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Cost Efficient Rotation and Tillage Options to Sequester Carbon and Mitigate GHG Emissions from Agriculture in Eastern Canada

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Abstract

The economic efficiency of cropping options to mitigate net GHG emissions from agriculture in Eastern Canada was analyzed. Data on yield response to tillage (moldboard plow and chisel plow) and six corn (*Zea mays* L.)-based rotations were obtained from a 20-year field experiment in Ontario. Budgets were constructed for each cropping system while GHG emissions were measured for soil carbon and were estimated for nitrous oxide according to IPCC methodology. Complex crop rotations with legumes, such as corn-corn-soybeans (*Glycine max.* L.)-wheat (*Triticum aestivum* L.) with red clover (*Trifolium pratense* L.) underseeded, have higher net returns and substantially lower GHG emissions than continuous corn. Conservation tillage reduces GHG emissions due to lower input use but sequestration levels did not vary significantly between tillage systems. Rotation had a much bigger effect on the mitigation potential of GHG emissions than tillage. However, opportunity costs of more than \$200 per Mg CO_2 eq ha^{-1} $year^{-1}$ indicate the limits to increase the mitigation potential beyond the level of the most profitable cropping system.

Keywords: Carbon sequestration, Greenhouse gas emissions, Cost efficiency

1 Introduction

As a signatory to the Kyoto Protocol, Canada has committed itself to reducing national emissions of greenhouse gases (GHG) to a level 6% lower than the amount emitted in 1990. Although agriculture contributes only 10% of the total anthropogenic GHG-emissions within Canada, the sector can contribute to the GHG mitigation target in several ways: 1) reducing direct and indirect emissions, 2) increasing the retention of CO_2 by sequestration of carbon in the soil, or 3) offering offset options associated with the production of bio-fuels and biomass energy or materials that would replace fossil sources. Which of these methods for reducing GHG levels should be targeted and the corresponding policy instrument to induce its adoption, depends on both the mitigation potential of the management practice and the opportunity costs to firms of its adoption.

The view that agriculture could significantly cut net GHG levels at relatively low cost compared to other sectors in the economy is based on the carbon sequestration potential of the Canadian Prairies. McConkey *et al.* (2003) estimated that the elimination of bare fallow in a Prairie crop rotation would annually sequester 27–430 kg C ha^{-1} and that the adoption of conservation tillage sequesters 67–512 kg ha^{-1} of carbon annually. Given the large area and adoption potential of sink enhancing practices, such as reduced summer-fallow and tillage, Boehm *et al.* (2004) forecasted a mitigation potential from 4 to 15.6 Mt CO_2-eq $year^{-1}$ in Canada for 2008. Opportunity costs for carbon sequestration increases with the level of sequestration but regional studies of the Great Plains region suggest there will be some adoption at costs of less than $10 per tonne of CO_2 (Antle *et al*., 2001).

While the cost effectiveness of GHG mitigation by agriculture in the Great Plains region appears to be driven by carbon sequestration associated with conservation tillage practice impacts on soil disturbance and rotation, this may not reflect the situation in Eastern Canada. For example, while tillage reductions may increase carbon sequestration in Western Canada, there is evidence to suggest that it may have little effect in Eastern Canada (Angers *et al*., 1997; Yang and Kay, 2001; Deen and Kataki, 2003). In addition, sequestered carbon is a temporary mitigation option as the stored carbon can be released when cropping systems change. For these reasons, the cost-effectiveness of a wider range of GHG mitigation strategies for Eastern Candian agriculture should be considered. In addition to considering the cost-effectiveness of farm management systems in terms of carbon sequestration, effects on direct and indirect GHG emissions need to be considered (Kulshreshtha *et al*., 2000). Nitrogen and energy inputs into an agricultural system can be altered through management changes such as those associated with tillage, crop selection within a rotation, or fertility practices. For example, including legumes in a rotation has complex effects on fluxes of C and N in the soil (Drinkwater *et al.*, 1998) and as a result of their ability to biologically-fix nitrogen may have undesirable impacts similar to fertilization with industrially-fixed nitrogen (Crews and Peoples 2004).

The purpose of this paper is to examine the cost-effectiveness of Eastern Canadian cropping systems to reduce GHG levels. A unique aspect of the study is a 20 year field trial on 15 cropping systems that vary by crop choice and tillage system. The paper begins by describing the experiment followed by the method used to calculate the amount of carbon sequestered from empirical observations. The IPCC methods for estimating nitrous oxide emissions from the soil due to crop residues, fertilizer and N-fixation are then presented followed by the emission estimates from direct and indirect energy use associated with fuel consumption on the farm and input manufacturing. The resulting total net GHG emissions for each system are then compared to net returns calculated base on observed experimental yields and prices. The trade-off curves illustrate the abatement costs associated with crop rotation (including cover crops) and tillage system in reducing net GHG emissions.

2. Material and Methods

2.1 Data and experimental design

The data for this study were taken from an experiment, which was established in 1980 at the Elora Research Station of the University of Guelph. The site has a Woolwich silt loam soil (Soil Taxonomy: Typic Hapludalf; FAO system: Albic Luvisol). Average annual rainfall for the region is 800mm with rainfall distribution approximately uniform over the year. Average monthly temperatures for January, April and July are –4.7, 8.3 and 22.2C, respectively.

The experiment provides data on crop and soil response to two levels of tillage and seven different corn-based crop rotations. An eighth rotation consisted of continuous alfalfa (*Medicago sativa* L.). Aside from continuous corn, the other corn-based rotations consisted of two years of corn, followed by either soybeans, alfalfa, barley (*Hordeum vulgare* L.) or soybeans with winter wheat. The rotations involving barley or wheat were implemented with and without red clover underseeded into the cereal. Each rotation except continuous corn and continuous alfalfa was replicated once with a two-year lag so that each cropping sequence began every second year.

Each main rotation plot of the field experiment was split into two levels of tillage. Conventional tillage consisted of fall moldboard plowing to a depth of 15-20 cm followed by spring secondary tillage with a field cultivator (10 cm depth) and packer. The other tillage system was slightly less aggressive and involved chisel plowing in the fall to a depth of 15-20 cm and spring secondary tillage with a field cultivator (10 cm depth) except prior to winter wheat when only a tandem disc was used. The experiment was designed in a split plot design with four replications for each tillage-rotation combination.

The plots were maintained so that growth factors such as fertility or pest did not differ between plots. N-fertilization rates were based on general recommendations for Ontario (OMAF, 2002). While actual application rates on a given crop did not vary between rotations, the economic and environmental analysis that follows did account for N-credits from other crops in the rotation (see Table 1).

2.2 Net GHG emissions of the cropping systems

The GHG-mitigation effect of the choice between different cropping options was estimated from carbon sequestration, determined as described in the previous section, supplemented with estimations of N_2O-emissions from the soil and energy related emissions due to the production process based on IPCC methodology. The mitigation potential is expressed relative to the emissions of continuous corn rotation under conventional tillage. The mitigation rates of CO_2, CH_4 and N_2O are expressed according to their global warming potential in CO_2 equivalents per ha and year (CO_2 eq ha^{-1} $year^{-1}$). Sequestered carbon in the soil was considered as permanent sink.

2.2.1. Calculation of carbon sequestration

The carbon sequestration potential of the tillage-rotation combination was based on the measurement of organic matter content in the soil of each experimental plot in 1999 and 2000. Five soil cores were taken prior to tillage operations in the fall after corn harvest from each plot at depths of 0-5, 5-10, 10-20, 20-30, and 30-40 cm. The composite depth samples for each plot were analyzed for bulk density and organic carbon. Soil bulk density was calculated using the internal diameter of the core sampler, the segment depth, and a 105°C oven-dry soil weight. Organic carbon was calculated as the difference between total carbon content and inorganic carbon (after placing samples in a muffle furnace for five hours at 475°C) determined by a Leco SC-444 method. Soil carbon storage on an equivalent soil mass basis was calculated as per Ellert and Bettany (1995) and Yang and Wander (1999). Soil carbon storage was calculated for a soil mass of 4800 Mg ha^{-1} , which at this site is obtained from an average sample depth of 34 cm. Rotation and tillage effects on soil carbon storage was calculated using an analysis of covariance which performed linear adjustments based on relative plot position within the replicate and elevation.

Carbon sequestration rates for all management options were compared to the continuous corn rotation with conventional tillage, since this was the management prior to the experiment on the field and a common practice at that time. The difference was divided by the number of years of the experiment to arrive at annual sequestration rates of carbon.

2.2.2 Estimation of nitrous oxide emissions

The N_2O emissions from the soil induced by crop production were estimated based on biological nitrogen fixation, crop residues, synthetic fertilizer inputs and indirect emissions, according to IPCC methodology (Houghton *et al*., 1997). Total emissions from the soil (E_{N_2O}) is the sum of nitrogen sources from crop residues (E_{CR}), biological N-fixation of legumes (E_{BN}), synthetic fertilizer (E_{SN}), and indirect emissions ($E_{indirect}$) from nitrogen which has been translocated from the agricultural ecosystem to neighbouring ecosystems from where a part of it is expected to be released as N_2O ($E_{N_2O} = E_{CR} + E_{BN} + E_{SN} + E_{indirect}$). The resulting value in terms of N is multiplied by 1.57 to convert it into N_2O. The estimation of each element is explained below.

Emission rates from crop residues were calculated as a function of dry matter yield and crop specific N-content factors according to:

$$E_{CR} = 2 * Yield_{DM} * NCONT_{Crop} * (1 - F_R) * EF_D$$

where $Yield_{DM}$ is the dry matter yield of the crops, which is twice the amount of actual yield to account for all biomass from the planted crop, including roots, leafs, straw; $NCONT_{CROP}$ is the crop specific nitrogen content of the crops, which is assumed as 1.5% of the dry matter biomass for corn, barley and wheat and 3 % for soybeans; F_R is the fraction of the crop biomass removed from the fields, which is assumed to be 0.45; and EF_D is the default emission factor of 1.25% for nitrogen in the soil, which is assumed to be released as N_2O, according to Houghton *et al.* (1997).

Emissions due to the biological fixation of legumes were calculated as follows:

$$E_{BN} = A * Yield_{DM} * 0.03 * (1 - F_R) * EF_D,$$

where 0.03 is the legume specific N-content of the plant biomass and the factor A is an adjustment to assess the total crop biomass, which is 2 for all legumes except alfalfa, where it is assumed to be 1 (Matin *et al*., 2004). The impact of cover crops on the production of crop residues and the nitrogen fixation potential of legumous cover crops is not considered at the national scale with the IPCC methodology due to lack of data. However, it is likely that both crop residues and nitrogen fixation of cover crops do impact the total N_2O emissions of cropping systems. We calculated the emissions from cover crops assuming a biomass production of 2 Mg ha^{-1}, which was the average dry matter yield of the cover crop in the experiment, and a N content of the biomass of 3%.

Emissions from synthetic fertilizer applications were obtained by multiplying a default emission factor (EF_D) by the amount of nitrogen (N_{SYN}) applied less 10%, which represents applied nitrogen lost through volatilization (Houghton *et al.*, 1997):

$E_{SN}= N_{SYN} * 0.9 * EF_D$.

In addition to the direct emissions of N_2O from the soil, there are indirect emissions from fertilizer application due to leaching or volatilization of nitrogen. The indirect N_2O emissions from fertilizer use were calculated as:

$$E_{indirect} = N * Frac_V * EF_V + N * Frac_L * EF_L$$

where $Frac_V$ is the fraction of 10% of the applied nitrogen, which is assumed to be volatilized and deposited back on the soil; EF_V is the emission factor for this fraction, which is assumed to be 1% (Houghton *et al.*,1997); and $Frac_L$ is the fraction leached or translocated via run off. Instead of the default IPCC value, a lower value of 0.15 was used according to Matin *et al*. (2004). EF_L is the default emission factor of 2.5% for that fraction.

2.2.3 Estimation of GHG emissions from fuel, on farm energy use and farm inputs

The GHG-relevant emission coefficients due to fuel consumption were taken from the assumptions of Canada’s Greenhouse Gas Inventory (Matin *et al.,* 2004). The work rates of the implements and the fuel consumption of the tractor determined in-field fuel use. Crop drying also uses fuel and it was assumed that 24 l liquefied petroleum gas (LPG) per Mg of corn were needed to dry corn from its 24.5% moisture content at harvest down to 15.5% (OMAFRA, 2005a). For soybeans fuel consumption due to drying was assumed to be 13 l LPG per Mg of soybeans (OMAFRA, 2005a).

Emissions from manufacturing the cropping inputs were based on the methodology proposed by Kulshreshtha and MacDonald (2000). The emission coefficients from fertilizer, fuel consumption and machinery repairs are given in Table 2. Quantities of fertilizer and fuel used have been described above while estimates of repair costs of different cropping systems are outlined below. GHG emissions from pesticide manufacturing and from seed production were ignored as were other on-farm energy uses and induced energy use, which are marginally affected by the choice of cropping system.

2.3 Profitability analysis

Net returns for each cropping system were obtained by subtracting the costs of production from gross revenue, which was obtained by multiplying observed yields by the 1999 to 2003 average crop prices. Prices were \$130 Mg^{-1} for corn, \$277 Mg^{-1} for soybeans, \$127 Mg^{-1} for soft white wheat, \$119 Mg^{-1} for barley and \$85 Mg^{-1} for alfalfa hay (OMAFRA, 2005b). In addition to the sale of grain, it was assumed that 124 bales ha^{-1} straw were harvested and sold at a price of \$1.5 $bale^{-1}$ from wheat and barley fields regardless of grain yield.

Costs of production were based on the 2005 Field Crop Budgets for Ontario (OMAFRA, 2005a) with some adjustments for the cover crop and additional pesticide applications which were necessary in some of the rotations (Table 3). Underseeding red clover into wheat and barley was assumed to cost \$37 ha^{-1} and a further cost of \$43 ha^{-1} was assessed to rotations in the chisel plow system for fall chemical burn down of this red clover. Also, a \$55 ha^{-1} charge for corn rootworm insecticide was assessed whenever corn followed corn.

Annual fertilizer N rates were 160 kg N ha^{-1} for corn, 8 kg N ha^{-1} for soybeans, 110 kg N ha^{-1} for winter wheat, 60 kg N ha^{-1} for barley, and 10 kg N ha^{-1} for alfalfa in the first year. The fertilizer rates to corn after a crop other than corn were adjusted according to N-credits in Table 1 (Janovicek and Stewart, 2004). 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-year 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 based on work rates as noted above. Total fuel use for tillage operations was assumed to be 6 l ha^{-1} less fuel for the chisel plow systems compared to the moldboard plow system. The fuel price was \$0.60 l^{-1} and an additional 15% to total fuel use is added for lubricants. Drying charges were assumed to be \$16 Mg^{-1} for corn and \$8 Mg^{-1} for soybeans. Further yield dependent costs such as storage, trucking and marketing fees were calculated according to values from the Crop Budgets (OMAFRA, 2005a).

The estimated costs were subtracted from the calculated revenue to obtain net returns to land, labour and management for an individual crop in a given tillage system. The net returns for each crop were averaged over the 20 years of observation (five complete rotations) in order to obtain the yearly net revenue associated with each rotation-tillage combination.

3 Results

3.1 GHG emission levels

3.1.1. Carbon sequestration

Crop rotation affected carbon sequestration with the highest carbon storage after 20 years where alfalfa had been planted continuously and lowest in the corn-corn-soybean-soybean rotation (Table

4). Carbon storage of soils in the corn-corn-alfalfa-alfalfa rotation were significantly higher than in the corn-corn-soybean-soybean rotation. Rotations which included cereals and red clover had soil carbon levels which were between those observed for continuous alfalfa and a corn-corn-soybean-soybean rotation.

The continuous alfalfa rotation had the highest sequestration rates at 514 kg C ha^{-1} yr^{-1}. Soils cultivated with continuous corn and the rotations involving cereals had carbon levels between the highs noted for rotations with alfalfa and the lows for rotations with soybeans.

Carbon content in the soil was not affected by tillage system. This result was not unexpected since the two tillage systems evaluated do not significantly differ in degree and depth of soil displacement. Also, Angers *et al.* (1997), Yang and Kay (2001), and Deen and Kataki (2003) similarly found that tillage had little affect on carbon sequestration levels in eastern Canadian soils.

3.1.2 N_2O emissions from fertilizer use

The calculated N_2O-emissions expressed in CO_2 equivalents by crops are presented in Figure 1. The estimated emission values are highest for corn, when planted after a red clover cover crop. Even though the red-clover cover crop lowers the fertilization requirement of the following corn crop and thus reduces the emissions from fertilization by more than 200 kg CO_2 eq ha^{-1}, these gains are more than compensated by emissions from N-fixation of the legumes and crop residues of the cover crop. The lowest N_2O emissions from the soil are associated with the production of barley since the N inputs into the system are low. For wheat, soybeans and alfalfa the estimated N_2O emissions are approximately the same, even though the source of emissions differs between the legumes and wheat.

The calculated emission values represent the best available knowledge on N_2O emissions knowing that there is a great degree on uncertainty with the emission coefficients. The mechanisms behind N_2O emissions from agricultural systems are not well understood and existing databases on N_2O emissions are characterized by a very high level of variability, which supports our use of the emission factor approach of the IPCC methodology (Petersen *et al.*, 2005). While the estimation of N_2O from legumes may be overestimated with the current IPCC approach as has been suggested by Gregorich *et al.* (2005), Gibbons *et al*. (2005) found taking the uncertainty into account for a dairy and beef farm in England did not affect the conclusions on the most appropriate emission reducing strategy.

3.1.3 GHG-emissions from on-farm energy use and manufacturing of the inputs

GHG-emissions from on-farm fuel use and induced emissions due to the manufacturing of fertilizers and the machinery by crop are illustrated in Figure 2. GHG emissions are highest among crops for corn because of the high-energy requirements from fertilizer processing and high emissions due to crop drying. Across all treatments, average GHG emissions from corn for on-farm energy use and input manufacturing are 1200 kg CO_2 eq ha^{-1}. The lower fertilizer requirement on corn in a rotation with a red clover cover crop reduced emissions by about 250 kg CO_2 eq ha^{-1}, which more than offsets the higher N_2O emissions due to the legume cover crop (Fig. 1). However, the extent of the offset varies with N-fixation ability of the legume. Emissions from fuel use vary between the crops from 250 kg to 550 kg CO_2 eq ha^{-1} with the highest values for alfalfa because of the high energy demands of harvest and multiple harvests during a given year. Substitution of the moldboard plow with the chisel plow results in an additional 30 kg CO_2 eq ha^{-1} for all crops.

3.1.4 Net GHG emission levels

The total GHG emission levels from fertilizer use plus direct and indirect energy use less the amount of carbon sequestered are compiled on an annual basis for each system in Table 5. Annual nitrous oxide emissions from the soil range from 1379 kg CO_2 eq ha^{-1} with continous alfalfa to 2082 kg CO_2 eq ha^{-1} with continuous corn under a moldboard plow tillage system. These N_2O emissions are lower if barley is part of the rotation and slightly higher if a cover crop is included. Changing to conservation tillage decreases such N_2O emissions by less than 100 kg CO_2 eq ha^{-1}. Emissions from direct and indirect energy use vary from 509 kg CO_2 eq ha^{-1} for continuous alfalfa to 1277 kg CO_2 eq ha^{-1} for continuous corn. Adding a cereal crop to the rotation increases GHG emissions from fuel and input manufacturing while adding a cover crop decreases it due to lower fertilizer needs. The lower fuel use with conservation tillage also reduces emissions from these sources by approximately 20 kg CO_2 eq ha^{-1} compared to the mouldboard plow systems.

Sequestered carbon reduces total GHG levels and is greatest for the system that generates the lowest levels of emissions before accounting for the sink potential. Continuous alfalfa sequesters 513 kg CO_2 eq ha^{-1} annually. In contrast, a corn-soybean rotation releases 73 kg CO_2 eq ha^{-1} compared to a continuous corn rotation. The inclusion of a cereal and/or a cover crop in the rotation increases sequestration levels while tillage has no impact.

Total net GHG emissions for continuous corn with the moldboard plow (3359 kg CO_2 eq ha^{-1}) are 1984 kg CO_2 eq. ha^{-1} higher than the lowest emitting system, which is continuous alfalfa (1375 kg CO_2 eq ha^{-1}). The next highest emitting system rotation of corn-soybeans-wheat, which is the typical rotation in the region, emits an average of 900 kg CO_2 eq. ha^{-1} less than continuous corn across both tillage systems. Differences between other corn rotations (excluding alfalfa) are less than 400 kg CO_2 eq ha^{-1} with the differences increasing with the inclusion of barley, a cover crop and/or conservation tillage. With the exception alfalfa-based systems, nitrous oxide emissions from the soil represent approximately two-thirds of total net GHG emission with the remainder primarily from direct and indirect energy use. Sequestration can offset total GHG emissions but the potential for significant reduction is limited in eastern Canadian cropping systems.

3.2 Profitability of cropping systems

Net returns were affected by tillage and rotation as well as by interaction effects between tillage and rotation. Rotations containing wheat had the highest annual net returns. Compared to continuous corn, corn-based rotations with wheat were \$53 ha^{-1} and \$82 ha^{-1} more profitable under a moldboard system and \$110 ha^{-1} and \$112 ha^{-1} with a chisel plow tillage system (Table 6). Including soybeans in the rotation increased profitability of the corn-based cropping systems in both tillage systems but the response was greater in the chisel system. Overall, net returns for rotations that included barley did not differ from continuous corn. Tillage differences for all rotations were relatively small and did not differ by more than \$18 ha^{-1}. The exception to this finding was continuous corn in which the returns were lower under a chisel plow tillage system due to relatively low continuous corn yields in that system compared to the mouldboard plow. Continuous alfalfa and alfalfa in rotation with corn had significantly higher net returns than continuous corn in both of the tillage systems. Substitution of wheat in place of second-year soybeans resulted in higher net returns over the rotation in the chisel plow system at the 10% level of significance; in the moldboard plow system, net returns only increased when wheat was underseeded with red clover at the 10% level of significance. More detail regarding yield and economic return of the various rotation and tillage systems are discussed by Meyer-Aurich *et al.* (2005).

3.3 Trade-offs between GHG-mitigation and farm profitability

Net GHG emissions and farm returns are illustrated together for all cropping systems in Figure 3 with the exception of continuous alfalfa which is not a common practice for most Eastern Canadian farmers due to autotoxicity concerns. The highest net returns are for a corn-corn-soybean-wheat rotation that is underseeded with red clover. Under conventional tillage, the net GHG emissions are 2335 kg CO_2 eq ha^{-1}, where 2595 kg CO_2 ha^{-1} stem from the production process of which 169 kg CO_2 eq ha^{-1} is sequestered in the soil (Table 5). This management option mitigates more than one Mg CO_2 eq ha^{-1} $year^{-1}$ of GHG emissions compared to continuous corn and net returns are approximately \$100 ha^{-1} greater. Thus, this system is preferred to continuous corn in terms of the environment and farm profitability. The same corn-soy-wheat rotation without the cover crop is slightly less profitable, emits higher net GHG levels, and is thus considered inefficient to the rotation with the cover crop. GHG levels can be reduced by replacing wheat and soybeans with either alfalfa or barley. The steepness of the trade-off curve indicates that such mitigation will be costly. For example a switch from the moldboard plowed corn-corn-soybeans-wheat rotation with red clover underseeded to wheat to the same rotation plowed with the chisel plow results in \$304 opportunity cost per ton of CO_2 mitigation. Any other change in the cropping system, which provides a mitigation of emissions, also results in opportunity costs of \$200 to \$1000 per Mg of abated CO_2 eq GHGs.

4. Conclusions

In Eastern Canada, management practices associated with crops in a rotation had a significant effect on GHG emissions. Difference in GHG emissions between moldboard and chisel plow systems were minimal in comparison to rotation effects. The integration of legumes into corn based cropping systems provides multiple benefits, including higher yields, cost savings, carbon sequestration,and the mitigation of GHGs. Diversifying a corn rotation with soybeans and wheat underseeded with red clover results in \$100 ha^{-1} higher net returns and a mitigation of more than 1000 kg CO_2 eq ha^{-1}GHG compared to continuous corn. Even though legumes contribute considerably to the emissions of GHG by fixing nitrogen in the soil, these emissions are offset by reduced emissions from less fertilizer use and the reduced induced emissions from manufacturing the fertilizer. This cropping practice seems to be a win-win situation since it provides benefits for the farmer and the environment. However, a further mitigation of GHGs requires significant opportunity costs to the farmer and questions on farm mitigation efforts beyond the ones which are economically superior.

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Figures

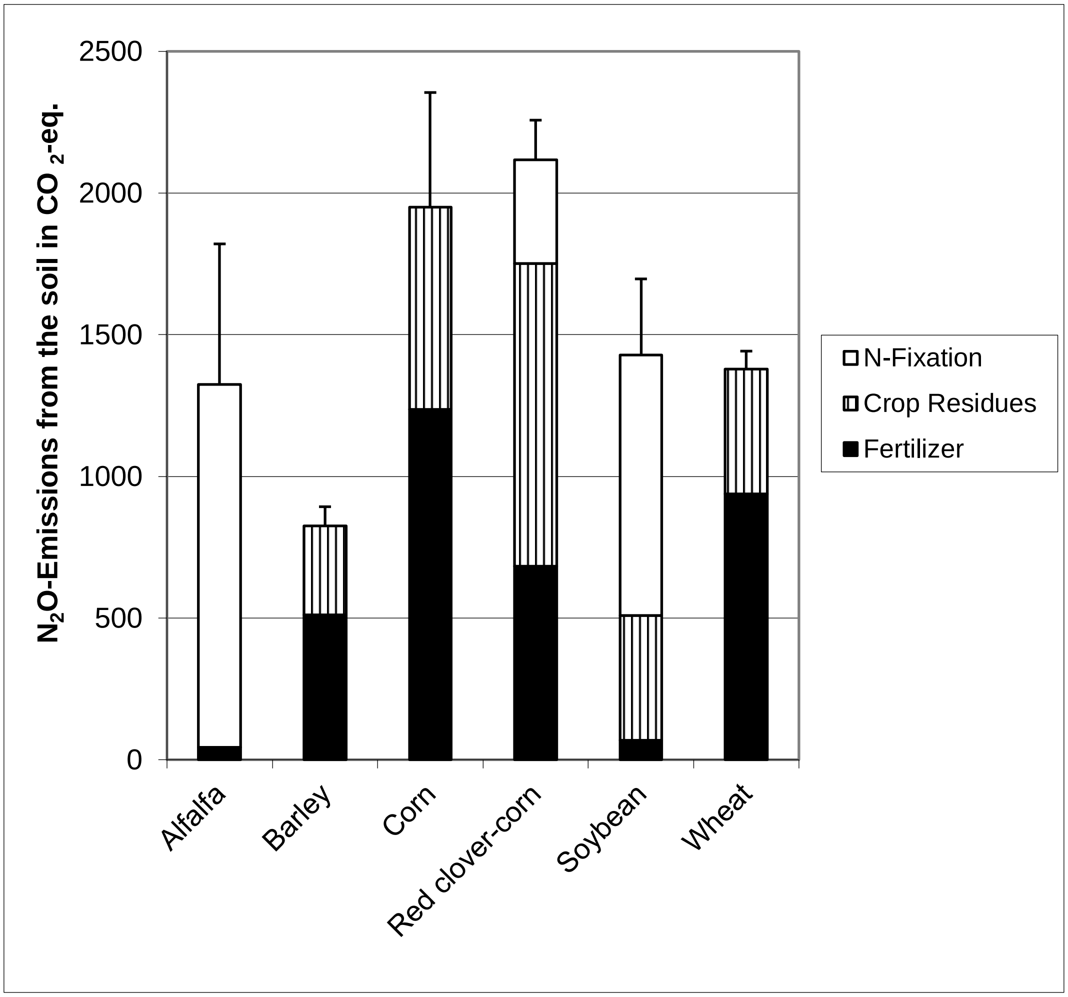

Fig. 1. Estimated 20 years average N_2O emissions (direct and indirect) of the crops over all treatments from nitrous fertilizer, crop residues and nitrogen fixation according to IPCC accounting methodology

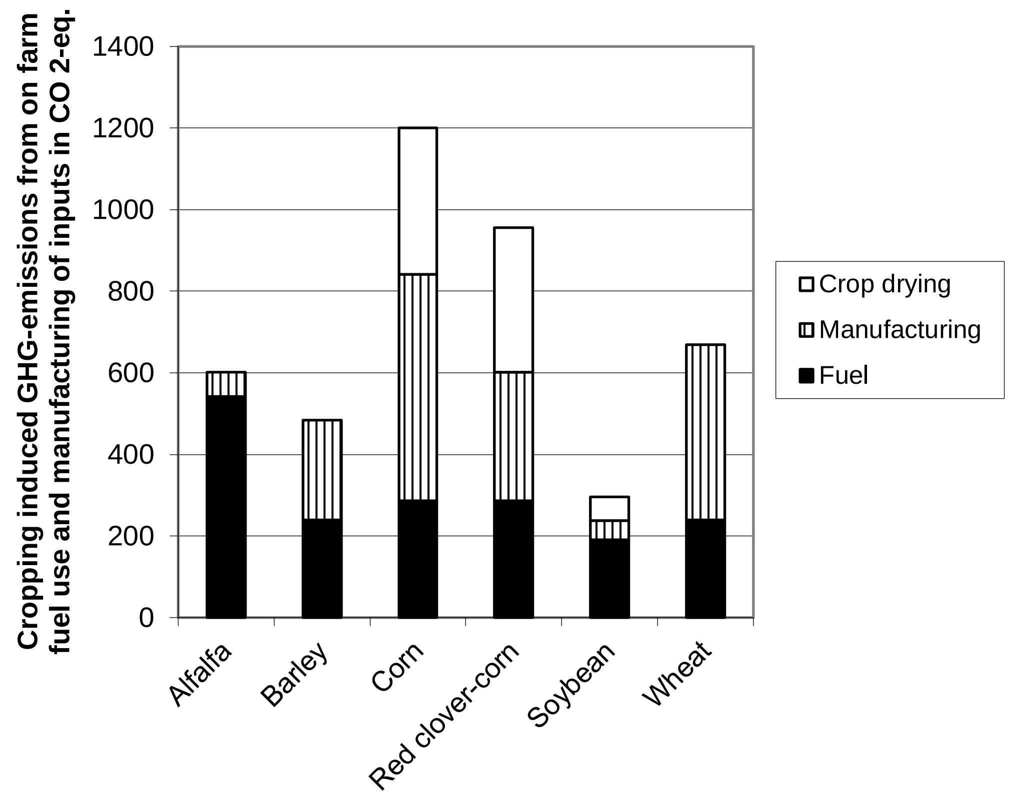

Fig.2. Induced GHG emissions by fuel use and manufacturing of the inputs

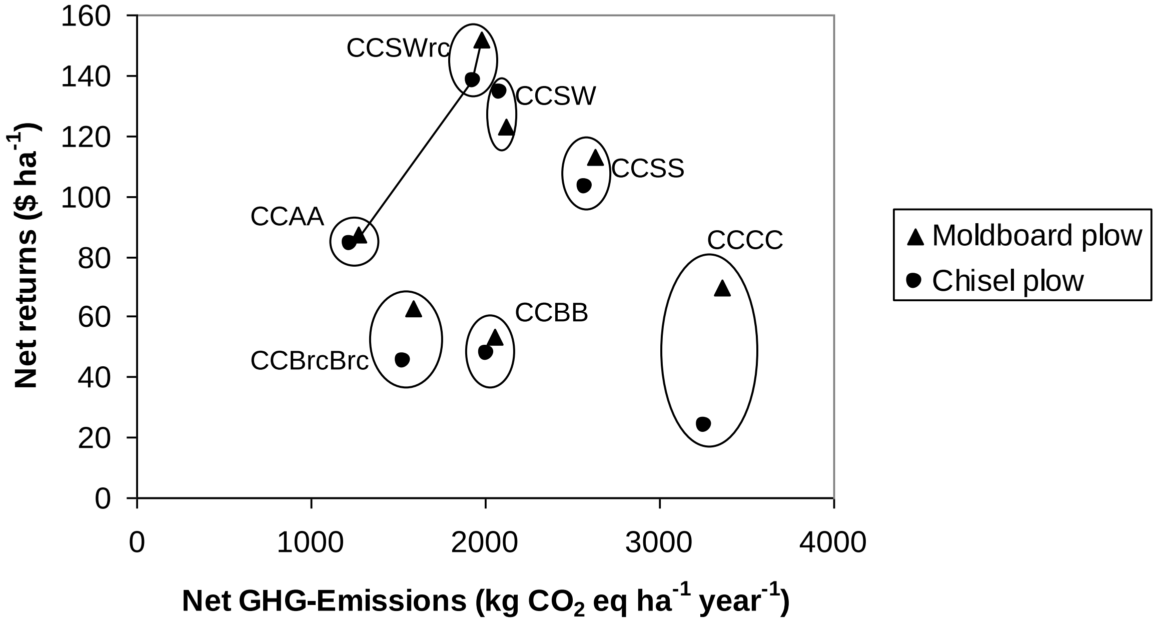

Fig 3. Trade off of GHG emissions versus net return to the farmer

Table 1. Crop rotations analyzed in this study and N input

Rotation	Rotation code	N-Input	N-Credit [a]	Accounted N-Input
		--kg ha^{-1} over four years --		
Corn-corn-corn-corn	CCCC	640	0	640
Corn-corn-barley-barley	CCBB	440	10	430
Corn-corn-barley with red clover-barley with red clover	CCBrcBrc	440	70+10	360
Corn-corn-soybeans-soybeans	CCSS	336	50	286
Corn-corn-soybeans-winter wheat	CCSW	438	10	428
Corn-corn-soybeans-winter wheat with red clover	CCSWrc	438	70+10	358
Corn-corn-alfalfa-alfalfa	CCAA	330	110	220

[a] N-credits for corn according to Janovicek and Stewart, 2004

Table 2. Estimated Emissions Coefficients for farm inputs

Input Type	Unit	CO_2	CH_4	N_2O	Source
Fertilizer Manufacturing	g per kg of fertilizer	1,510	0.001	0.015	Kulshreshtha and MacDonald (2000)
Fuel	g per liter	2,730	0.13	0.10	Matin et al. (2004)
Fuel Manufacturing	g per liter of Diesel	335	651	1.61	Kulshreshtha and MacDonald (2000)
Machinery	g per $ of repairs	428	0.010	0.028	
Fuel use for crop drying	g per liter	1,770	0.311	0.015	

Table 3. Cost structure of corn, soybeans, wheat, barley and alfalfa production in the different tillage systems

	Production costs									
	Corn		Soybeans		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[a]	187		39		28		22		-	
Fuel and lubricants	31	27	20	16	26	21	26	21	56	54
Variable machine costs and Overhead expenses[b]	264	262	210	208	249	248	236	235	279	278
Sum	972	966	551	545	660	654	619	613	593	589

[a] Drying and trucking costs assuming average yield for each crop (corn: 8.5 Mg ha^{-1}, soybeans: 2.7 Mg ha^{-1}, wheat: 5.1 Mg ha^{-1}, barley: 3.7 Mg ha^{-1}, alfalfa: 7 Mg ha^{-1})

[b] Including costs on interest on operating capital, rent, marketing fees, storage and labour costs

Table 4. Carbon content on plots with different rotations based on equivalent mass of 4800 Mg ha^{-1} (the average depth for this mass is 34 cm)

Rotation[a]	Total C	Difference from CCCC	Sequestered carbon per year
	--Mg C ha^{-1}--		Mg C ha^{-1} yr^{-1}
CCCC	77.7bc		
CCBB	79.2bc	1.4	0.071
CCBrcBrc	81.6bc	3.9	0.193
CCSS	76.3c	-1.5	- 0.073
CCSW	80.4bc	2.6	0.130
CCSWrc	81.1bc	3.4	0.169
CCAA	83.5ab	5.8	0.289
AAAA	88.0a	10.3	0.513
SE	2.55		
LSD (p=0.05)	6.0		

[a] Rotation code is given in Table

Table 5. Average annual emissions from different crop rotations in moldboard plow (MP) and chisel plow (CP) tillage systems.

	CCCC [a]		CCBB		CCBrcBrc		CCSS		CCSW		CCSWrc		CCAA		AAAA
	MP	CP	MP	CP	MP	CP	MP	CP	MP	CP	MP	CP	MP	CP	MP
							----kg CO_2 eq ha^{-1} $year^{-1}$ ----								
N_2O emissions from the soil															
Crop Residues	718	677	517	508	618	608	564	553	573	576	681	673	368	367	0
Fertilizer	1364	1364	916	916	767	767	610	610	912	912	763	763	469	469	21
N-Fixation	0	0	0	0	91	91	441	437	232	241	333	340	647	634	1358
Sum	2082	2041	1433	1424	1476	1466	1615	1600	1717	1729	1777	1776	1484	1470	1379
Emissions from direct and indirect energy use															
Crop Drying	361	341	180	180	182	182	206	201	192	191	199	193	185	185	0
Fuel use	131	114	121	104	121	104	111	94	116	99	116	99	183	171	199
Fuel manufacturing	175	153	162	140	162	140	148	126	155	133	155	133	246	229	266
Machine manufacturing	18	18	20	20	20	20	18	18	19	19	19	19	30	30	35
Fertilizer manufacturing	592	592	398	398	333	333	265	265	396	396	331	331	204	204	9
Sum	1277	1218	881	842	818	779	748	704	878	838	820	775	848	819	509
GHG Mitigation from C-Sequestration	0	0	260	260	708	708	-268	-268	477	477	620	620	1060	0	0
Net GHG emission mitigation from all sources	3359	3259	2054	2006	1586	1537	2631	2572	2118	2090	1977	1931	1272	3359	3259

[a] Rotation code is given in Table 1