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Impact of Tillage and Rotation on Yield and Economic Performance in Corn-based Cropping Systems

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ABSTRACT

The objective of our research was to identify economically efficient corn [*Zea mays* (L.)] based tillage-rotation combinations using a 20-yr data set from a long-term experiment in Ontario, Canada. Seven rotations in two tillage systems (moldboard and chisel plow) were analyzed. We found multiple benefits associated with diversifying rotations in both tillage systems The integration of soybean [*Glycine max* (L.) Merr.] or soybean and wheat [*Triticum aestivum* (L.)] resulted in 7 to 11% higher corn yields in the chisel tillage system. In the plow tillage system corn yield in rotation with soybean and wheat increased by 5%, when wheat was underseeded with red clover [*Trifolium pratense* (L.)]. These diversified rotations resulted in an increase in yearly net returns of $51 to $64 in the moldboard tillage system and $96 to $108 in the chisel tillage system. The diversification of rotations reduces variance of net return and thus makes the rotations attractive to risk averse producers. Furthermore diversified rotations showed less response to price changes. Diversified rotations evaluated in this study also proved to be less affected by increasing energy costs. Red clover seeded into wheat resulted in 5% higher yields for the following corn crop in the moldboard system. Rotations that included red clover cover lowered production risk but did not have higher net returns than comparable rotations without red clover. However, the potential for red clover to reduce N fertilization requirements for the following corn, was not considered in this study. Yield penalties due to chisel plowing with financial consequences were only observed in continuous corn. In all other rotations the effect of tillage was negligible. An increase in energy costs forces farmers to switch to crops with lower inputs rather than switch to reduced tillage.

LENGTH and complexity of crop rotations has decreased in North America. A possible reason for this trend includes the removal of crops that provide low returns relative to other crop options. Producers often consider short-term profitability in determining crop selection; however it may be more appropriate to consider profitability over the full length of a rotation cycle. The advantages of crop rotation over the complete rotation include higher yields, reduction of crop diseases, spreading the workload for planting and harvesting over a longer time period (OMAF, 2002). For example, the use of legume cover crops in rotations has been declining but such crops can have beneficial effects on yields of subsequent crops in the rotation (Riedell et al., 1998; Singer and Cox, 1998; Vyn et al., 2000) and also represent a significant N fertilizer replacement value. Not only may average crop yields be influenced by rotation, yield variability may also be affected. Assessing the riskiness of alternative rotations requires yield data on complete rotations over time.

Yield of individual crops in a rotation sequence are influenced significantly by tillage system. Crop yields are increased more under reduced tillage systems when in rotation as compared to continuous cropping (Raimbault and Vyn, 1991; Griffith et al., 1988; Wilhelm and Wortmann, 2004). This effect is accentuated when additional stresses are imposed on the crop, such as for corn yield in cool springs (Wilhelm and Wortmann, 2004). Katsvairo and Cox (2000a, 2000b) produced similar conclusions from a 6-yr trial under low and high chemical management schemes for corn–soybean–wheat systems in New York. Thus, assessing the feasibility of crop rotations should consider tillage effects.

In Ontario, the chisel plow is the predominant alternative to moldboard plowing (Vyn et al., 1994). The substitution of the moldboard plow with the chisel plow results in lower machinery costs, reduced labor requirements, and greater protection of the soil (Uri et al., 1999; Weersink et al., 1992). However, possible yield penalties due to reduced tillage have to be offset against the advantages of chisel plowing. The response of crop yields to tillage varies depending on site characteristics and management practices with the likelihood of a yield increase to conservation tillage greatest on well-drained soils (Griffith and Wollenhaupt, 1994).

The selection of rotation and tillage system by a producer depends on the net returns for the whole system and not just individual components in isolation of the other elements. The effect of the crop rotation and tillage system on profitability and variation in profit has been assessed by Zentner et al. (2002a, 2002b) for dryland grain farming in the Canadian Prairies. However they have not been systematically evaluated to the same extent for eastern North America. Katsvairo and Cox (2000a) found the highest net returns for a corn–soybean rotation under low input use and a moldboard plow tillage system, but they did not examine variability of profit. To our knowledge no study has assessed the sensitivity of the optimal rotation and tillage system to changing prices.

The objective of our study was to assess the long-term effects of tillage, rotation, and tillage × rotation interactions on yield, costs, and net revenue for seven corn-based rotations in two different tillage systems. Variability in yields, net returns, and sensitivity of the optimal cropping system to producer risk attitudes were determined using yield data from 20 yr of field observations of seven 4-yr crop rotations. The long-term yield data provides a unique opportunity to assess the feasibility of crop rotations and tillage systems over time and to account for the effects of risk. Given increasing concerns over rising energy costs and the fact that crop rotations and tillage systems vary in terms of energy consumption the effect of energy costs on optimal system was also examined.

MATERIALS AND METHODS

Field Study

Twenty years (1982–2001) of crop yield data for the economic analysis was obtained from the long-term rotation-tillage experiment located at the Elora Research Station near Elora, ON (43°39′ N, 80°25′ W, elevation 376 m). Thirty-year normal (1971–2000) annual precipitation, recorded at the nearest Environment Canada Meteorological station located at Guelph, ON is 920 mm with average monthly totals which range from 75 to 95 mm for the growing season months (April–September) (Meteorological Services Canada, 2006). Average monthly temperatures for January, April, and July are—7.6, 5.9 and 19.7°C, respectively (Meteorological Services Canada, 2006). The corn growing season is rated as receiving 2650 Ontario Crop Heat Units (Brown and

Bootsma, 1993) which is approximately equivalent to 1050 growing degree days (GDD) (base 10°C) or 83 Minnesota Relative Maturity Days.

The soil is a Woolwich silt loam (Typic Hapludalf; FAO taxonomy: Albic Luvisol) with Ap horizon contents of clay at 170 g kg^{-1}, silt at 540 g kg^{-1}, sand at 290 g kg^{-1}, and organic C at 33 g kg^{-1}. The soil is classified as well drained and the experimental site was systematically tile drained.

The experimental design is a randomized block split-plot with four replications. Seven rotation treatments, consisting of six 4-yr rotations and continuous corn (C-C-C-C), were randomly assigned to the main plots. The cropping sequence in the 4-yr rotations was comprised of 2 yr of corn followed by 2 yr of rotation crop(s). The rotation cropping sequences for the 4-yr rotations were: 2 yr of barley (C-C-B-B); 2 yr of barley underseeded with red clover (C-C-B[rc]-B[rc]); 2 yr of soybean (C-C-S-S); soybean followed by soft white winter wheat (C-C-S-W); soybean followed by soft white winter wheat underseeded with red clover (C-C-S-W[rc]) and 2 yr of alfalfa (C-C-A-A). Each of the 4-yr rotations were duplicated with cropping sequences which were 2 yr out of phase so that when a given rotation was planted to first-year corn it’s duplicate was planted to the first year of the rotation crop(s). For example, the C-C-S-S rotation had two sets of plots with cropping sequences for the same 4-yr period of the rotation cycle which were comprised of corn–corn–soybean–soybean and soybean–soybean–corn–corn.

Primary tillage system was the split-plot treatment, consisting of either fall moldboard or fall chisel plowing to a depth of 15 to 20 cm. Before winter wheat establishment in the chisel system, two passes of a tandem disk was substituted for fall chisel plowing. Similar secondary tillage, usually consisting of two passes of a field cultivator and packer within 1 d of crop seeding, occurred in both tillage systems. An overview of the operation sequences in the different cropping systems is given in Table 1.[ID]TBL1[/ID]

Seeding rates for the various crops were 74○000 seeds ha^{-1} for corn, 90 kg ha^{-1} for soybean, 110 kg ha^{-1} for wheat, 100 kg ha^{-1} for barley (*Hordeum vulgare* L.), and 15 kg ha^{-1} for alfalfa. Red clover was either frost seeded into winter wheat in late March or early April or drill-seeded simultaneously with barley at a rate of 13 kg ha^{-1}. Fertilizer inputs for the various crops were applied at rates that equalled, or exceeded, recommended rates (OMAF, 2002). Herbicides were applied to ensure that crop productivity was not adversely affected by weed competition. For rotations with cereals underseeded to red clover an additional fall application of glyphosate was applied in the chisel plow system to minimize the likelihood of volunteer regrowth in the next year’s crop. Although changes in hybrids/varieties over time were necessary to ensure hybrids/varieties represented best available yield potential, changes did not occur mid-cycle.

Production Cost and Revenue Assumptions

The cost structure for the crops in the different tillage systems (Table 2)[ID]TBL2[/ID] is based on the 2005 Field Crop Budgets for the province of Ontario (OMAFRA, 2005a) with the following specific adjustments.

Underseeding red clover into the wheat and barley was assumed to cost \$37 ha^{-1}. A further cost of \$43 ha^{-1} was assessed to rotations in the chisel plow system for fall chemical burn down of red clover. Also, a \$55 ha^{-1} charge for corn rootworm insecticide was assessed whenever corn followed corn.

Unless otherwise stated, the economic analysis for the various crops did not take into account changes in N fertilizer rates associated with rotation N credits. Annual fertilizer N rates were 160 kg N ha^{-1} for corn, 8 kg N ha^{-1} for soybean, 110 kg N ha^{-1} for winter wheat, 60 kg N ha^{-1} for barley, and 5 kg N ha^{-1} for alfalfa. The N applied to soybean and alfalfa was associated with application of 8–32–16 as a starter fertilizer. Corn received 225 kg ha^{-1} of 8–32–16 applied at planting, and winter wheat and barley received 50 kg ha^{-1} of liquid 10–34–0. The remainder of N requirements for corn, wheat, and barley were assumed to be supplied using preplant applications of urea. Crop removal balances for P and K were calculated and the rates of the appropriate P and K fertilizer sources were added to maintain soil fertility. Fertilizer prices were based on a survey of retail prices over a 5-yr period (2001–2005), which were \$403 Mg^{-1} for urea, \$360 Mg^{-1} for 8–32–16, \$459 Mg^{-1} for 10–34–0 (liquid), \$284 Mg^{-1} for muriate of potash (0–0-60), and \$418 Mg^{-1} for triple super phosphate (0–46–0) (McEwan, 2005).

Fuel expenses for the different tillage systems were estimated according to the work rates of the implements and the fuel consumption of the tractor. For a 100 kW tractor the work rate of a chisel plow at 1.3 ha h^{-1} is about twice the work rate of a moldboard plow at 0.7 ha h^{-1} (Molenhuis, 2001). With this work rate and a fuel consumption of 21.6 L h^{-1}, the fuel consumption of the chisel plow is 6 L ha^{-1} lower than the ha^{-1} fuel consumption of the moldboard plow. For our calculations a fuel price of \$0.60 l^{-1} and an additional 15% for lubricants were assumed. According to these calculations fuel cost savings with reduced tillage are \$4.14 ha^{-1}. Including additional savings for depreciation of the machinery, we estimated the cost savings for the reduced tillage in this experiment at \$6 ha^{-1}. This corresponds well with the difference in custom rates for chisel and moldboard plowing in Ontario, which range from \$4.9 to \$7.4 ha^{-1} (OMAFRA, 2005c).

Moisture content of the grains was not affected by tillage or rotation. Thus drying charges were calculated as a function of crop yields as \$16 Mg^{-1} grain for corn, which represents the cost of drying corn from a water content of 235 to 155 g kg^{-1}. Consequently, differences in drying costs between systems only reflect differences in corn yield. A slight drying charge was also assigned to soybean, in accordance with suggested charges outlined in the 2005 Field Crop Budgets (OMAFRA, 2005a), which reflects the difficulty which occasionally occurs with getting soybean harvested at a moisture content which is less than or equal to 130 g kg^{-1}. Further yield dependent costs such as storage, trucking, and marketing fees were calculated according to default values given with the Crop Budgets (OMAFRA, 2005a).

Crop revenues were obtained by multiplying the observed yields for the various rotation and tillage combinations by the 1999 to 2003 average crop prices. The average crop prices for that period were \$130 Mg^{-1} for corn, \$277 Mg^{-1} for soybean, \$127 Mg^{-1} for soft white wheat, \$119 Mg^{-1} for barley and \$85 Mg^{-1} for alfalfa hay (OMAFRA, 2005b). For barley and wheat it was assumed, regardless of the grain yield, that 124 bales ha^{-1} straw were harvested and sold at a price of \$1.5 bale^{-1}.

The estimated costs were subtracted from the calculated revenue to obtain net returns to land and management for an individual crop in a given tillage system. The net returns for each crop were averaged over each 4-yr rotation period to obtain the yearly net revenue associated with each rotation-tillage combination. Over the 20-yr duration of this experiment, average yearly net revenues were calculated independently for five rotation cycles.

Statistical and Sensitivity Analysis

Crop yield and associated net return data were analyzed using an analysis of variance appropriate for a randomized complete block split-plot design with repeated measures over time using the Mixed Procedure of SAS ver. 8.02 (SAS Institute, Cary, NC). Over the 20-yr period from which the economic analysis was conducted, the 4-yr rotations had completed five cycles with rotation cycle (i.e., one through five) considered the repeated measure factor in the statistical analysis model. For continuous corn, the rotation cycle value associated for the 4-yr rotations for a given year was also assigned to continuous corn data. Rotation, tillage, rotation cycle, and their interactions were considered fixed effects. Block, years within cycle, and any interactions associated with these terms were considered random effects. Overall rotation net revenues were analyzed by first averaging the individual crop net revenues by plot within each rotation cycle before conducting analysis of variance. Residuals for all analyses of variance were evaluated for normality based on the Shapiro–Wilk test in the “univariate procedure” of SAS and studentized residuals were calculated to detect outliers. Unless otherwise indicated, the type I error for all statistical tests was $P = 0.05$. Differences in yield and net revenue among rotations and tillage systems, unless otherwise stated, were identified using a protected LSD test at $P = 0.05$.

There is often a trade-off between average net returns and the variability in those returns among different cropping systems. To assess the effects of risk on the choice of management practice, the certainty equivalent for each of the rotation-tillage combinations was calculated. Robison and Barry (1987) approximated the certainty equivalent (CE) by:

$$CE = XXX - o.5\ \lambda\ Var(x)$$

where XXX represents the expected value of the net returns of a management option, Var(x) is the variance of net returns for that system and λ is the value of the Pratt–Arrow absolute risk aversion coefficient, which is a measure of the farmer’s desire to avoid risk. The certainty equivalent is the amount of money for which a risk averse producer is indifferent between taking an option for which the returns are uncertain vs. an option with no uncertainty. For our analysis we considered a risk aversion coefficient, which resulted in positive certainty equivalents for at least one management option. Negative certainty equivalents indicate that with the assumed risk aversion there are no incentives for the farmer to choose the management option. Note that the certainty equivalent value of a given system will increase with increases in mean net returns and decrease with increases in the variability of those returns and increases in the degree to which producers want to avoid risk.

The sensitivity of the optimal rotation and tillage systems to changing prices was also conducted to consider increases in energy prices and decreases in commodity prices. The first scenario analyzed the implications of an increase of energy prices by 50%. It was assumed that such an increase in energy prices would increase fertilizer prices by 25% and the custom rates for trucking, fertilization, and spraying increase to the extent of the share of fuel costs of custom rates, which were estimated at 5%. In the second scenario, a price reduction for all crops of 10% was assumed.

RESULTS AND DISCUSSION

The primary focus of this paper is to discuss the average long-term effects of rotation and tillage on crop yields and associated economics over the 20-yr duration of this study. Interactions between rotation or tillage with rotation cycle did occasionally occur, however, since the intended scope of this paper is to present and discuss only long-term average results the rotation × cycle and tillage × rotation × cycle interactions will not be discussed.

Average weather conditions over the 20-yr period of this study did not differ substantially from expected long-term normals. Average seasonal (10 May–30 September) Ontario Crop Heat Unit accumulation was 2740 CHU (1050 GDD at base 10°C) which was about 100 CHU higher than the long-term rating for this region. Average growing season monthly precipitation totals ranged from 70 to 95 mm, which were within 10 mm of the long-term monthly total precipitation normals.

Crop Yield

Corn, soybean, wheat, and alfalfa yields were not affected by the presence of obvious weed competition or occurrence of disease. However, barley yields did tend to decline over the duration of this study due, in part, to increasing frequency and severity in later years of net blotch (Pyrenophera teres).

Yearly variability in yield differed among crops with the highest variability associated with alfalfa and lowest with wheat. The linear trend corrected coefficient of variation over all tillage and rotation treatments were 22% for alfalfa, 18% for corn and barley, 16% for soybean, and 13% for wheat. Yield standard deviations for each crop were not affected by rotation or tillage system (data not shown).

First-year corn was affected by rotation, with the magnitude of rotation response affected by tillage (rotation by tillage interaction $P = 0.0058$). For both tillage systems, yields were lowest when corn was planted continuously and highest following a alfalfa or red clover (Table 3).[ID]TBL3[/ID] First-year corn yields did not differ among the three rotations that contained a forage legume (i.e., alfalfa and underseeded red clover). Corn yields for the three rotations that contained a forage legume averaged 0.35 Mg ha^{-1} (4.3%) over continuous corn in the moldboard system and 0.94 Mg ha^{-1} (12.8%) in the chisel system.

In the chisel plow system, corn yields following soybean were 0.55 Mg ha^{-1} (7.4%) over continuous corn and 0.40 Mg ha^{-1} (5.1%) less than the average yield for the three rotations containing a forage legume. In the moldboard system, yield differences between soybean and the other rotations were smaller and not significant.

Larger yield differences between continuous and first-year corn in the chisel plow system can be partially attributed to the relatively large yield reduction associated with chisel plowing where corn was planted following corn (Table 3). Continuous corn yields in the chisel system were 0.65 Mg ha^{-1} (8.2%) less than those obtained in the moldboard system. For the other rotations, first-year yield reductions associated with the chisel system were substantially less with the largest

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reductions occurring following soybean (0.28 Mg ha^{-1} [3.4%]) and wheat underseeded with red clover (0.32 Mg ha^{-1} [3.8%]).

Corn yields were also affected by rotation and tillage when the various rotations were planted to second-year corn (Table 3). The rotation by tillage interaction was not significant; therefore discussion of second-year corn yield responses will be restricted to average rotation and tillage effects. Second-year corn yields for rotations that did not include a forage legume were generally lower compared to where planted continuously (Table 3). The largest yield reduction was associated with the soybean–soybean–corn–corn rotation, where yields averaged 0.36 Mg ha^{-1} (4.1%) less than continuous corn. Similar yield differences for second-year corn following soybean and continuous corn were reported in Wisconsin (Porter et al., 1997).

The highest second-year corn yields were in the alfalfa-based rotation (Table 3). However, second-year corn yields were not similar among rotations which contained a forage legume; with yields in rotations which contained underseeded red clover that were 0.29 to 0.39 Mg ha^{-1} (3.2–4.3%) less than those obtained in the alfalfa-based rotation.

Tillage effects for second-year corn, although statistically significant, were relatively small; with yields in the chisel system averaging 0.16 Mg ha^{-1} (1.8%) less than in the moldboard system (Table 3). In general, corn yield reductions associated with the chisel system for years when rotations were planted to second-year corn were about 25% of the reductions observed for continuous corn for years when rotations were planted to first-year corn.

Continuous corn yields for years when rotations were planted to second-year corn averaged 0.95 Mg ha^{-1} (11.9%) higher in the moldboard system, and 1.30 Mg ha^{-1} (17.6%) higher in the chisel system, when compared to average yields obtained for years when rotations were planted to first-year corn. Higher average yields for years when rotations were planted to second year corn indicate that growing conditions during these years were, in general, less stressful when compared to years when rotations were planted to first-year corn. On average, June mean monthly temperature was 1°C lower and precipitation 15 mm higher for years planted to first-year corn compared to years planted to second-year corn. Relatively cool and wet June weather conditions often experienced during years when rotations were planted to first-year corn may, in part, explain the lower yields often obtained during these years when compared to years when rotations were planted to second-year corn.

First-year soybean yields were highest for the rotation that included wheat underseeded with red clover, producing yields which were 0.18 Mg ha^{-1} (7.2%) higher than the rotation comprised of only corn and soybean. First-year soybean yield increase associated with substituting the second year of soybean with wheat was fully realized only when the wheat was underseeded with red clover. It should be noted that these first-year soybean yield responses to rotation are the result of differences in cropping sequence that occurred 3 yr before the seeding of first-year soybean.

First-year soybean yields averaged 0.07 Mg ha^{-1} (2.7%) higher in the chisel compared to the moldboard system (Table 4).[ID]TBL4[/ID] Second-year soybean yields were not affected by tillage. Although tillage effects on first-year soybean yields were statistically significant, the size of yield response was relatively small and consistent with reports from Nebraska and Iowa that

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suggest minimal soybean yield differences in moldboard and chisel systems (Wilhelm and Wortmann, 2004; Yin and Al-Kaisi, 2004).

Rotation and tillage did not affect wheat (Table 4) or first-year barley yields (Table 5).[ID]TBL5[/ID] Second-year barley yields also were not affected by rotation, but did average 0.32 Mg ha^{-1} (8.7%) lower in the chisel plow system. Alfalfa yields also were not affected by tillage, with an average dry matter yield of 4.9 Mg ha^{-1} in the seeding year and 9.1 Mg ha^{-1} in the second year.

Crop Specific Rotation and Tillage Effects on Costs and Net Revenue

Costs of production varied among the various crops with the highest costs associated with corn (Table 2). Soybean had the lowest production costs, which were 60% of the costs associated with corn production. Production costs of barley, wheat, and alfalfa were slightly higher than for soybean. Higher corn production costs were mostly attributed to seed, fertilizer, and drying charges which were substantially greater than for the other crops.

Energy cost savings associated with use of the chisel system is relatively small compared to the total energy related cost for the various production systems evaluated. The energy cost savings due to the change of the tillage system of $4.14 ha^{-1} represent 2 to 4% of the total on-farm energy related expenses for fuel, lubricants, and crop drying.

The combination of lower yields and added expense of insecticide application resulted in relatively low net revenue for corn when planted continuously compared to first-year corn planted in rotation (Table 3). When planted in rotation net revenue of corn in the moldboard system was $63 to $102 ha^{-1} higher than in continuous corn. However, the choice of rotation crops did not affect the net return of first-year corn in the moldboard system. In the chisel system the integration of crops other than corn resulted in an increase of the net revenue for corn of $95 to $168 ha^{-1}. The highest net revenues for first-year corn in that tillage system were achieved in rotations with barley and alfalfa. (Table 3). In the chisel system highest net returns for first-year corn in the chisel system was when following barley or alfalfa. However, in the chisel system red clover did not increase net revenue over the rotations without cover crop, because the added expense associated with chemical control of the red clover more than offset the value of any increased yields associated with following red clover.

Rotation effects on net revenue for second-year corn were entirely due to variations in yields among the various rotations (Table 3). Net revenue for second-year corn following soybean was $39 ha^{-1} lower than where corn was planted continuously.

The cost savings associated with the chisel system often did not compensate for the reduced revenue associated with reduced yields (e.g., in continuous corn) and for the added expense associated with chemical control measures for red clover.

First-year soybean net revenue response to rotation was entirely due to differences in yield (Table 4). Higher soybean yields associated with the presence of wheat underseeded with red clover instead of soybean 3 yr earlier increased net revenue by $46 ha^{-1}. The combination of slightly higher yields and lower costs associated with the chisel system increased net revenue by $23 ha^{-1}. Tillage did not significantly affect net revenue for second year soybean. Yin and Al-

Kaisi (2004) also found higher net returns of soybean when plowed with a chisel plow instead of the moldboard plow.

Net returns for wheat (Table 4) and barley (Table 5) were reduced when red clover was underseeded, an effect that was mainly due to the costs associated with seeding red clover. Tillage did not affect net revenue of wheat or first-year barley. In the second year of barley, yield penalties due to chisel instead of moldboard plowing resulted in a reduction of net revenue of $29 ha^{-1}. Tillage had negligible effect on net revenue associated with either first- or second-year alfalfa.

Rotation and Tillage System Effects on Overall Net Revenue

Overall net returns were affected by rotation, with the magnitude of rotation response affected by tillage system (Rotation by Tillage Interaction $P = 0.0067$). Averaged over all five cycles, the rotations which contained wheat had the highest yearly net returns, which were $51 ha^{-1} to $64 ha^{-1} over those calculated for continuous corn in the moldboard system (Table 6). [ID]TBL6[/ID]The profitability associated with rotation increased in the chisel system, with yearly returns for rotations which included wheat ranging from $96 to $108 ha^{-1} over those calculated for continuous corn. Although rotating with 2 yr of soybean increased profitability in both tillage systems, the response was greater in the chisel system where profitability was increased by $68 ha^{-1} over where corn was planted continuously. Greater profitability associated with rotation in the chisel system can, in part, be explained by the relatively low continuous corn yields in the chisel system (Table 3). In fact, the chisel system was associated with substantially lower net returns than moldboard only following continuous corn ($46 ha^{-1}). Tillage differences for the other rotations were relatively small and did not differ by more than $17 ha^{-1}.

Substitution of wheat in place of second-year soybean resulted in higher net returns over the rotation in the chisel plow system; in the moldboard plow system net returns were only increased when wheat was underseeded with red clover at the 10% level of probability. Averaged over rotation cycles and tillage, the rotations which included wheat had yearly net returns which were $30 ha^{-1} (SE = 14.1, $P = 0.0335$) higher than for the rotation comprised exclusively of corn and soybean.

Overall net returns for rotations that included barley or alfalfa did not differ from continuous corn (Table 6). Although rotations that included barley or alfalfa had relatively high first-year corn yields and net revenues (Table 3), low net returns associated with barley and alfalfa (Table 5) more than offset the revenue gains associated with higher first-year corn yields.

The full economic benefit of including wheat in the rotation in the moldboard system was fully realized only when underseeded with red clover where economic returns were $32 ha^{-1} over the rotation that included second-year soybean instead of wheat (Table 6).

The presented calculations provide only a conservative economic analysis because N-credits were not accounted for in the rotations. Janovicek and Stewart (2004) have shown that fertilization rates to corn can be reduced by up to 110 kg N ha^{-1} following legumes. Applying rotation N credits to first-year corn as suggested by Janovicek and Stewart (2004) would reduce production costs by $2 ha^{-1} in the C-C-B-B and C-C-S-W rotations, $7 ha^{-1} in the C-C-S-S

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rotation, \$18 ha^{-1} in the C-C-B(RC)-B(RC) and C-C-S-W(RC) rotations, and \$24 ha^{-1} in the C-C-A-A rotation.

Risk and Sensitivity Analysis

Relative profitability of the various rotations was somewhat unstable over the five cycles (data not shown). Profitability patterns were induced more by random year effects than by the trends of yield increase over time. While corn–soybean–wheat rotations were the most profitable in all five cycles, profitability of continuous corn was among the highest in some of the cycles and among the lowest in all other cycles. Similarly, for the corn–soybean rotation four of the five cycles provided similar net returns while net returns in one of the five cycles was significantly lower.

Variation of net returns over the five cycles was highest in the continuous corn rotation. Variation was drastically reduced by integration of additional crops into the rotation, demonstrating that diversification of crop rotation not only increases the average net return but also reduces variation (Barlett test, $P = 0.041$ in the moldboard system and $P = 0.027$ in the chisel system). Reduced variation of net return associated with crop rotation may be due to the lower yield variability associated with soybean and wheat, or it may reflect the effect of having multiple crops on minimizing yield and net return risk.

The most profitable rotation-tillage combinations were also the most effective choices for a risk-averse decision maker (Table 7). [ID]TBL7[/ID]With increased risk aversion the relative rankings of the corn–alfalfa and continuous corn rotations fell because of relatively high yield variation in those rotations. For example, increasing the risk aversion coefficient to 0.01 from 0 (risk neutral) reduced the certainty equivalent value of the corn–alfalfa rotations by \$216 with a moldboard plow and \$225 ha^{-1} with a chisel plow while falling by only \$103 to \$116 ha^{-1} for the barley-based rotations. Thus, the relative rankings fall for the former rotations for risk averse farmers. The integration of red clover did not affect the ranking of the rotation-tillage systems under risk. The most profitable systems remain the most preferred when risk is considered. The diversification of the rotation reduces production risk in contrast to planting corn continuously. Similar findings have been observed by Helmers et al. (2001) for rain-fed cropping in Nebraska. They compared a corn–soybean rotation with corn and soybean planted continuously and found that production risk was reduced when the crops were planted in rotation, even though yield variance was higher in the rotated crops than for the sole crops planted continuously. Zentner et al. (2002a) also found that crop diversification reduces business risk for wheat-based crop rotations in western Canada.

The effects of price changes on net return of the rotations and the percentage change of net return are presented in Table 8. [ID]TBL8[/ID]An increase in energy prices by 50% with its effects on fuel price, fertilizer prices, and custom rates reduced net return by 33 to 253%, depending on the choice of the cropping system. Increased energy prices reduce the relative profitability of moldbord plow systems compared to chisel plow systems but the effect is small since the energy cost savings due to the change of the tillage system represent 2 to 4% of the total energy related expenses. In contrast, rising energy prices are more likely to affect the choice of crop rotation since relative energy-related expenses of drying and fertilizer between crops are higher than for tillage systems. Drying and fertilization costs are highest for corn among the crop (see Table 2) so the continuous corn rotation is most affected by an increase in energy costs. The

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corn–soybeans–wheat rotations were least affected by the assumed increase in energy prices. The advantages of the legume-based rotations would be further increased if N-fertilization credits were taken into account as discussed above.

A general reduction in crop prices by 10% reduced net return by more than the 50% increase in energy prices (Table 8). The impacts are largest for rotations focused on corn whereas corn–soybean–wheat rotations were least affected by output price changes. However, output prices are not likely to change proportionately and it is relative price changes that will largely influence the profitability of cropping systems.

CONCLUSIONS

This study demonstrates the economic benefit of integrating crops such as soybean, wheat, barley, or legumes into a corn-based rotation in either moldboard and chisel plow system. The benefit of including wheat was particularly evident. Of the rotations evaluated in this study, rotations that included wheat consistently provided net returns that were the highest and most stable. Net returns of rotations that included wheat were also the least sensitive to increasing energy costs.

Underseeding of red clover into wheat had no effect on wheat yields and resulted in slightly but not significantly ($P < 0.07$) increased yields of the subsequent corn crop. However, net returns of rotations that included underseeded red clover into wheat did not result in lesser net returns compared to rotations that included wheat not underseeded to red clover. While returns did not differ, the analysis in this study did not consider the value of red clover in terms of N credit to the subsequent corn crop, an effect that could be significant particularly under the scenario of a 50% increase in energy costs.

Continuous corn was the only rotation in which chisel plowing had a significant economic impact with overall revenues that were less than those in the moldboard system. For all other rotations no significant differences in net returns were found between tillage systems for a given crop rotation. Since chisel plowing only requires half the working time than moldboard plowing, this could be an increasingly attractive alternative.

The long-term analysis of the experiment provides evidence, that diversified rotations reduce risk in term of both price and yield. With increased energy prices, as well as with reduced crop prices, cropping systems with low production costs were better than cropping systems with high inputs, which rely on high crop prices. Even though chisel plowing has lower fuel consumption, it is more efficient to select appropriate crops and increase rotation complexity than to change the tillage system as a response to increased energy prices.

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Table 1. Schedule of field operations for crop rotations(not including rotations with alfalfa).

Year(crop) rotation†	Timing	Operations	
		Moldboard plow system	Chisel plow system
1 (corn)	Oct.–Dec.	Moldboard plowing	Chisel plowing
	20 Apr.–May	fertilizer application, secondary tillage (two passes of a field cultivator and packer), seeding with starter fertilizer application, preplant herbicide application	
	Oct. –Nov.	Harvest	
	Oct. –Dec.	Moldboard plowing	Chisel plowing

2 (corn)	**20 Apr. –May**	**fertilizer application, secondary tillage (two passes of a field cultivator and packer), seeding with starter fertilizer application and corn rootworm insecticide application, preplant herbicide application**	
	Oct. –Nov.	**Harvest**	
	Oct. –Dec.	**Moldboard plowing**	**Chisel plowing**
3 (barley, soybean)	**Apr.–May**	**fertilizer application, secondary tillage (two passes of a field cultivator and packer), seeding, postemergent herbicide application**	
	Aug. –Oct.	**Harvest**	
	Sept. –Nov.	**Moldboard plowing**	**Chisel plowing (before winter wheat two passes of a tandem disk instead of chisel plowing)**
	Oct. –Nov.	**seeding (only wheat) after two passes of a field cultivator and packer**	
	Mar. –Apr.	**red clover broadcast (winter wheat only)**	
4 (barley, soybean, wheat)	**Mar. –Apr.**	**fertilizer application, secondary tillage (two passes of a field cultivator and packer), seeding of soybean, barley, and barley with red clover, postemergent/preplant herbicide application**	
	Aug. –Oct.	**Harvest**	
	Sept. –Oct.		**glyphosate application only in rotations with red clover underseed**

† Each rotation was duplicated with a rotation 2 yr out of phase so that when a given rotation was planted to first-year corn its duplicate was planted to the first year of the rotation crop. Rotation cycles occurred 1982 to 1985, 1986 to 1989, 1990 to 1993, 1994 to 1997, 1998 to 2001.

Table 2. Cost structure of corn, soybean, wheat, barley, and alfalfa production in the different tillage systems.†

	Production costs									
	Corn		Soybean		Wheat		Barley		Alfalfa	
Input	Moldboard	Chisel	Moldboard	Chisel	Moldboard	Chisel	Moldboard	Chisel	Moldboard	Chisel
	$\$\ ha^{-1}$									
Seed	150		93		91		80		68	
Fertilizer	210		66		207		135		99	
Herbicides	86		79		15		76		24	
Custom work for fertilizer and pesticides	44		44		44		44		66	
Energy related yield variable costs‡	187		39		28		22		–	
Fuel and lubrican	31	27	20	16	26	21	26	21	56	54

ts Variable machine costs and overhead expenses §	264	262	210	208	249	248	236	234	279	278
Sum	972	966	551	545	660	654	619	613	592	589

† Data from 2005 Field Crop Budgets (OMAFRA, 2005a) with specific modifications (see text), additional rotation specific costs are not considered.

‡ Drying and trucking costs assuming average yield for each crop (corn: 8.5 t ha^{-1}, soybean: 2.7 t ha^{-1}, wheat: 5.1 t ha^{-1}, barley: 3.7 t ha^{-1}, alfalfa: 7 t ha^{-1}).

§ Including costs on interest on operating capital, rent, marketing fees, storage and labor costs.

Table 3. Rotation and tillage effects on first and second-year corn grain yield (155 g kg^{-1} moisture), and associated net revenue, averaged over years 1982 to 2001.

	First-year corn				Second-year corn	
	Yield		Net revenue			
Treatment	Moldboard	Chisel	Moldboard	Chisel	Yield	Net revenue
	—Mg ha^{-1}—		— $ ha^{-1}—		–Mg ha^{-1}–	—$ ha^{-1}—
Rotation†						
C-C-C-C	7.98‡	7.33‡	19‡	–45‡	8.77§	107§
C-C-B-B	8.26	8.36	104	121	8.57	85
C-C-B(rc)-B(rc)	8.34	8.33	113	74	8.70	99
C-C-S-S	8.15	7.87	92	68	8.41	68
C-C-S-W	8.06	8.01	82	83	8.51	79
C-C-S-W (rc)	8.42	8.10	121	50	8.60	89
C-C-A-A	8.24	8.38	102	123	8.99	130
SE	0.116		12.4		0.087	9.3
LSD (*P* = 0.05)	0.34¶		36¶		0.26#	28#
Tillage						
Moldboard					8.73	100
Chisel					8.57	88
SE					0.041	4.4
LSD (*P* = 0.05)					0.12††	NS††

† C = corn, B = barley, rc = underseeded red clover, S = soybean, W = winter wheat, A = alfalfa.

‡ Yield and net revenue in years, when the crops of the other rotations were planted in the first year.

§ Yield and net revenue in years, when the crops of the other rotations were planted in the second year.

¶ LSD values represent least significant differences for all tillage-rotation combinations.

LSD values represent least significant differences for different rotations.

†† LSD values represent least significant differences for different tillage systems.

Table 4. Rotation and tillage effects on yield of first and second year soybean (130 g kg^{-1} moisture and winter wheat (145 g kg^{-1} moisture), and associated net revenue, averaged over years 1982 to 2001.

	First-year soybean		Second-year soybean		Wheat	
Treatment	Yield	Net revenue	Yield	Net revenue	Yield	Net revenue

	—Mg ha^{-1}—	—$ ha^{-1}—	—Mg ha^{-1}—	—$ ha^{-1}—	—Mg ha^{-1}—	—$ ha^{-1}—
Rotation†						
C-C-S-S	2.50	146	2.30	93		
C-C-S-W	2.59	170			5.10	174
C-C-S-W(rc)	2.68	192			5.15	142
SE	0.036	9.6	0.023	6.1	0.043	5.2
LSD (P = 0.05)‡	0.13	33			NS	24
Tillage						
Moldboard	2.56	158	2.34	99	5.10	152
Chisel	2.63	181	2.26	86	5.16	165
SE	0.018	4.5	0.032	8.6	0.033	4.0
LSD (P = 0.05)§	0.06	15	NS	NS	NS	NS

† C = corn, S = soybean, W = winter wheat, rc = underseeded red clover.

‡ LSD values represent least significant differences for different rotations

§ LSD values represent least significant differences for different tillage systems

Table 5. Rotation and tillage effects on yield of first and second year barley (140 g kg^{-1} moisture and alfalfa (0 g kg^{-1} moisture) and associated net revenue, averaged over years 1982 to 2001.

	First year		Second year	
Treatment	Yield	Net revenue	Yield	Net revenue
	Mg ha^{-1}	$ ha^{-1}	Mg ha^{-1}	$ ha^{-1}
		Barley		
Rotation†				
C-C-B-B	3.81	20	3.42	–24
C-C-B(rc)-B(rc)	3.95	–1	3.56	–45
SE	0.060	6.7	0.037	4.2
LSD (p = 0.05)‡	NS	NS	NS	19
Tillage				
Moldboard	3.92	11	3.65	–20
Chisel	3.83	8	3.33	–49
SE	0.054	6.1	0.027	3.1
LSD (p = 0.05)§	NS	NS	0.09	11
		Alfalfa		
Rotation†				
C-C-A-A	4.94	–173	9.08	177
SE	0.060	5.1	0.073	6.8
Tillage				
Moldboard	5.06	–165	9.12	178
Chisel	4.83	–181	9.04	175
SE	0.084	7.1	0.103	9.7
LSD (p = 0.05)§	NS	NS	NS	NS

† C = corn, B = barley, rc = underseeded red clover, A = alfalfa.

‡ LSD values represent least significant differences for different rotations.

§ LSD values represent least significant differences for different tillage systems.

Table 6. Rotation and tillage effects on yearly net revenue averaged from 1982 to 2001.

	Tillage	
Rotation	Moldboard plow	Chisel plow
	—-$ ha^{-1} (SD)—-	
C-C-C-C†	70 (164)	24 (167)

C-C-B-B	**51 (94)**	**46 (99)**
C-C-B(rc)-B(rc)	**45 (93)**	**28 (91)**
C-C-S-S	**102 (120)**	**92 (105)**
C-C-S-W	**121 (93)**	**132 (97)**
C-C-S-W(rc)	**134 (102)**	**120 (95)**
C-C-A-A	**63 (147)**	**60 (147)**
SE		
C-C-C-C (*n* = 20)	**17.2**	
Rotation (*n* = 40)	**12.1**	
LSD (tillage, 0.05)		
C-C-C-C	**42‡**	
Rotations	**35§**	

† C = corn, B = barley, rc = underseeded red clover, S = soybean, W = winter wheat, A = alfalfa.

‡ LSD values represent least significant differences for all tillage-rotation combinations with continuous corn.

§ LSD values represent least significant differences for all tillage-rotation combinations not including continuous corn.

Table 7. Ranking of rotation-tillage combinations based on expected net return and certainty equivalents based on yield response at different risk aversion coefficients (λ).

	Risk attitude			
	Neutral (λ = 0)		Averse (λ = 0.01)	
Rotation†	**CE‡**	**Ranking**	**CE‡**	**Ranking**
	–$ ha^{-1}–		–$ ha^{-1}–	
	Moldboard			
C-C-C-C	70	7	–75	10
C-C-B-B	51	10	–52	7
C-C-B(rc)-B(rc)	45	12	–71	9
C-C-S-S	102	5	–20	5
C-C-S-W	121	3	14	3
C-C-S-W (rc)	134	1	25	1
C-C-A-A	63	8	–153	13
	Chisel			
C-C-C-C	24	14	–126	12
C-C-B-B	46	11	–59	8
C-C-B(rc)-B(rc)	28	13	–84	11
C-C-S-S	92	6	–21	6
C-C-S-W	132	2	24	2
C-C-S-W (rc)	120	4	11	4
C-C-A-A	60	9	–165	14

† C = corn, B = barley, rc = underseeded red clover, S = soybean, W = winter wheat, A = alfalfa.

‡ CE: Certainty equivalent.

Table 8. Impact of price changes on net return of the rotation-tillage combinations

	Energy price scenario†		Crop price scenario‡	
Rotation	**Moldboard**	**Chisel**	**Moldboard**	**Chisel**
	——$ ha^{-1} yr^{-1} (% change relative to base scenario in Table 5)——			
C-C-C-C§	7b¶ (–89%)	–36d (–253%)	–40b (–157%)	–79d (–433%)
C-C-B-B	5b (–90%)	1cd (–97%)	–35b (–168%)	–39c (–186%)
C-C-B(rc)-B(rc)	–1b (–102%)	–16cd (–159%)	–42b (–193%)	–58cd (–310%)
C-C-S-S	61a (–40%)	53 b(–42%)	14a (–86%)	7b (–93%)

C-C-S-W	**75 a(–38%)**	**88a (–33%)**	**29a (–76%)**	**39a (–70%)**
C-C-S-W(rc)	**88a (–34%)**	**77ab (–36%)**	**40a (–71%)**	**27 ab(–78%)**
C-C-A-A	**17 c(–74%)**	**15c (–75%)**	**–23b (–137%)**	**–25c (–142%)**
SE#				
C-C-C-C (*n* = 20)	**17.2**		**15.1**	
Rotation (*n* = 40)	**12.1**		**10.7**	

† For fuel and strongly energy related processes a price increase of 50% ($1.04 per liter fuel) was assumed, for N fertilizers a price increase of 25% ($1.10 per kg N) was assumed.

‡ For all crops a 10% reduction in prices was assumed.

§ C = corn, B = barley, rc = underseeded red clover, S = soybean, W = winter wheat, A = alfalfa.

¶ Within column (tillage system) rotation means followed by the same letter are not different according to a protected paired *t* test at $p = 0.05$.

 # Standard error of rotation by tillage means where the means are comprised of 20 observations for continuous corn and 40 observations for the 4-yr rotations.