the literature. Based on the original seeding rate targets, it was estimated that only 56 – 61% of seeds established plants with the drill at Lucan 11, Moore11, and Arthur12. Establishment with the drill at Moore12 was more successful at 86%. The literature reports 68 – 93% plant establishment with the drill (Bohner, 2007a; Bohner and Earl, 2010; Cox and Cherney, 2011; Oplinger and Philbrook, 1992; VanKoughnet, 2011) indicating it is possible that some estimates of plant survivability are underestimated due to an overestimate of seeding rate. However, the only real concern is Moore11 because it was the only location to exhibit a large plant stand difference between the drill and row planter (26% lower plant establishment with the drill at Moore11 [$P<0.0001$] vs. 14% at Lucan11 [$P<0.0001$], 9% at Moore12 [$P<0.0001$], and 1% at Arthur12 [$P=0.4895$]). Under the premise that a calibration error resulted in a lower seeding rate with the drill than the row planter at Moore11, the observed yield differences may not be fully attributed to planter type, but rather a combination of planter type and seeding rate.

To explore the potential impact of an error in seeding rate with the drill at Moore11, an estimate of actual seeding rate can be made based on a number of assumptions. Assuming that plant survival is 11% lower with the drill than the planter (this is the average difference observed at Lucan11 and Moore12 at the third trifoliate stage, and falls within the range found by Bohner [2010] and Staggenbord et al. [2004]), as opposed to the 27% reduction observed at Moore11, plant survival with the drill would have been 71% of the seeded population. Using the observed density of 24.6 plants m^{-2}, the calculated effective seeding rate would have been 342,000 seeds ha^{-1} with the drill. This compares to 440,000 seeds ha^{-1} sown with the planter, or a difference of

22%. Ontario data illustrates soybeans can be relatively insensitive to seeding rates and can compensate yield at low plant densities (Bohner, 2007a). In one instance, 95% of maximum yield was obtained with a seeding rate as low as 254,000 seeds ha^{-1} (Bohner, 2007a). Similarly De Bruin and Pedersen (2008a) found that 95% of maximum yield occurred with pre-harvest population between 194,000 - 291,000 plants ha^{-1}, but could occur with densities as low as 118,800 plants ha^{-1}. Other studies also demonstrate yield compensation at low plant populations (Pedersen and Lauer, 2002; Wells, 1991; Wells, 1993). Since both the calculated seeding rate and recorded pre-harvest plant density with the drill at Moore11 are within these ranges, it is probable that the yield of the drill is at least 95% of maximum yield as influenced by plant densities. This is a probable scenario considering the growing conditions post-planting were optimal throughout the 2011 season. Therefore, assuming the yield with the drill at Moore11 is at 95% maximum yield, the minimum yield reduction actually caused by the drill is calculated to be 2.3% (7.3% observed yield difference subtract 5% yield loss due to seeding rate error equals 2.3%). This brings the yield differential caused by planter type into a similar range observed at Lucan11 and Moore12. Although seeding rate discrepancies at Moore11 cannot be definitively eliminated, it is safe to conclude that planter type still had a significant effect on soybean yield at the Moore11 location.

Soybean plant development: Planter type generally did not influence plant development. Only at Arthur a significant developmental advancement occurred (see emergence section above). However, Figure 3-3 depicts an interesting observation made after the V3 developmental measurements. Visual advancements in soybean growth were noticed with Nearly Complete Removal over No Removal in NT environments (no plant development data available after V3).

But, in the No Removal level, the canopy appears more vigorous when seeded with the row planter compared to the drill. It appears that plant growth is delayed with the drill, possibly caused by plant stresses from poor residue management and row closure. These growth differences illustrate the potential for a NT yield deficit; however actual yields observations suggest compensatory growth occurred since yields were statistically similar (Yusuf et al., 1999).

Plant development response in the Tillage x Removal Model: With just the row planter, plant development was significantly affected by tillage; yet the response varied depending on the interaction with stage ($P<0.0001$, Table 3-3). Results from developmental measures at the unifoliate leaf staging may be extrapolated to reflect emergence differences since delayed emergence corresponds to delayed early season plant development.

Averaged across all sites, the NT systems demonstrated rapid early plant development. Plants in NT and SC + NT were similar in their developmental progress to most other till systems including the Moldboard Plow and Disc Ripper (Table 3-4). These results contrast much of the literature which illustrates vegetative development and emergence delays to NT (DeFelice et al., 2006; Johnson and Lowery, 1985; Meese et al., 1991; Vyn et al., 1998; Yusuf et al., 1999). A possible explanation for this discrepancy may be that the settings of the depth gauge wheels on the seeding equipment were not adjusted according to tillage system. Differences in soil firmness across tillage treatments may have resulted in slight variability in seeding depth, with possibly deeper seed placement in aggressively tilled systems than NT. Since deeper planting extends the time to emergence (Banks and Gilmour, 1979; Hammon et al., 2002; Stanton, 2013) actual emergence and early development differences attributed to tillage may have been concealed. A second, and more plausible cause for similar plant development progress between NT and other tillage systems is soil temperatures differences were minimal and biologically insignificant averaged across all locations (i.e. maximum difference of 0.8˚C, $P<0.0001$). The literature attributes rapid emergence and plant development in CT to warmer soil temperature than NT (Meese et al., 1991; Vyn et al., 1998) as hypocotyl elongation and plant development are accelerated with increasing soil temperature (Hatfield and Egli, 1974; Hopper et al., 1979; Tyagi and Tripahti, 1983; Weber and Miller, 1972). Since soil temperature means across systems did not differ greatly, emergence and early development in NT was equivalent to aggressively tilled systems.

Timing of secondary tillage following the Disc affected early season plant development. Spring cultivation resulted in 10% of a leaf stage developmental delay relative to fall cultivation at VC ($P=0.0034$). Compared to all tillage systems, plants in Fall Disc & Spring Cultivation were the least developed but were statistically indifferent from only the Fall & Spring RTS systems (both with and without stalk chopping). RTS treatments with spring tillage also experienced delayed development relative to the Fall RTS, but only statistically if there was a preceding pass in the fall.

Developmental differences at the VC stage cannot be solely attributed to a single soil parameter (i.e. soil moisture). Soybean growth and development is primarily determined by soil temperature (Duke et al., 1979; Meese et al., 1991; Weber and Miller, 1972), but can be influenced by numerous soil properties such as moisture (Hoogenboom et al., 87; Vyn et al., 1998), soil fineness (Hooker, 2000), bulk density (Hallmark and Barber, 1981), soil crusting, and nutrient availability (Osborne and Riedell, 2006). In this study, biologically insignificant temperature differences may have limited the magnitude of early development differences across tillage systems. Yet with respect to the development trends detected in response to tillage timing, it would appear that development was affected by soil moisture. Both lower soil water content and delayed development were observed in the spring tilled systems compared to the fall tilled counterparts.

Trends in plant development differences at the VC stage averaged across all sites are similar to the emergence trends at Arthur12. One of the greatest similarities is that the same treatments which were statistically the fastest to reach 185,000 emerged plants ha^{-1} at Arthur12 were also the most developed treatments at the VC stage averaged across all sites. Secondly, plants in spring tillage in the minimum till systems was delayed relative to fall only or NT; especially the Disc treatments. Considering development was unaffected by the tertiary interaction involving tillage, stage, and location (Table 3-3), Arthur12 was not solely influencing development responses at VC. This supports the theory that emergence differences averaged across all sites were not detected due to rapid establishment and non-stressed environments.

Results obtained at the V3 stage reveal differences in the progression of plant development across tillage systems. Most significant differences at the VC staging disappeared by the V3 timing (Table 3-4), indicating development slowed in the initially advanced treatments, and accelerated in those that were initially delayed. Development of NT was notably slowed relative to other tillage systems as plants approached the V3 stage. For example, NT was more advanced than Fall & Spring RTS systems and the Fall Disc & Spring Cultivation at the VC timing. By V3 these differences were not detected. Similarly, the developmental difference between fall timing and spring secondary tillage following the disc was reduced from 10% of a leaf stage at VC (P=0.0034) to 7% at V3 (P=0.3874). The Fall & Spring RTS systems also advanced to be similarly developed as soybeans in the Fall RTS system by the V3 stage. Aggressive tillage also displayed accelerated crop development relative to other systems as the

Moldboard Plow became more developed than any other tillage system. Specifically, the Plow was more advanced than NT by 43% of a leaf stage at V3 (P<0.0001). Yusuf et al. (1999) support this finding as they also reported greater leaf area in CT vs. NT prior to R1. Similar advancements in early season plant biomass accumulation in CT have been observed in the literature (Vyn et al., 1998; Webber et al., 1987). Plants in the Disc Ripper treatment (which is the most aggressive form of conservation till in this study) were also more developed than NT (with and without stalk chopping), Spring RTS, and Fall Disc & Spring Cultivation systems. Aside from the Plow and Disc Ripper, all other tillage systems were all statistically equivalent in leaf appearance as NT.

Rapid vegetative growth accelerates canopy closure and maximizes light interception which increases biomass yield potential (Dohlman and Long, 2009). However, seed yield in the Moldboard Plow was not the highest, despite being the most vegetatively developed and expressing the fastest canopy fill. Late season compensatory growth in NT treatments is identified to be the yield equalizing factor if early season biomass differences were observed (Board and Harville, 1994; Pedersen and Lauer, 2004b; Yusuf et al., 1999; Webber et al., 1987). Results from the current research would indicate advanced maturity in CT may have actually limited yield relative to other tillage systems (at least in 2012, data not shown). The Moldboard Plow was the most advanced maturing treatment; with one third of pods ripe at the time of measurement (targeted at a location-averaged R7 staging). The Disc Ripper was the next most advanced system with 13% mature pods, although this was statistically greater than only SC + NT by 12% (P=0.0368). The remaining tillage systems were all statistically equal in timing of crop maturity. These results mimic the trends observed at V3, demonstrating that accelerated early season plant development translated into early crop maturity. Thus, treatments that were developmentally advanced at V3 could not capitalize on the advantage of accelerated early season growth and canopy closure. This response may have been caused by a restricted photosynthetic sink in CT (i.e., insufficient seed number for the photosynthetic capacity of the plant). The literature reports accelerated canopy development results in a larger photosynthetic capacity at the time of flowering, which creates a potential for greater pod count and yield in soybean (Carpenter and Board, 1997; Cooper, 2002; Frederick et al., 2001). However, similarities in yield components measured in this study indicate either i. the developmental advantage observed at V3 was not biologically significant enough to provide a yield enhancement opportunity, or ii. flowers and pods were aborted as a result of increased drought stress experienced in CT (Frederick et al., 2001; Pedersen and Lauer, 2004a). If the latter possibility is true then soybeans in CT may have had the photosynthetic capacity to continue supporting seed fill late in the season if the seeds were not aborted mid-season. In effect, plants in the Moldboard Plow could have been senescing prematurely because of a restricted photosynthetic sink, and consequently were more mature at the R7 measurement timing.

Table 3-9. Number of days required to attain 50% emergence† in seven tillage systems seeded with the row planter and seed drill at Arthur, ON and Moorefield, ON in 2012.

Tillage system	Arthur			Moorefield		
	Seed drill	Row planter	Advancement in drill emergence	Seed drill	Row planter	Advancement in drill emergence
	------------------------- Number of days -------------------------					
No-till (NT)	35.3 ab‡	35.1 bc	-0.2 ns	10.7 b	10.4 a	-0.3 ns
Stalk Chop + NT	34.7 bc	35.3 bc	0.6 ns	10.7 b	10.2 a	-0.5 ns
Fall & Spring Residue Tillage Specialist (RTS)	35.5 ab	35.8 ab	0.3 ns	10.3 ab	10.4 a	0.1 ns
Fall RTS	34.8 bc	35.0 bc	0.2 ns	10.2 ab	10.2 a	0.0 ns
Fall Disc & Spring Cultivate	36.1 a	36.7 a	0.6 ns	10.0 ab	10.1 a	0.1 ns
Fall Disc & Cultivate	34.3 c	34.9 c	0.6 ns	9.9 ab	10.3 a	0.4 ns
Moldboard Plow	32.3 d	34.9 c	2.6 ***	9.8 a	9.9 a	0.1 ns

† Emergence was recognized when the cotyledons extended above the soil surface. Fifty percent emergence occurred when the visually estimated emerged population reached 185,000 plants ha^{-1} at Arthur12 and 244,500 plants ha^{-1} at Moore12.

‡Means with the same letter within the same planter type and location indicate means are not significantly different according to Fischer's Protected LSD Test at P=0.05.

***Indicates significantly different from zero at P=0.0001

ns - Indicates not significantly different at P=0.05

Table 3-10. Analysis of variance for seedling emergence†, soil ammonium and nitrate concentrations‡ (NH_4^+ and NO_3^- respectively), number of nodules plant^{-1}§, and yield components¶ in response to tillage and residue removal at Lucan, ON and Moorefield, ON in 2011, and Arthur, ON and Moorefield, ON in 2012.

		Emerg-ence		NH_4^+ ppm	NO_3^- ppm	Number of nodules		Pods plant^{-1}	Seeds plant^{-1}	Seed weight plant^{-1}
Source of variation	**df**	P>F	**df**		P>F		**df**		P>F	
Location (L)	1	<.0001	3	0.0012	<.0001	0.0001	3	0.0051	0.0035	0.0231
Tillage (T)	9	0.0086	4	0.8716	0.6343	0.2952	2	0.0814	0.1931	0.1329
Residue Removal (R)	2	0.3442	1	0.5527	0.8585	0.043	1	0.3164	0.1136	0.083
T × R	18	0.8975	4	0.0849	0.6038	0.2683	2	0.0805	0.2349	0.1165
L × T	9	0.0169	12	0.4688	0.0972	0.2153	6	0.0549	0.146	0.1393
L × R	2	0.2412	3	0.3769	0.223	0.0591	3	0.1447	0.0425	0.0234
L × T × R	18	0.6641	12	0.1598	0.2191	0.897	6	0.0381	0.1875	0.2976

† Emergence was evaluated in all tillage systems and residue removal levels, but was only measured in 2012

‡ $NH4^+$ and $NO3^-$ concentrations were measured in NT, SC + NT, Spring RTS, Fall RTS, and the Moldboard Plow, and in No (residue) Removal and Nearly Complete Removal levels.

§Nodule number plant^{-1} was counted in the same tillage and residue removal levels as soil nitrogen. Nodules were counted on three plants randomly selected from the experimental unit.

¶ Yield components, consisting of pods plant^{-1}, seeds plant^{-1}, and seed weight plant^{-1} were counted on 30 plants in No-till, Spring RTS, and Moldboard plow tillage systems and in the No Removal and Nearly Complete (residue) Removal levels.

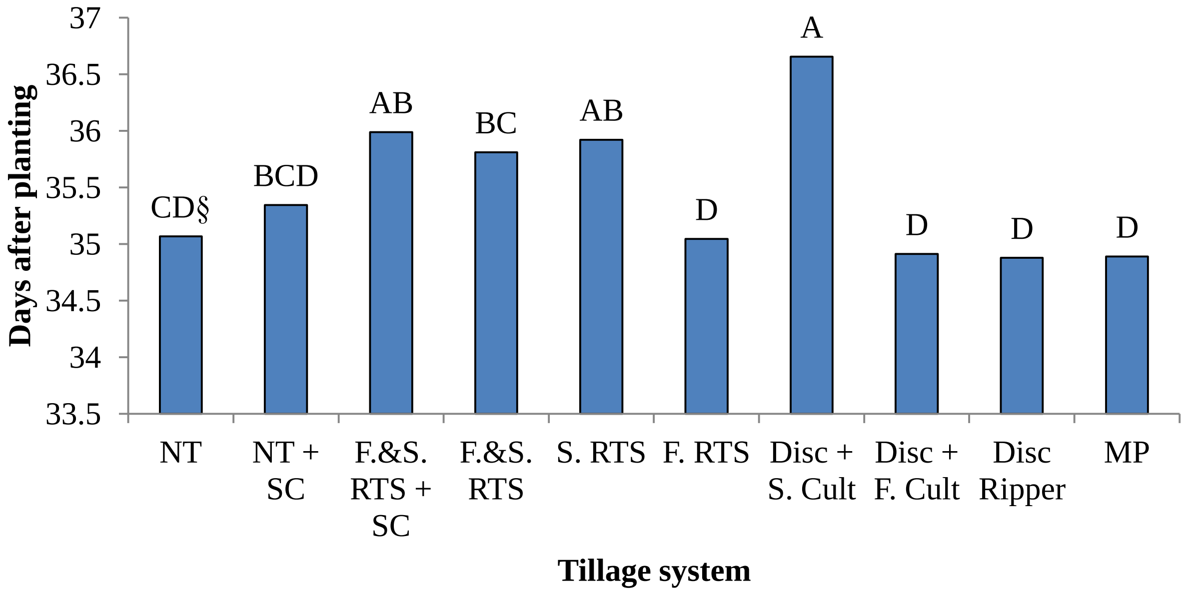

Figure 3-2. Days after planting to attain 185,000 emerged plants ha^{-1} in response to tillage system† averaged across residue removal levels‡ in Arthur, ON in 2012 when sown with a row-unit planter.

†NT: No-till, SC: Stalk chop, F.: Fall, S.: Spring, RTS: Residue Tillage Specialist (manufactured by Salford Farm Equipment), Cult: Cultivate, MP: Moldboard plow

‡Residue removal levels include No Removal, Nearly Complete Removal and Intermediate Removal.

§Means with the same letters are not significantly different according to Fischer's Protected LSD Test at P=0.05

Figure 3-3. Plot view of soybeans seeded in the No-Till treatment with the drill (left) and row planter (right) in No Removal (foreground) and Nearly Complete Removal (background, marked by red stakes) 49 days after planting in Moorefield, ON in 2012.

3.4 Nitrogen response

Averaged across all residue removal levels, tillage systems, and locations, 56 kg N ha^{-1} applied broadcast at planting increased soybean yield by 0.14 Mg ha^{-1} (4.7%, P=0.0016, Table 3-11). Minimum tilled systems or treatments with high amounts of surface residue coverage responded similarly to N fertilizer as systems with minimal residue cover, as evidenced by the lack of significant interaction between N with residue removal level, tillage system or locations. Meese et al. (1991) also observed a 2 – 4% yield increase to N fertilizer application which was also unaffected by tillage. Numerous other studies indicate a 1 – 5% yield improvement with N application in soybeans (Lamb et al., 1990; Meese et al, 1991; Osborne and Riedell, 2006; Osborne and Riedell, 2011; Salvagiotti et al., 2009; Scharf and Wiebold, 2003; Stone et al., 1985). The yield advantage observed in these studies was often year dependent. In the current study, dissection of the N x location yield interaction (Table 3-12), although insignificant (P=0.2266), also suggests that the positive response to N varied with location. Contrasts (not shown) reveal a significant response to N fertilization was only observed at Lucan11 (0.171 Mg ha^{-1}, P=0.0407), Arthur12 (0.163 Mg ha^{-1}, P=0.0476), and Moore12 (0.228 Mg ha^{-1}, P=0.0086).

Visual differences between N treatments were observed early in the growing season. Soybeans in N treated plots expressed darker green canopies and lush growth compared to plots with no N fertilizer. This difference was captured in plant development measurements as N fertilizer accelerated vegetative development at V3 by 20% of a trifoliate averaged across locations (P<0.0001). However, developmental differences were specific to location and the timing of measurement (Table 3-11). Development responses to N fertilization correspond with the yield response to N fertilizer at each location. The three locations that had a positive yield response to N also exhibited accelerated development at the V3 stage. Soybeans at Lucan11 were similar in leaf number (P=0.1443), but there was a trend for advanced development with the N fertilizer treatment vs. non-fertilized at V3 (Table 3-13). N fertilizer improved yield by 4.3% at Lucan. Development at Moore11 did not respond to N, and consequently, resulted in similar grain yields. N fertilized plants at V2 at Arthur12 were 8% of a leaf stage more developed than non-fertilized, and at Moore12 they were 52% greater at V3 (Arthur12 was measured a few days early). The corresponding yield improvement to N fertilization was 9.6% and 7.8% at Arthur and Moore12 respectively. Therefore accelerated vegetative development corresponded to a positive yield response to N fertilizer.

Osborne and Riedell (2006 and 2011) similarly attribute an N yield response to rapid early growth. It was determined that dry matter accumulation prior to the R4 growth stage was up to 17% greater in N treated soybeans than non-fertilized. Yield was improved by 5%. Starling et al. (2000) also discovered starter N fertilizer positively influenced vegetative growth and yield. Although the units of the growth measurements in the literature (g biomass m^{-2}) vary from the measures of plant development used in the current research (number of leaves per plant), they are essentially describing a similar trait. Nitrogen application can accelerate canopy growth and vegetative development, which can increase light interception and photosynthetic capacity of the crop canopy. However it does not always translate into a yield response (e.g., Terman, 1977; Yusuf et al., 1999). Additionally in certain conditions, as in Moore11, N fertilization may not have any effect on development, growth, or yield.

The lack of response to N fertilization observed at Moore11 may be due to relatively high soil nitrate concentration. In contrast, soil nitrate concentration was the lowest at the Moore12 site; both development and grain yield responded to N fertilizer at this site (Table 3-12). Others report soybean responses to N occur when soil nitrate concentration are below 85 kg NO_3 ha^{-1} in the top 0.60 m (Lamb et al., 1990; Osborne and Riedell, 2011; Scharf and Wiebold; 2003; Stone et al., 1985). Specifically, Osborne and Riedell (2006) observed a 5% yield response, in South Dakota, when soil nitrate was below 20 kg ha^{-1} in the top 0.30 m. Scharf and Wiebold (2003) observed a small yield response of 67 kg ha^{-1} if soil tests were below 50 kg NO_3 ha^{-1} in the top 0.30 m in Missouri.

While soil nitrate levels varied across locations in the current research study, they did not vary within locations due to residue removal levels or tillage system (Table 3-10). The interaction between N application and residue removal was also insignificant with respect to yield. This result was not expected. Because the decomposition of corn residues immobilizes soil nitrate (Power et al. 1986; Stemmer et al. 1990), it was expected that high stover biomass associated with increasing corn yields would prolong net immobilization (Green et al., 1995). Alternatively, NT conditions could delay mineralization as microbial access to residue is minimized (Stemmer et al., 1990), but more importantly, cold soils slow soil warming and biological activity (Andraski and Bundy, 2008). Therefore, soil nitrate tests were expected to be low following high residue treatments.

Although a 4% yield response is a substantial yield improvement to N application in soybeans, it is questionable whether the management practice is economically viable. The average price for urea fertilizer in 2013 in Ontario was \$588.66 $tonne^{-1}$ (\$1.28 kg^{-1} N, Ontario farm input monitoring project, 2013). When applied at 56 kg N ha^{-1}, the cost of the fertilizer alone is \$71.66 ha^{-1}. At an average yield gain of 0.14 Mg ha^{-1}, soybean prices would need to be \$511.86 Mg^{-1} to break even. In 2011, the average market price for soybean was \$448.66 ha^{-1} (data not available for 2012 or 2013; OMAF statistics, 2013); therefore the risk of losing money would deter many growers from adopting the practice of applying N to soybeans. However, at

Moore12, with a yield gain of 0.23 Mg ha^{-1} to N application, the financial break-even becomes \$311.57 Mg^{-1}. If growers can target fields that are low in soil nitrate, N application becomes much more economically viable. Continuing research should focus on nitrate depleted soils, such as fine textured, wet soils, or soils with high quantities of surface residue biomass, which may reveal greater yield responses to N. Additional research investigating the N fertilizer rates below 56 kg ha^{-1} could also be used to determine if the financial break-even can be reduced.

Table 3-11. Analysis of variance for measured soil and plant characteristics in response to nitrogen application†, tillage‡, residue removal, and timing of measurement§ at Lucan, ON and Moorefield, ON in 2011, and Arthur, ON and Moorefield, ON in 2012.

Source of variation		Soil moisture	Soil temperature		Emergence		Plant development	Plant density	Yield
	df	P>F		df	P>F	df	P>F		
Location (L)	3	<.0001	<.0001	1	<.0001	3	0.0001	<.0001	<.0001
Tillage (T)	2	0.0964	0.1109	2	0.0148	2	0.0517	0.0484	0.0381
Residue Removal (R)	2	0.3680	0.0015	2	0.2577	2	0.1272	0.0559	0.4283
Nitrogen (N)	1	0.4717	0.9006	1	0.6613	1	0.0002	0.8316	0.0016
Stage (S)	4	<.0001	-	-		1	<.0001	<.0001	-
T × R	4	0.0001	0.4787	4	0.3187	4	0.9693	0.5547	0.3745
N × T	2	0.3076	0.9501	2	0.3004	2	0.7815	0.4998	0.6266
N × R	2	0.9054	0.9834	2	0.2363	2	0.6037	0.9226	0.1921
L × T	6	0.3539	0.0842	2	0.0507	6	0.0936	0.6453	0.7674
L × R	6	0.5895	0.8493	2	0.3940	6	0.0112	0.4485	0.3745
L × N	3	0.1761	0.8281	1	0.8915	3	0.0121	0.5338	0.2266
T × S	8	0.6754	0.9609	-	-	2	0.0456	0.7352	-
R × S	8	0.1157	0.3823	-	-	2	0.0303	0.9733	-
N × S	4	0.1324	0.9972	-	-	1	0.0002	0.0419	-
L × S	12	<.0001	<.0001	-	-	3	<.0001	0.8849	-
N × T × R	4	0.5856	0.9969	4	0.8287	4	0.8123	0.8361	0.1815
L × T × R	12	0.1955	0.9971	4	0.1800	12	0.8481	0.0052	0.0173
L × N × T	6	0.6689	0.9755	2	0.5396	6	0.7912	0.5722	0.7551
L × N × R	6	0.2168	0.9949	2	0.1675	6	0.9675	0.3623	0.0804
T × R × S	16	0.4828	0.9989		-	4	0.9020	0.7856	-
N × T × S	8	0.7917	0.9980		-	2	0.8541	0.6159	-
L × T × S	24	0.3443	0.0.9991		-	6	0.0984	0.4957	-
N × R × S	8	0.7778	0.9999		-	2	0.9938	0.7079	-
L × R × S	24	0.4914	0.5817		-	6	0.0502	0.0211	-
L × N × S	12	0.5733	0.9990		-	3	0.0008	0.4720	-
L × N × T × R	12	0.9797	0.9998	4	0.7726	12	0.9090	0.3880	0.1875
N × T × R × S	16	0.9783	-	-	-	4	0.8009	0.8839	-
L × T × R × S	48	0.7417	-	-	-	12	0.9343	0.1314	-
L × N × T × S	24	0.9460	-	-	-	6	0.6562	0.2104	-
L × N × R × S	24	0.9664	-	-	-	6	0.9680	0.2643	-
L × N × T × R × S	48	-	-	-	-	12	0.9987	0.9338	-

† Nitrogen application refers to a broadcast application of urea fertilizer at a rate of 0 or 122 kg ha^{-1} (56 kg ha^{-1} nitrogen) applied at planting.
‡ Tillage systems include: Spring RTS, SC + Fall and Spring RTS, and Fall Disc Ripper
§ Time of measurement, also referred to as Stage – varies depending on the response variable. Soil moisture and temperature measurements occurred at 0, 3, 7, 14, and 28 days after planting. Development measurements occurred at the unifoliate and third trifoliate leaf stages and plant density was recorded at the third trifoliate leaf stage and at pre-harvest.

Table 3-12. Soybean yield response to nitrogen fertilization† at Lucan, ON and Moorefield, ON in 2011, and Arthur, ON and Moorefield, ON in 2012 with corresponding soil nitrate† at each location.

Location	0 kg N ha^{-1}	56 kg N ha^{-1}	Yield advantage to N fertilization	Soil nitrate concentration
	Yield (Mg ha^{-1})			ppm
Lucan, 2011	3.76	3.93	0.16 *	11.9 b‡
Moorefield, 2011	3.28	3.28	0.00	15.4 a
Arthur, 2012	1.78	1.94	0.17 *	8.8 c
Moorefield, 2012	2.96	3.19	0.23 *	7.6 c
Average	2.95 b	3.09 a	0.14 **	

† Soil nitrate values at each location are averaged across tillage systems and residue removal levels

‡ Means with the same letter in soil nitrate or average yield are not statistically different according to Fischer's Protected LSD Test at P=0.05

*, ** Indicates significantly different from zero at P=0.05 and P=0.001, respectively

Table 3-13. Number of leaves plant^{-1}† in the nitrogen treatments at Lucan, ON and Moorefield, ON in 2011, and Arthur, ON and Moorefield, ON in 2012, taken when the majority of plants at a location were approximately at the unifoliate and third trifoliate growth stage.

Location	Unifoliate stage		Third trifoliate stage	
	0 kg N ha^{-1}	56 kg N ha^{-1}	0 kg N ha^{-1}	56 kg N ha^{-1}
	Number of leaves plant^{-1}			
Lucan, 2011	0.70 c‡	0.76 b	3.69 a	3.77 a
Moorefield, 2011	0.71 b	0.71 b	3.81 a	3.83 a
Arthur, 2012	0.69 c	0.70 c	3.58 b	3.76 a
Moorefield, 2012	0.92 c	0.92 c	4.18 b	4.70 a
Average	0.76 c	0.77 c	3.81 b	4.02 a

† Leaf number designations are the following: 0 = VE, 1 = VC, 2 = V1, 3 = V2, 4 = V3, 5 = V4.

‡ Different letters in the same row indicate leaf number is significantly different at α=0.05.

Chapter 4. General Discussion

4.1 Research contributions

It was suspected that high amounts of residue on the soil surface has been reducing soybean performance with NT in Ontario, which have caused many growers to revert back to more tillage, or removing residue, or applying fertilizer N. Consequently, it has been perceived that soybean performance is compromised with NT because of unfavourable soil moisture profiles, cooler soil temperatures, reduced N availability, delayed plant development and nodulation, reduced planter performance and stand establishment responses. The objective of this research was to evaluate soybean performance across a range of residue management strategies and determine which soil and plant variables were most responsible for yield differences, if any, between NT and CT. In addition, if the mechanisms that contribute to a yield deficit could be identified, it would indicate potential management solutions that could minimize the yield loss.

NT growers may become increasingly dissatisfied with their soybean crop if they adopt stalk chopping combine heads or if they chop residue after harvest. The results from this research validate the assumption of a productivity deficit to NT practices relative to CT, but only when residue was stalk chopped and soybeans were seeded with the drill. The primary cause of this yield decrease appeared to be tied to horizontal residue orientation and the drill's reduced ability to move stover away from the seed row, which resulted in higher soil moisture. This finding agrees with meta-analyses which reported reduced NT success with increasing soil moisture (DeFelice et al., 2006; Toliver et al., 2012). Removing chopped residue improved soybean yield; however, avoiding stalk chopping operations or seeding with a row planter were more successful alternatives. Therefore, the increasing frequency of a NT yield deficit is likely attributed to the increased use of stalk chopping combine heads followed by drill seeded soybeans as opposed to strictly higher corn biomass on the soil surface. However, it is important to note that not all chopper heads are created equal in their residue sizing ability. It appears, through this research that corn heads that cut stover into small pieces can lead to yield reductions if the chopped residue is not managed properly.

Although the positive yield response to the row planter was observed in SC + NT and Fall Disc & Cultivate, other tillage systems also trended higher yield with the row planter. When averaged across tillage and residue removal levels, certain locations responded to planter type more than others. More responsive locations also exemplified increased plant stands with the row planter. This confirms the hypothesis that the row planter achieves greater yield than the drill due to greater plant density; but contrary to the second half of the hypothesis, this response was unaffected by surface residue coverage. Increasing seeding rates with the drill may be a potential solution to eliminate the yield difference between planter types (Bertram and Pederson, 2004; Bohner, 2007a; Devlin et al., 1995; Oplinger and Albaugh, 1996).

The hypothesis that N fertilizer will improve soybean yield in high surface residue conditions was rejected. Residue removal and tillage system did not affect the response to N fertilizer. This was likely caused by similar soil nitrate concentration between residue removal levels. However, differences in soil nitrate across locations explained some of the location response to N fertilizer. As soil nitrate decreased, the soybean yield response increased with the application of N fertilizer. This supports previous work which indicated greater yield response to N in low soil nitrate testing environments (Beard and Hoover, 1991; Scharf and Wiebold, 2003). These results suggests that if stover biomass continues to increase and significantly delay N mineralization (as reported by Andraski and Bundy [2008] and Green et al. [1995]), there is potential for soybeans to express greater response to N under increasing residue cover.

The primary hypothesis, that residue management strategies such as minimal tillage, stalk chopping, residue removal, planter configuration, or N application can be used to alleviate the yield deficit observed with NT, is rejected. Residue removal and planter type did not stimulate a yield response compared to NT alone, while stalk chopping and minimal tillage actually reduced yield from NT. Similarly soybeans were unaffected by N fertilizer across varying surface residue levels. The reason is that NT yield was equal to CT. This may be attributed to favourable weather conditions for NT (i.e., late planting in 2011 and dry season in 2012). Cool and wet growing seasons after planting would likely exemplify a yield deficit and possibly a greater response to residue management. Regardless this research supports NT success for soybeans grown in rotation following a corn crop.

4.2 Research limitations

The interpretation of results was a challenge across residue removal levels, perhaps due to variable amounts of surface residue across the removal treatments. For instance, corn grain yields were significantly lower in Arthur compared to Lucan, resulting in 33% less stover biomass in the No Removal level. In reality, responsiveness to the marginal residue removal may produce marginal effects on soybean performance. In addition, poor residue removal treatment segmentation at Lucan11 resulted in similar stover weights between Intermediate Removal and Nearly Complete Removal. This was caused by equipment limitations. Since removal levels were not quantitatively defined (i.e. stover weight m^{-2} or percent surface coverage), residue removal treatments were variable across and within locations. This may explain the general absence of yield response to residue removal. If possible, future residue removal work should quantitatively define treatment levels to minimize experimental error.

The objective of this research was to evaluate soybean performance in response to residue management following high yielding corn (i.e. >12 Mg ha^{-1}). However, three of the four sites produced corn in the previous year with yields at or below the provincial average (10.7 Mg ha^{-1}, OMAF statistics [2013]). Results from this study indicate that opportunities to significantly improve soybean performance in fields with only moderate levels of corn residue may be limited. Inferences may be made to predict responses in high levels of corn residue, but the response is still unknown.

Mechanisms describing yield trends were determined by comparing treatment means generated by univariate analyses of other measured variables. The greatest disadvantage with this approach is that it describes yield through one response variable, while yield is actually determined by a combination of multiple genetic and environmental factors (Hallmark and Barber, 1981; Hoogenboom et al., 1987; Hooker, 2000; Meese et al., 1991; Osborne and Riedell, 2006; Vyn and Hooker, 2002; Vyn et al., 1998). However, using measured variables as covariates in the yield model would have been inappropriate considering those variables were not independent of fixed effects. Thus treatment variation would have been double-counted between treatments and soil and plant response variables. A second problem with this approach is that yield trends could not be fully explained through the measured plant and soil variables. Other un-measured variables affected by residue management, such as root depth, drought stress, seedbed fineness, bulk density, etc may also be responsible. However, due to a limited labour force and the labour laws capping work week hours, not all of these measures could be obtained.

4.3 Future research

Stalk chopping residue adversely affected drill performance in NT conditions, but the row planter managed residue well and resulted in a 12.4% yield gain. The specific planter configuration was influential in this response, suggesting that soybeans may respond differently to alternative planter configurations. Future research in residue management could explore different combinations of planter accessories (i.e. row cleaners, coulters/ number of disc blades, closing wheels, down pressure control, etc) to determine the consistency of configuration performance across a range of NT environments. This would determine the actual mechanism of enhanced yield (i.e., seed row tillage and corresponding moisture reductions, residue management in the seed row and increased plant establishment, or inherent design of the row planter which increases uniform seed spacing and depth control) and may also provide an opportunity for further yield improvement. In addition, the yield response to planter type across locations was influenced by plant density. Seeding at higher populations with the drill may equilibrate early season stand counts and eliminate the yield disparity. A cost-benefit analysis of the different options would assist growers with their seeding equipment decisions.

Nearly complete stover removal improved drill performance in SC + NT conditions averaged across locations by 0.26 Mg ha^{-1}, and it improved yield by 0.43 Mg ha^{-1} with the row planter at Moore12. Bohner (2010) demonstrated a similar yield gain to residue removal with the row planter in NT conditions and speculated the response was attributed to early planting. Moore12 was also seeded during an early to average time frame for the region. The inconsistent, yet considerable yield increase to removal in the current research necessitates further investigation, with a focus on early planting, to determine if a real yield opportunity exists. In addition, this research should focus on above average yielding corn fields (i.e. >12.5 Mg ha^{-1}) and quantitatively define residue removal treatments. In the current research soybean yield increasingly responded to N fertilizer as soil nitrate decreased across locations. Surface residue cover did not influence nitrate concentration or yield; however, corn yields in the previous growing seasons were notably below the original target of 12 Mg ha^{-1}. Increasing stover biomass on the soil surface delays soil warming and mineralization which leads to soil nitrate shortages. It may be possible that soybean yield will be more responsive to N fertilizer at sites with above average corn yield.

References

Aase, J. and F. Siddoway. 1980. Stubble height effects on seasonal microclimate, water balance, and plant development of notill winter wheat. Agric. Meteor. 21:1-20.

Adee, E., E. Oplinger, and C. Grau. 1994. Tillage, rotation sequence, and cultivar influences on brown stem rot and soybean yield. J. Prod. Agric. 7:321-347.

Al-Kaisi, M., and J. Guzman. 2013. Effects of tillage and nitrogen rate on decomposition of transgenic *Bt* and near-isogenic non-*Bt* maize residue. Soil and Tillage Res. 129:32-39.

Andrade, F. and P. Abbate. 2005. Response of maize and soybean to variability in stand uniformity. Agron. J. 97:1263-1269.

Andraski, and Bundy. 2008. Corn residue and Nitrogen source effects on Nitrogen availability in no-till corn. Agron. J. 100:1274-1279.

Anonymous. 2013. 20/20 Air Force, How it works. http://www.precisionplanting.com/Products/20-20-Airforce/How.aspx Accessed June 29, 2013.

Banks L. and A. Gilmour. 1979. Effects of sowing depth on field emergence of soybeans. Austral. J. of Exp. Ag. and Animal Husbandry, 19:719-724.

Barzegar, A., A. Hashemi, S. Herbert, and M. Asoodar. 2004. Interactive effects of tillage system and soil water content on aggregate size distribution for seedbed preparation in Fluvisols in southwest Iran. Soil and Tillage Research, 78:45-52.

Beard, B. H., and R. M. Hoover. 1971. Effect of nitrogen on nodulation and yield of irrigated soybeans. Agron. J. 63:815–816.

Bertram, M., and P. Pedersen. 2004. Adjusting management practices using glyphosate-resistant soybean cultivars. Agron. J. 96: 462-468.

Beyaert, R., and P. Voroney. 2011. Estimation of decay constants for crop residues measured over 15 years in conventional and reduced tillage systems in a coarse-textured soil in southern Ontario. Can. J. of Soil Sci. 91:985-995.

Blevins, R., M. Smith, G. Thomas, and W. Frye. 1983. Influence of conservation tillage on soil properties. J. Soil Water Conserv. 38:301-304.

Board, J. and W. Hall. 1984. Premature flowering in soybean yield reductions at non-optimal planting dates as influenced by temperature and photoperiod. Agron. J. 76:700-704.

Board, J., and B. Harville. 1994. A criterion for acceptance of narrow-row culture in soybean. Agron. J. 86:1103-1106.

Bohner. H. 2005. Advancing no-till soybean production. Crop Advances: Field crop reports.

Bohner, H. 2007. Soybean planting date evaluations. Crop Advances: Field crop reports.

Bohner, H. 2010. Soybean tillage systems to manage corn residue. Crop Advances: Field crop reports.

Bohner, H. and H. Earl. 2010. Increasing profits through precision seeding and seed treatment. Crop Advances: Field crop reports.

Bohner, H., B. Deen., and G. Stewart. 2011. Soybean tillage systems. Crop Advances: Field crop reports.

Bohner, H., H. Earl, and A. Pfeffier. 2012. Evaluating early planting and long season varieties of soybeans. Crop Advances: Field crop reports.

Bohner, H. 2013. Personal communication.

Braunack, M. and A. Dexter. 1989. Soil aggregation in the seedbed: A review. I. Properties of aggregates and beds of aggregates. Soil Tillage Res. 14:281-198.

Bristow, K. 1988. The role of mulch and its architecture in modifying soil temperature. Aust. J. Soil Res. 26:269-80.

Bussiere, F. and P. Cellier. 1994. Modification of the soil temperature and water content regimes by a crop residue mulch: experiment and modelling. Agric. Forest. Meteor., 68:1-28.

Byker, H. N. Soltani, D. Robinson, F. Tardif, M. Lawton, P. Sikkema. 2013. Control of glyphosate-resistant Canada fleabane [*Conyza Canadensis* (L.) Cronq.] with preplant herbicide tankmixes in soybean [*Glycine max.* (L.). Merr.]. Can. J. Plnt. Sci. 93(4):659-667.

Carpenter, A. and J. Board. 1997. Branch yield components controlling soybean yield stability across plant populations. Crop Sci. 37:885-891.

Cassel, D., C. Raczkowski, H.Denton. 1995. Tillage effects on corn production and soil physical conditions. Soil Sci. Soc. Am. 59:1436-1443.

Cassman, K., A. Dobermann, and D. Walters. 2002. Agroecosystems, nitrogen-use efficiency and nitrogen management. Agronomy and Horticulture – Faculty Publications., 31:132-140.

Chantigny, M., D. Angers, D. PreAvost, R. Simard, and F. Chalifour. 1999. Dynamics of soluble organic C and C mineralization in cultivated soils with varying N fertilization. Soil Biol. and Biochem. 31:543-550.

Conley, S., S. Rowntree, J. Suhre, N. Weidenbenner, E. Wilson, V. Davis, S. Naeve, S. Casteel, B. Diers, P. Esker, and J. Specht. 2012. Genetic Gain x Management Interactions in Soybean: I. Planting Date. ASA, CSSA and SSSA international annual general meeting. Cincinnati, OH.

Conservation Technology Information Center. 1997. Conservation tillage: a checklist for US farmers, West Lafayette, IN.

Cooper, R. 2003. A delayed flower barrier to high yielding soybeans. Field Crops Res. 82:27-35.

Cox, W., J. Cherney. 2011. Growth and yield responses of soybean to row spacing and seeding rate. Agron. J. 103:123-128.

DeBruin, J., and P. Pedersen. 2008. Soybean seed yield response to planting date and seeding rate in the upper Midwest. Agron. J. 100:696-703.

Deen, B. Unpublished. Elora long term tillage trial data.

DeFelice, M., P. Carter, S. Mitchell. 2006. Influence of tillage on corn and soybean yield in the United States and Canada. Crop Management.

Devlin, D.., D. Fjell, J. Shroyer, W. Gordon, B. Marsh, L. Maddux, V. Martin, and S. Duncan. 1995. Row spacing and seeding rate for soybean in low and high yielding environments. J. Prod. Agric. 8:215–222.

Di Ciocco, C., E. Penon, C. Coviella, S. Lopez, M. Diaz-Zorita, F. Momo, and R. Alvarez. 2011. Nitrogen fixation by soybean in the Pampas: relationship between yield and soil nitrogen balance. Agrochimica, 55:305-313.

Dick, W., E. McCoy, W. Edwards, R. Lal. 1991. Continuous application of no-tillage to Ohio soils. Agron. J. 83:65-73.

Dohleman, F., S. Long. 2009. More productive than maize in the mid-west: How does miscanthus do it? Plant Physiol. 150:2104-2115.

Doran, J., W. Wilhelm, and J. Power. 1984. Crop residue removal and soil productivity with no-till corn, sorghum, and soybean. Soil Sci. Soc. Am. 48:640-645.

Duke, S, L. Schrader, C. Henson, J. Servaites, R. Vogelzang, J. Pendleton. 1979. Low root temperature effects on soybean nitrogen metabolism and photosynthesis. Plant Physiol. 63:956-962.

Economics and Business group. 2013. Ontario farm input monitoring project, Oct 2. Ridgetown campus. http://www.fpccq.qc.ca/Files/R%C3%A9sultats%20Universit%C3%A9Guelph%20Octobre2013.pdf

Egli, D. 1993. Relationship of uniformity of soybean seedling emergence to yield. J. Seed Technol. 17:22–28.

Egli, D., and J. Leggett. 1973. Dry matter accumulation patterns in determinate and indeterminate soybeans. Crop Sci. 13:220-222.

Egli, D., J. Leggett, and J. Wood. 1978. Influence of soybean seed size and position on the rate and duration of filling. Agron. J. 70:127-130.

Elmore, R. 1990. Soybean cultivar response to tillage systems and planting date. Agron. J. 82:62-73.

Elmore, R. 1991. Soybean cultivar response to planting rate and tillage. Agron. J. 83:829-832.

Environment Canada. 2013. http://climate.weather.gc.ca/climate_normals/stnselect_e.html?provBut=Go&province=ONT&lang=e&page=51 accessed July 2, 2013.

FAOSTAT: 2012a Production, crops, soybean data 2010. http://faostat.fao.org/site/567/DesktopDefault.aspx?PageID=567#ancor accessed June 12, 2012.

FAOSTAT: 2012b Production, about, food and agriculture commodities production, soybean 2010. http://faostat.fao.org/site/339/default.aspx accessed June 11, 2012.

Fehr, W., C. Caviness, D. Burmood, and J. Pennington. 1971. Stage of development descriptions for soybeans, *Glycine max* (L.) Merrill. Crop Sci. 11:929-931.

Flores, S., D. Saxena, G. Stotzky. 2005. Transgenic Bt plants decompose less in soil than non-Bt plants. Soil Biol Biochem 37:1073 – 1082

Follings, J., N. Soltani, D. Robinson, F. Tardif, M. Lawton, P. Sikkema. 2013. Control of glyphosate resistant giant ragweed in soybean with preplant herbicides. Agricultural Sciences, 4:195-205.

Fortin, M. 1993. Soil temperature, soil water, and no-till corn development following in row residue removal. Agron. J. 85:571-576.

Gantzer, C., and G. Blake. 1978. Physical characteristics of Le Sueur loam soil following no-till and conventional tillage. Agron. J. 70:853-857.

Green, C., A. Blackmere, and R. Horton. 1995. Nitrogen effects on conservation of carbon during corn residue decomposition in soil. Soil Sci. Soc. Am. J. 59:453-459.

Griffith, D, J. Mannering, and W. Moldenhauer. 1977. Conservation tillage in the Eastern Corn Belt. J. Soil Water Conserv., 32:20-28.

Grisso, B., D, Holshouser, J. Hutcheson, B. Pitman. 2001. Drills vs. planters for no-till double-crop soybean: Agronomics, Economics, and Equipment Setup. http://bsesrv214.bse.vt.edu/Grisso/Papers/SoybeanFieldDay2001Report.pdf Accessed June 29, 2013.

Hallmark, W., and S. Barber. 1981. Root growth and morphology, nutrient uptake, and nutrient status of soybeans as affected by soil K and bulk density. Agron. J. 73:779-782.

Hammon, B., D. Egli, and G. Koning. 2002. Seed vigor, soilborne pathogens, preemergent growth and soybean seedling emergence. Crop Sci. 42:452-457.

Hardy, R., R. Burns, R. Hebert, R. Holsten, and E. Jackson. 1971. Biological nitrogen fixation: A key to world protein. p. 561–590. In T.A. Iie and E.G. Mulder (ed.) Biological nitrogen fixation in natural and agricultural habitats. Plant Soil Spec. Martinus Nijhoff, The Hague, the Netherlands.

Hatfield, J. and D. Egli. 1974. Effect of temperature on the rate of soybean hypocotyl elongation and field emergence. Crop Sci. 14:423-426.

He, P., J. Jin, W. Zhou. 2001. Effect of N application on accumulation and translocation of carbon and nitrogen compounds in two maize cultivars with different senescent appearance. J. Plant Nutr. 24: 671-681

Heal O. W., J. M. Anderson, and M. J. Swift. 1997. Plant Litter Quality and Decomposition: An Historical Overview. Cadisch, G., and K. E. Giller. Driven by nature plant litter quality and decomposition. Cab International. Wallingford, UK.

Herbek, J., L. Murdock and R. Blevins. 1986. Tillage system and date of planting effects on yield of corn on soils with restricted drainage. Agron. J. 78:824-826.

Hobbs, P. and R. Obendorf. 1972. Interaction of initial seed moisture and imbibitional temperature on germination and productivity of soybean. Crop Sci. 12:664-667.

Hoogenboom, G., M. Huck, C. Peterson. 1987. Root growth rate of soybean as affected by drought stress. Agron. J. 79:607-614.

Hooker, D. 2000. Corn and soybean performance as affected by seedbed characteristics in alternative tillage systems on fine-textured soils: a multi-variable approach. Ph.D. thesis Univ. of Guelph. Guelph, ON.

Hopper, N., J. Overholt and J. Martin. 1979. Effect of cultivar, temperature and seed size on the germination and emergence of soya beans (*Glycine max* (L.) Merr.). Ann. Bot. 44:301-308.

Horton, R., K. Bristow, G. Kluitenberg and T. Sauer. 1996. Crop residue effects on surface radiation and energy balance – review. Theor. Appl. Climatol. 54:27-37.

Hume, D. and D. Blair. 1992. Effect of numbers of *Bradyrhizobium japonicum* applied in commercial inoculants on soybean seed yield in Ontario. Can. J. Microbiol. 38:588-593.

Janovick, K., W. Deen, and T. Vyn. 2006. Soybean response to zone tillage, twin-row planting, and row spacing. Agron. J. 98:800-807.

Johnson, R. 1994. Influence of no-till on soybean cultural practices. J. Prod. Ag. 7:43-49.

Johnson, M.D., and B. Lowery. 1985. Effect of three conservation tillage practices on soil temperature and thermal properties. Soil Sci. Soc. Am. J. 49:1547-1552.

Johnson, J., R. Allmaras and D. Reicosky. 2006. Estimating source carbon from crop residues, roots and rhizodeposits using the national grain-yield database. Agron. J. 98:622-636.

Jones, D., and E. Gamble. 1993. Emergence and yield of soybean as influenced by seedlot vigour, seed moisture, and soil temperature. Plant Var. and Seeds 6:39-46.

Jung, H., and C. Sheaffer. 2004. Influence of Bt transgenes on cell wall lignification and digestibility of maize stover for silage. Crop Sci. 44:1781–1789.

Karayel, D. 2009. Performance of a modified precision vacuum seeder for no-till sowing of maize and soybean. Soil and Tillage Research. 104:121-125.

Karayel, D. and A. Oxmerzi. 2007. Comparison of vertical and lateral seed distribution of furrow openers using a new criterion. Soil and Tillage Research, 95:69-75.

Kiszonas, A. 2010. Tillage effects on soybean growth, development and yield. M.Sc. thesis. Iowa State Univ., Ames, IA.

Kladivko, E., D, Griffith and J. Mannering. 1986. Conservation tillage effects on soil properties and yield of corn and soya beans in Indiana. Soil and Tillage Research, 8:277-287.

Klocke, N., R. Currie and R. Aiken. 2009. Soil water evaporation and crop resides. T. Asabe 52:03-10.

Kulkarni, nd. http://www.uaex.edu/Other_Areas/publications/PDF/FSA-1015.pdf

Lamb, J. A., Rehm, G. W., Severson, R. K., and Cymbaluk, T. E. 1990. Impact of inoculation and use of fertilizer nitrogen on soybean production where growing seasons are short. J. Prod. Agric. 3:241-245.

Leask, W. and T. Daynard. 1973. Dry matter yield, in vitro digestibility, percent protein, and moisture of corn stover following grain maturity. Can. J. Plant Sci. 53:515-522.

Lehman, M., S. Osborne, D. Prischmann-Voldseth, and K. Rosentrater. 2010. Insect-damaged corn stalks decompose at rates similar to Bt-protected, non-damaged corn stalks. Plant Soil, 333:481-490.

Lindemann, W. and G. Ham. 1979. Soybean plant growth, nodulation, and nitrogen fixation as affected by root temperature. Soil Sci. Soc. Am. J. 43:1134-1137.

Lindemann, W., G. Randall, and G. Ham. 1982. Tillage effects on soybean nodulation, $N_2(C_2H_4)$ fixation, and seed yield. Agron. J. 74:1067-1070.

Liu, W. , M. Tollenaar, G. Stewart and W. Deen. 2004. Impact of Planter Type, Planting Speed and Tillage on Stand Uniformity and Yield of Corn. Agron. J. 96:1668-1672.

Lueschen, W., J. Ford, S. Evans, B. Kanne, T. Hoverstad, G. Randall, J. Orf and D. Hicks. 1992. Tillage, row spacing and planting date effects on soybean yield following corn or wheat. J. of Prodn. Agriculture, 5(2):254-260.

Martin, S., L. Darrah and B. Hibbard. 2004. Divergent selection for rind penetrometers resistance and its effects on European corn borer damage and stalk traits in corn. Crop Sci. 44:711-717.

Meese, B., P. Carter, E. Oplinger, J. Pendleton. 1991. Corn/Soybean rotation effect as influenced by tillage, Nitrogen and hybrid/cultivar. J. Prodn. Agriculture, 4(1):74-80.

Mehmet, O. 2008. Nitrogen rate and plant population effects on yield and yield components in soybean. African J. of Biotech. 7:4464-4470.

Mendes, I., M, Hungria and M. Vargas. 2003. Soybean response to starter nitrogen and *Bradyrhizobium* inoculation on a cerrado oxisol under no-tillage and conventional tillage systems. Revista Brasileira de Ciencia do Solo, 27:81-87.

Mielke, L., J. Doran, and K. Richards. 1986. Physical environment near the surface of plowed and no-tilled soils. Soil and Tillage Research, 7:355-366.

Mitchell, J., P. Singh, W. Wallender, D. Munk, J. Wroble, W. Horwath, P. Hogan, R. Roy and B. Hanson. 2012. No-tillage and high residue practices reduce soil water evaporation. California Ag. 66:55-61.

Moore, S. 1991. Uniformity of plant spacing effect on soybean population parameters. Crop Sci. 31:1049-1051.

Mungai, N., P. Motavalli, K. Nelson and R. Kremer. 2005. Differences in yields, residue composition and N mineralization dynamics of Bt and non-Bt maize. Nutr. Cycling Agroecosyst. 73:101-109.

Munkvold, G., C. Martinson, J, Shriver and P. Dixon. 2001. Probabilities for profitable fungicide use against gray leaf spot in hybrid maize. Phytopathology, 91:477-484.

National Soybean Research Laboratory, 2012. http://www.nsrl.uiuc.edu/ Accessed November 12, 2012.

Neave, M., and s. Rayburg. 2007. A field investigation into the effects of progressive rainfall-induced soil seal and crust development on runoff and erosion rates: The impact of surface cover. Geomorphology 87:278-290.

Nicolardot, B., S. Recous, B. Mary. 2001. Simulation of C and N mineralisation during crop residue decomposition: A simple dynamic model based on the C:N ratio of the residues. Plant and Soil 228:83-103.

Nyvall, R. 1999. Field crop diseases. Iowa State Univ. Press, Ames.

OMAF statistics. 2013. http://www.omafra.gov.on.ca/english/stats/crops/index.html Accessed August 15, 2013.

OMAFRA. 2009. Agronomy Guide for field crops, Publication 811. Chapter 2. Soybeans. Table 2-16. Phosphate and potash recommendations for soybeans based on OMAFRA-accredited soil tests.

Omonode, R., D. Smith, A. Gal, and T. Vyn. 2010. Soil nitrous oxide emissions in corn following three decades of tillage and rotation treatments. Soil Sci. Soc. Am. J. 75:152-163.

Oplinger, E.S., and M.J. Albaugh. 1996. Soybean plant density for optimum productivity. Field Crops 27.424. Agronomy Advice. Dep. of Agron., Univ. of Wisconsin, Madison.

Oplinger, E., and B. Philbrook. 1992. Soybean planting date, row width, and seeding rate response in three tillage systems. J. Prod. Agric. 5:94-99.

Osborne, S. and W. Riedell. 2006. Starter nitrogen fertilizer impact on soybean yield and quality in the Northern great plains. Agron. J. 98:1569-1574.

Osborne, S. and W. Riedell. 2011. Impact of low rates of nitrogen applied at planting on soybean nitrogen fixation. J. Plant Nutr. 34:436-448.

Parker, D. 1962. Decomposition in the field of buried and surface-applied cornstalk residue. Soil Science society proceedings 1962:559-562.

Paul, P., L. Madden, C. Bradley, A. Robertson, G.Munkvold, G. Shaner, K. Wise, D. Malvick, T. Allen, A. Grybauskas, P. Vincelli and P. Esker. Meta-analysis of yield response of hybrid field crn to foliar fungicides in the U.S. corn belt. Phytopathology, 101:1122-1132.

Pedersen, P. and J. Lauer. 2003a. Corn and soybean response to rotation sequence, row spacing and tillage system. Agron. J. 95:965-971.

Pedersen, P. and J. Lauer. 2003b. Soybean agronomic response to management systems in the upper Midwest. Agron. J. 95:1146-1151.

Pedersen, P., and J. Lauer. 2004a. Response of soybean yield components to management system and planting date. Agron. J. 96:1372-1381.

Pedersen, P., and J. Lauer. 2004b. Soybean growth and development in various management systems and planting dates. Crop Sci. 44:508-515.

Perez-Bidegain, M., R. Cruse and A. Ciha. 2007. Tillage system by planting date interaction effects on corn and soybean yield. Agron. J. 99:630-636.

Power, J., J. Doran, W. Wilhelm. 1986. Uptake of nitrogen from soil, fertilizer, and crop residues by no-till corn and soybean. Soil Sci. Soc. Am. J. 50:137-142.

Roland, C. 1992. Crop sequence and tillage system effects on soybean performance and soil physical properties. M.Sc. thesis, Univ. Of Guelph, Guelph, ON.

Rossi, F., M. Moschini, L. Fiorentini, F. Masoero, and G. Piva. 2003. Analytical composition and rumen degradability of isogenic and transgenic corn varieties. J. Sci. Food Agric. 83:1337–1341.

Rufty, T., D. Raper, and S. Huber. 1984. Alterations in internal partitioning of carbon in soybean plants in response to nitrogen stress. Can. J. Bot. 62:501-508.

Salvagiotti, F., K.G. Cassman, J.E. Specht, D.T. Walters, A. Weiss, and A. Dobermann. 2008. Nitrogen uptake, fixation and response to fertilizer N in soybeans: A review. Field Crops Res. 108:1–13.

Salvagiotti, F., J. Specht, K. Cassman, D. Walters, A. Weiss, and A. Dobermann. 2009. Growth and nitrogen fixation in high-yielding soybean: impact of nitrogen fertilization. Agron. J. 101:958-970.

Satchell, J. E. 1974. Litter – Interface of Animate/Inanimate Matter. Dickinson, C. H. and G. J. F. Pugh. Biology of Plant Litter Decomposition Volume 1. Academic Press. London and New York.

Saxena, D., and G. Stotzky. 2001. Bt corn has a higher lignin content than non-Bt corn. Am. J. Bot. 8:1704-1706.

Scharf, P., and W. Wiebold. 2003. Soybean yield responds minimally to nitrogen applications in Missouri. Crop Management. Available at www.plantmanagementnetwork.org/cm/.

Schipanski, M., L. Drinkwater, and M. Russelle. 2010. Understanding the variability in soybean nitrogen fixation across agroecosystems. Plant Soil, 329:379-397.

Seta, A., R. Blevins, W. Frye and B. Barfield. 1993. Reducing soil erosion and agricultural chemical losses with conservation tillage. J. Environ. Qual. 22:661-665.

Sewalt, V., W. Ni, H. Jung, and R. Dixon. 1997. Lignin impact on fiber degradation: increased enzymatic digestibility of genetically engineered tobacco. J. of Agric. Food Chem. 45:1977-1983.

Siemens, M., D. Wilkins, and R. Correa. Development and evaluation of a residue management wheel for hoe-type no-till drills. Transactions of the ASAE, 47:397-404.

Sij, J., F. Turner, and J. Craigmiles. 1979. “Starter nitrogen” fertilization in soybean culture. Commun. Soil Sci. Plant Anal. 10:1451-1457.

Sindelar, A., J. Coulter, J. Lamb, and J. Vetsch. 2013. Agronomic responses of continuous corn to stover, tillage, and nitrogen management. Agron. J. 105(6):1498-1506.

Staggenbord S., R. Taylor, and B. Wood. 2004. Soybean row spacing study. Kansas State University. http://www.ksre.ksu.edu/agronomy/soybean/Production/Spacing/Spacing.htm

Starling, M., W. Wood, D. Weaver. 1998. Starter nitrogen and growth habit effects on late-planted soybean. Agron. J. 90:658-662.

Staton, M. 2013. Soybean planting depth matters. Michigan State University. http://msue.anr.msu.edu/news/soybean_planting_depth_matters

Stemmer, M., M. Von Lutzow, E. Kandeler, F. Pichlmayer, and M. Gerzabek. 1999. The effect of maize straw placement on mineralization of C and N in soil particle size fractions. Europ. J. Soil Sci. 50:73-85.

Stone, L., D. Whitney, C. Anderson. 1985. Soybean yield response to residual NO3-N and applied N. Plant Soil, 84:259-265.

Tanner, C. and Shen, Y. 1990. Solar-radiation transmittance of flail-chopped corn residue layers. Soil Sci. Soc. Amer. J. 54:650-652.

Terman, G.L. 1977. Yields and nutrient accumulation by determinate soybeans, as affected by applied nutrients. Agron. J. 69:234–238.

Thibodeau, P., E. Jaworski. 1975. Patterns of nitrogen utilization in the soybean. Planta Berl. 127:133-147.

Toliver, D., J. Larson, R. Roberts, B. English, D. De La Torre Ugarte and T. West. 2012. Effects of No-till on yields as influenced by crop and environmental factor. Agron. J. 104:530-541.

Tollenaar, T., E. Lee. 2006. Dissection of physiological processes underlying grain yield in maize by examining genetic improvement and heterosis. Maydica, 51:399-408.

Tovar-Gomez, M., J. Emile, B. Michalet-Doreau, A. Barriere. 1997. In situ degradation kinetics of maize hybrid stalks. Animal Feed Science and Technology, 68:77–88.

Turnman, P., W. Wiebold, J. Wrather, and P. Tracey. 1995. Effect of planting date and tillage system on soybean root growth. J. Plant Ntr. 18:2579-2594.

Tyagi, S., and R. Tripathi. 1983. Effect of temperature on soybean germination. Plant and soil 74:273-280.

USDA. 2013. Carbon to Nitrogen ratios in cropping systems. USDA Natural Resources Conservation Service. http://soils.usda.gov/sqi/management/files/C_N_ratios_cropping_systems.pdf Accessed Oct 16, 2013

Uson, A., R. Poch. 2000. Effects of tillage and management practices on soil crust morphology under a Mediterranean environment. Soil and Tillage Research 54:191-196.

Valentinuz, O., and M. Tollenaar. 2004. Vertical profile of leaf senescence during the grain-filling period in older and newer maize hybrids. Crop Sci. 44:827-834.

VandenBygaart, A., R. Protz, and A. Tomlin. Changes in pore structure in a no-till chronosequence of silt loam soils, southern Ontario. Can. J. of Soil Sci. 79:149-160.

Van Kessel, C., C. Hartley. 2000. Agricultural management of grain legumes: hasit led to an increase in nitrogen fixation? Field Crops Research, 65:165-181.

Vasilas, B.L., R.W. Esgar, W.M. Walker, R.H. Beck, and M.J. Mainz. 1988. Soybean response to potassium fertility under four tillage systems. Agron. J. 80:5–8.

Vega C., V. Sadras, F. Andrade, and S. Uhart. 2000. Reproductive allometry in soybean, maize and sunflower. Ann. Bot. (London) 85:461–468.

Villamil, M., V. Davis, and E. Nafziger. 2012. Estimating factor contributions to soybean yield from farm field data. Agron. J. 104:881-887.

Vyn, T. and D., Hooker. 2002. Assessment of multiple- and single-factor stress impacts on corn. Field Crops Res. 75:123-137.

Vyn, T., J. Janovicek, and M. Carter. 1994. Tillage requirements for annual crop production in eastern Canada. *In* M.R. Carter, ed. Conservation tillage in agroecosystems. CRC Press, Boca Raton, FL.

Vyn, T., G. Opoku, and C. Swanton. 1998. Residue management and minimum tillage systems for soybean following wheat. Agron. J. 90:131-138.

Vyn, T., and D. Hooker. 2002. Assessment of multiple- and single-factor stress impacts on corn. Field Crops Res. 75:123-137.

Wagger, M., and Denton. 1992. Crop and tillage rotations: grain yield, residue cover, and soil water. Soil Sci. Soc. Am. 56:1233-1237.

Wagner-Riddle, T. Gillespie, C. Swanton. 1994. Rye cover crop management impact on soil water content, soil temperature and soybean growth. Can. J. Plant Sci. 74:485-495.

Webber, C., M. Gebhardt, and H. Kerr. 1987. Effect of tillage on soybean growth and seed production. Agron. J. 79:952-956.

Weber, D., and V. Miller. 1972. Efect of soil temperature on *Rhizobium japonicum* serogroup distribution in soybean nodules. Agron. J. 64:796-798.
Welz, H. and H. Geiger. 2000. Genes for resistance to northern corn leaf blight in diverse maize populations. Plant Breeding, 119:1-14.
West, T., D. Griffith, G. Steinhardt, E. Kladivko, and S. Parsons. 1996. Effect of tillage and rotation on agronomic performance of corn and soybean: Twenty-year study on a dark silty clay loam soil. J. Prod. Agric. 9:241-248.
Wildung, R., T. Garland, and R. Buschbom. 1975. The interdependent effects of soil temperature and water content on soil respiration rate and plant root decomposition in arid grassland soils. Soil Biol. Biochem. 7:373-378.
Wilhelm, W., J. Doran, and J. Power. 1986. Corn and soybean yield response to crop residue management under no-tillage production systems. Agron. J. 78:184-189.
Yanni, S., J. Whalen, and B. Ma. 2011. Field-grown Bt and non-Bt corn: yield, chemical composition, and decomposability. Agron. J. 103:486-493.
Yin, X. and M. Al-Kaisi. 2004. Periodic response of soybean yields and economic returns to long-term no-tillage. Agron. J. 96:723-733.
Yiridoe, E., T. Vyn, A. Weersink, D. Hooker, and C. Swanton. 2000. Farm-level profitability analysis of alternative tillage systems on clay soils. Can. J. Plant Sci. 80:65-73.
Yusuf, R., J. Siemens, and D. Bullock. 1999. Growth analysis of soybean under no-tillage and conventional tillage systems. Agron. J. 91:928-933.
Zhang, F., and D. Smith. 1994. Effects of low root zone temperatures on the early stages of symbiosis establishment between soybean [*Glycine max* (L.) Merr.] and *Bradyrhizobium japonicum*. J. of Experimental Bot. 45:1467-1473.
Zwahlen, C., A. Hillbeck, anc W. Nentwig. 2007. Field decomposition of transgenic Bt maize residue and the impact on non-target soil invertebrates. Plant Soil 300:245-257.

Appendix A. Site descriptions

The Lucan11 site is considered a 3000 crop heat unit (Weather Innovations Incorporated, 2013) growing area with a yearly average rainfall of 988 mm (Environment Canada, 2013). The soil is described as a moderately to imperfectly drained, Huron silty clay loam with systematic tile drainage every 7.6 m in a direction perpendicular to the plots. Soil test results prior to soybean planting reveal an organic matter content of 3.3%, a pH of 7.4 and Phosphorus and Potassium concentrations of 28 ppm according to the Sodium bicarbonate (Olson) test and 111 ppm according to the Ammonium acetate test respectively. The farmer practices a diverse crop rotation of corn-soybeans-wheat underseeded to red clover. Soybeans and wheat were sown in NT conditions in 2008 and 2009 respectively. Prior to growing corn, the soil was disced in the fall and cultivated in the spring. Corn grown in 2010 was Dekalb (Monsanto, Guelph, ON) hybrid 50-44 (3050 CHU, *Bt* hybrid) at 79,000 seeds ha^{-1} and was harvested in late October, yielding approximately 12.5 t ha^{-1} (200 bu ac^{-1}). No foliar fungicide was applied to the corn.

The Moorefield farms are rated as a 2800 crop heat unit zone, receiving 991 mm of rainfall per annum (Environment Canada, 2013). Both fields are described as either a Perth loam or a Gray-Brown Podzolic soil with 3.3% organic matter. They are imperfectly drained with systematic tile drainage every 18.3 m. In Moore11, soil tests were taken after soybean harvest which revealed a pH of 7.2 along with Phosphorus and Potassium concentrations of 22 ppm and 78 ppm respectively. Corn was planted into soybean stubble in 2010 at the Moore11 site. Pioneer hybrid 38D85 (2625 CHU, *Bt* hybrid) was sown at 79,000 seeds ha^{-1}, and harvested in mid-October yielding 10.3 t ha^{-1} (165 bu ac^{-1}). Tillage prior to the corn crop included chisel plow in the fall followed by two passes of the cultivator in the spring. The soybeans grown in the year prior were no-tilled and historical details prior to the 2009 crop year were unavailable.

Soil samples were taken prior to soybean planting in 2012 at the Moore12 site. Fertility concentrations were 32 ppm for Phosphorus and 145 ppm for Potassium, with a pH value of 7.6. The field was planted to corn in 2011, wheat in 2010 and soybeans in 2009. Both the soybeans and wheat were sown in NT conditions, but prior to corn the field was chisel plowed in the fall and cultivated twice in the spring. Pioneer corn hybrid P8906 HR (2650 CHU, *Bt* hybrid) was planted at 79,000 seeds ha^{-1}. A tassel stage fungicide was not applied and the corn was harvested in mid October, which yielded 11.0 Mg ha^{-1} (170 bu ac^{-1}).

Average climatic conditions at the Arthur12 site include a growing season of 2600 CHU and yearly rainfall of 917 mm (Environment Canada, 2013). The soil is a Gray-Brown Podzolic silt loam, with imperfect drainage. The site is systematically tile drained every 12.2 m diagonally across experimental units. Soil tests reveal an organic matter content of 3.8%, a pH of 7.5 and Phosphorus and Potassium concentrations of 10 and 109 ppm respectively. Corn was grown in 2011, wheat in 2010 and soybeans in 2009. Tillage prior to corn consisted of discing in the fall and cultivation in the spring, while tillage was not performed prior to wheat or soybeans. Two varieties of corn were sown in the trial location in 2011, Pioneer hybrid P7443 R (2100 CHU, not a *Bt* hybrid) and Hyland hybrid B256 Bt (~2100 CHU, *Bt* hybrid). The corn was planted in 0.76 m rows at 74,000 seeds ha^{-1} with no mid-season fungicide application. Harvest occurred in early October, with both varieties yielding approximately 9.7 t ha^{-1} (155 bu ac^{-1}).

Appendix B. Weather data

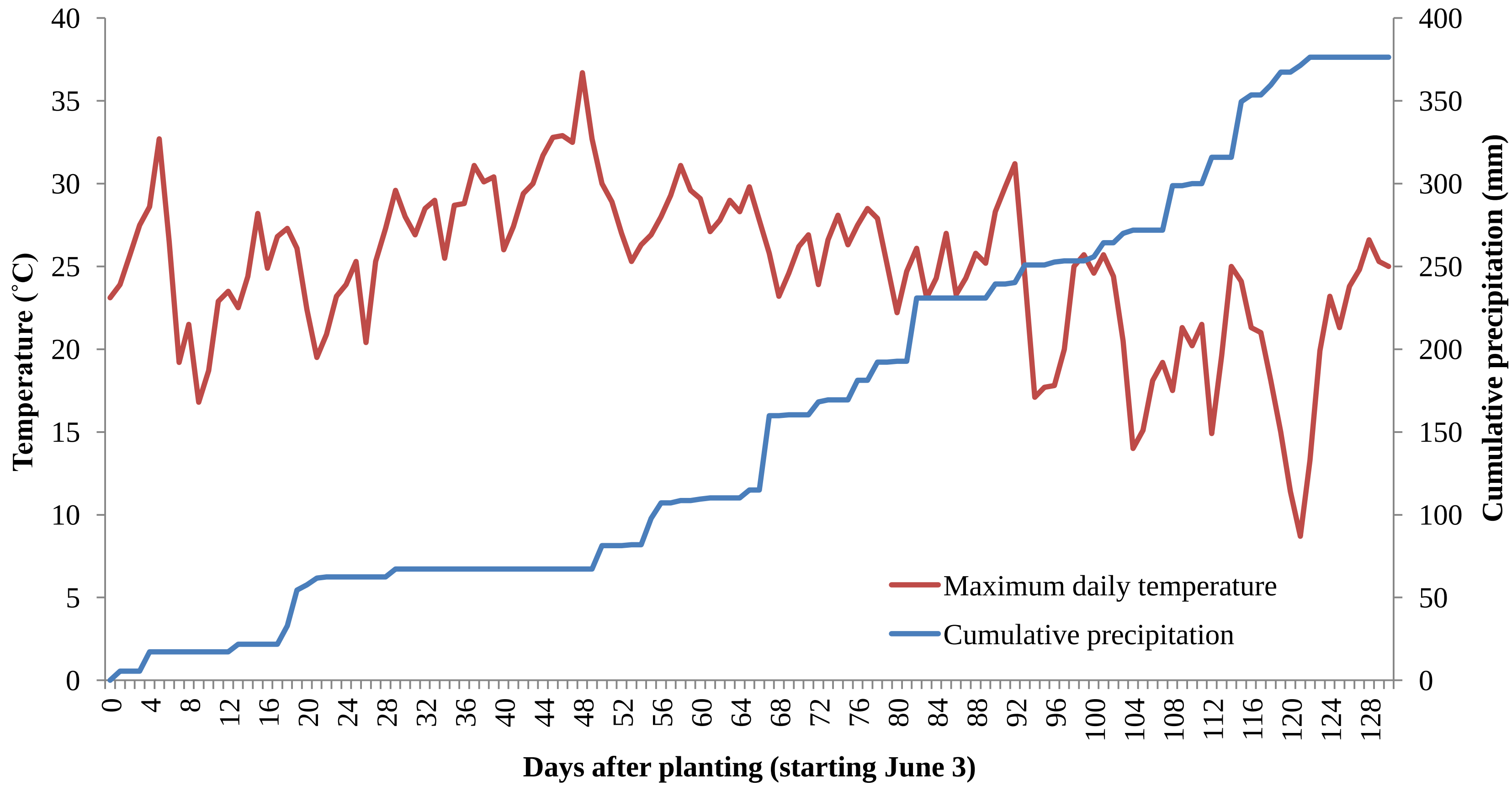

Figure B-1. Maximum daily temperature and accumulated precipitation in London, ON† from June 3, 2011‡ to October 11, 2011§.

† The London weather station is the closest one to Lucan, located approximately 25 km SouthEast of the Lucan location

‡ June 3rd is 0 days after planting at Lucan

§ October 11th is the day of harvest

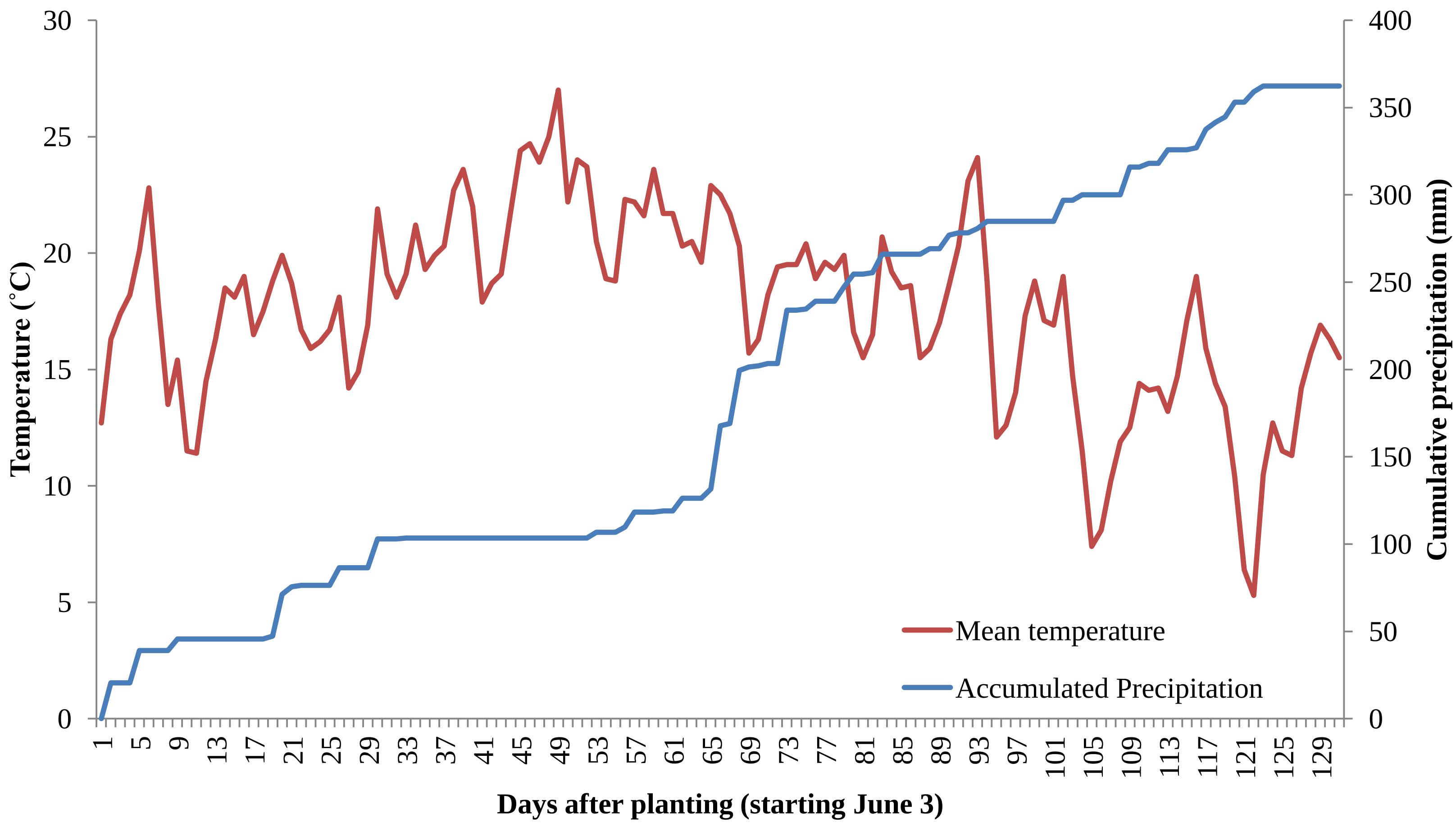

Figure B-2. Maximum daily temperature and accumulated precipitation at Elora, ON† from June 3, 2011‡ to October 10, 2011§.

† The Elora weather station is the closest one to the Moorefield site, located approximately 30 km SouthEast of Moorefield

‡ June 3rd is 0 days after planting at Moorefield in 2011

§ October 10th is the day of harvest

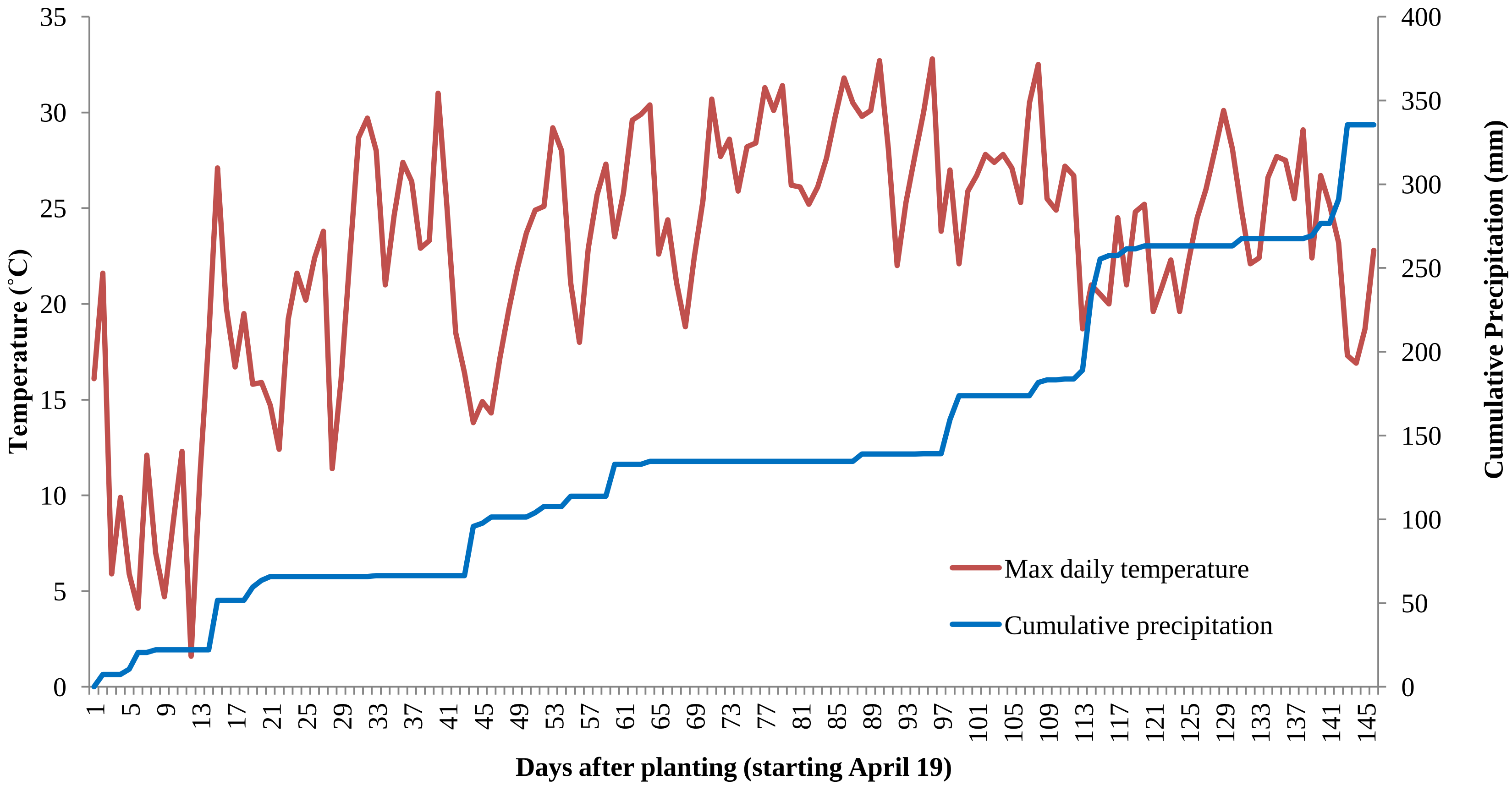

Figure B-3. Maximum daily temperature and accumulated precipitation at Mount Forest, ON† from April 19, 2012‡ to September 10, 2012§.

† The Mount Forest weather station is the closest one to the Arthur site, located approximately 15 km NorthWest of Arthur

‡ April 19th is 0 days after planting at Arthur

§ September 10th is the day of harvest

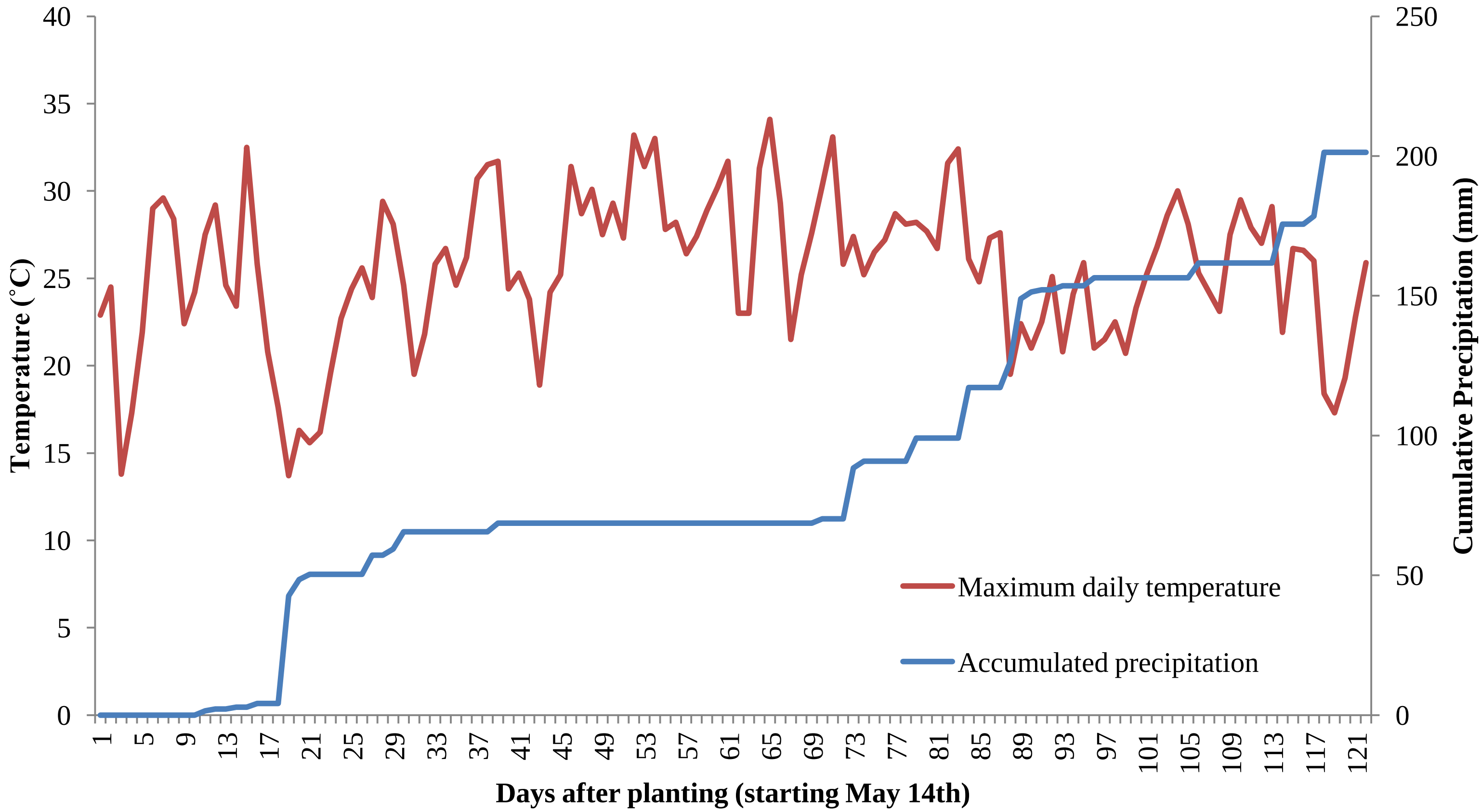

Figure B-4. Maximum daily temperature and accumulated precipitation at Elora, ON† from May 14, 2012‡ to September 12, 2012§.

† Elora weather station is the closest one to the Moorefield site, located approximately 30 km SouthEast of Moorefield

‡ May 14th is 0 days after planting at Moorefield in 2012

§ September 12th is the day of harvest

Appendix C. SAS statements

Example of Planter Type or Nitrogen Model (substitute Nitrogen for Planter type) SAS statements without repeated measures:

```
proc mixed data=nyield covtest cl;
class nitro site block till remove ;
model t_ha= site till remove nitro till*remove till*nitro remove*nitro
till*remove*nitro site*till site*remove site*nitro site*till*remove
site*till*nitro site*remove*nitro site*till*remove*nitro/ outp=npred
residual;
random block(site) till*block(site) remove*block(site) nitro*till*block(site)
till*remove*block(site);
run;
```

Example of Panter Type or Nitrogen Model SAS statements with repeated measures:

```
proc mixed data=nmoist maxiter=2000 covtest cl;
class nitro till remove site stage block;
model pctH2O= till remove nitro site till*remove till*nitro remove*nitro
till*remove*nitro site*till site*remove site*nitro site*till*remove
site*till*nitro site*remove*nitro site*till*remove*nitro stage stage*till
stage*remove stage*nitro stage*site stage*till*remove stage*till*nitro
stage*till*site stage*remove*nitro stage*remove*site stage*nitro*site
stage*till*remove*nitro stage*till*remove*site stage*till*nitro*site
stage*remove*nitro*site stage*till*remove*nitro*site / outp=npred residual;
random block(site) till*block(site) remove*block(site) nitro*till*block(site)
*nitro*block(site) nitro*remove*block(site);
repeated stage / sub=till*remove*nitro*block(site) type=sp(pow) (num);
lsmeans nitro*stage / pdiff;
run;
```

Example of Tillage x Removal Model SAS statements without repeated measures:

```
proc mixed data=y3 covtest cl;
class site block till remove year;
model t_ha= site till remove till*remove site*till site*remove
site*till*remove/ outp=trpred residual;
random  block(site) remove*block(site) till*block(site);
lsmeans site*till*remove / slice=site pdiff ;
run;
```

Example of Tillage x Removal Model SAS statements with repeated measures:

```
proc mixed data=moist2 maxiter=2000  covtest cl;
class till remove site stage block;
model pctH2O= site till remove till*remove site*till site*remove
site*till*remove stage stage*site stage*till stage*remove stage*till*remove
```

```
stage*site*till stage*site*remove stage*site*till*remove / outp=trpred
residual;
random block(site) remove*block(site) till*block(site)
till*remove*block(site);
repeated stage /  sub=till*remove*block(site) type = sp(pow) (num);
lsmeans site till remove stage site*stage till*stage till*remove remove*stage
/ pdiff slice=site;
run;
```

Coding to test for error assumptions:

```
*testing for normality;
proc univariate data=npred normal;
var studentresid;
histogram / normal (color =black w=3) barwidth =5 cfill=gray height=4 font='
arial'; run;

*testing random and independence of residuals;
proc plot data=npred;
plot resid*pred studentresid*(site till remove plant) ; run;

proc sort data=npred;
by studentresid; run;
```