Life Cycle Assessment of the Potential Carbon Credit from No- and Reduced-Tillage Winter Wheat in the U.S. Pacific Northwest

U. Zaher*, C. Stöckle*, K. Painter** and S. Higgins*

*Department of Biological Systems Engineering, Washington State University, P.O.Box 646120, Pullman, WA 99164-6120, USA, Fax: (509)335-2722, Tel: (509) 335-1578, zaheru@wsu.edu; stockle@wsu.edu

**Department of Agricultural Economics and Rural Sociology, University of Idaho, P.O.Box 442334, Moscow, ID 83844-2334, Fax: (208)885-5759 Tel: (208) 885-6041, kpainter@uidaho.edu

Abstract

Decisions about reducing agricultural land tillage to offset global warming potential (GWP) are based on the evaluation of the agricultural eco-system and the profitability to local farms. Carbon sequestration and nitrous oxide emissions from winter wheat (WW) cropping were evaluated by modeling typical dryland cropping systems in eastern Washington. Variations in rainfall, tillage intensity and crop rotation were considered. System boundaries were expanded to consider fertilizer production and use of machinery in a standard life cycle assessment (LCA) study. GWP was evaluated both for WW crop alone and also for the entire crop rotation. Potential earnings from carbon credits obtained by converting to reduced and no-till scenarios were evaluated and compared with conventional tillage farm budgets. Assuming equivalent yields across tillage regimes, tillage reduction is economically feasible in high rainfall zones. In lower rainfall zones, reduced tillage systems are less profitable than the conventional tillage systems, assuming equivalent yields. In addition, less carbon sequestration occurs when tillage is reduced in this region, which reduces potential earnings from carbon credits.

Key words: carbon credit, crop systems modeling, green house gases, life cycle assessment, no-till

Introduction

Climate change concerns are motivating interest in incentive-based agricultural practices that help reduce greenhouse gas (GHG) emissions. The United Nations Framework Convention on Climate Change and the Kyoto Protocol (UNFCCC, 2008) has framed agreements and protocols to reduce GHG emissions. The protocols utilize market-based mechanisms such as emission trading aimed at creating a carbon market where emissions/reductions can be exchanged. The US-EPA is applying cap-and-trade programs (Paltsev et al., 2007) on industrial emissions. So far, the capped emissions are focused on the power sector, which creates potential opportunities to lower emissions in other sectors such as agriculture, providing incentives for reductions that can be traded as carbon credits. Agriculture is the second global source of GHG emissions after the power sector (Minamikawa et al., 2009). It is also the largest land use category worldwide (Dutaur and Verchot, 2007). Because agriculture is the second leading emitter and leading land-use, and because agricultural emissions are not capped, it can be argued that agriculture should be a target for incentive-based emissions reductions.

Reduced-till (RT) or no-till (NT) agricultural practices reduce disturbance to top soil layers and reduce oxidation of soil organic carbon (SOC). RT and NT may therefore increase SOC storage compared to conventional-till (CT) (West and Post, 2002; Chatskikh and Olesen, 2007; Sainju et al., 2008). Some researchers found that NT and RT decreased nitrification and denitrification rates, which reduced N_2O emissions (Chatskikh and Olesen, 2007; Kroeze et al., 1999), while others found higher N_2O emissions during the first NT years followed by a decrease due to soil aggregation (Six et al., 2004). Alluvione et al. (2009) found that methane (CH_4) emissions tended to increase due to less CH_4 oxidation capacity of the soil under NT and RT compared to CT. However, other authors state that there is no significant difference in CH_4 fluxes of CT compared to NT and RT (Jacinthe and Lal, 2005; Mosier et al., 2006; Omonode et al., 2007). In fact, GHG emissions are not dependent on tillage only. Different factors interact and lead to different findings. For instance, Omonode et al. (2007) investigated different tillage scenarios and reported that CO_2 emissions were mainly dependent on crop rotation. It is difficult to determine the outcome of converting to RT and NT with certainty from field measurements only. Crop system models analyze interacting mechanisms giving reliable predictions of emissions from different land operations (Hammer et al., 2002).

Agriculture uses external resources with associated emissions such as fuel, fertilizers, and pesticides that also emit GHG. To fully evaluate GHG emissions associated with agriculture, a more comprehensive view of environmental impacts should also consider emissions from fuel consumption by equipment used for transportation and land operations (Koga et al., 2003; Mileusnic et al., 2009) and from production of fertilizers (Das and Kandpal, 1998). Although GHG emissions from other factors such as fuel used for machinery operations and production of fertilizers and equipment are relatively small, these factors make up significant portions of the standard costs within an enterprise budget and thus influence decisions to change tillage operations to RT or NT. A complete view of emission analyses should consider the economics of all factors.

Life Cycle Assessment (LCA) is an integrated approach to expand the field evaluation of emissions to broader boundaries that include external resources used in agricultural production. Finnveden et al. (2009) define LCA as a tool to assess the environmental impacts and resources used throughout a product's life cycle. LCA can also be extended beyond the evaluation of GHG emissions and Global Warming Potential (GWP). LCA is also used to evaluate the impacts of pesticides (Margni et al., 2002) on human health and ecosystems, and to compare fertilizer choices for cropping major commodities such as wheat (Charles et al., 2006).

In this paper, an LCA-based methodology was developed to evaluate potential carbon credits resulting from the utilization of NT and RT for winter wheat (WW) in selected locations in the dryland region of eastern Washington, and for selected WW-based rotations. Carbon sequestration and GHG emissions were evaluated using results from a simulation study reported by Stöckle et al. (2010, elsewhere in this report). The systems' boundaries were expanded to consider emissions from fuel consumption and fertilizer production. The market value of RT and NT was evaluated by considering budgets for the selected cropping systems (Painter, 2009) and associated carbon credits per unit mass of winter wheat dry grain (Mg WW_{dg}) and per unit area (ac) that is used in Chicago carbon exchange market (CCX).

Methodology

The methodology was developed and applied considering techno-, eco- and value-spheres as presented in Figure 25.1. This scheme expands LCA to consider market values and decision makers' perspectives (Hofstetter et al., 2000). Since this study is focused on the NT value in the carbon market, analysis in the value-sphere was focused on the carbon credit comparing NT, RT and CT scenarios as applied to dryland WW production in Washington, USA. In the techno-sphere, the cropping systems model, CropSyst (Stöckle et al., 1994; Stöckle et al., 2003), simulated WW-based systems in three zones with different precipitation: Pullman 460mm – 550mm (>18") , St John 380mm – 460mm (15"-18") and, Lind < 380mm (<15"). The LCA expanded the assessment to the ecosphere considering the emissions from equipment use and fertilizer production in addition to the GHG fluxes from the WW fields. The standard LCA steps start with the goal and scope definition (Guinee, 2002). The goal of the LCA was to evaluate the impact on climate change from switching from CT to RT or NT. The LCA was scoped to evaluate the GWP (Mg CO_2e) from GHG emissions and to evaluate the corresponding carbon credit of switching to RT and NT using two functional units. The first functional unit was GWP in Mg CO_2e Mg WW_{dg}^{-1} with allocation of emissions only to winter wheat grain production. The second functional unit was GWP in Mg CO_2e ac^{-1} y^{-1} considering WW-based crop rotations to compare with carbon credits and traded offsets in the CCX. Thus, the functional units linked the techno- and eco-sphere results with the carbon credit analysis in the value-sphere. The analysis in each sphere is described in more detail in the following sections.

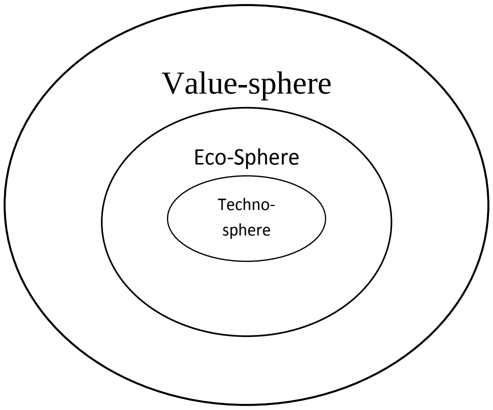

Figure 25.1: Life cycle evaluation domains

Simulated Scenarios

CropSyst, a comprehensive, process-oriented, multi-year and multi-crop simulation model, was used to evaluate emissions in the techno-sphere. Table 25.1 lists the simulated scenarios and the allocated LCA scenarios. Details on the use of the model, scenarios, and resulting SOC storage changes and N_2O emissions as a function of tillage intensity are given in Stöckle et al. (this report). Prior to running the scenarios, SOC was brought into equilibrium (i.e. initialized) by simulating 1000 years of the CT conditions for each location. In addition to tillage intensity, the enhancement of SOC decomposition due to tillage, a highly uncertain process poorly documented in the literature, was assessed by providing a lower and higher boundary of SOC oxidation enhancement due to tillage. The seven simulation scenarios were run for the lower oxidation limit and then repeated for the upper oxidation limit.

Table 25.1. Simulation and LCA scenarios

CropSyst simulations					LCA***
No.	Location	Rainfall mm y^{-1} (Zone)	Tillage*	Rotation**	Scenario No.
1	Pullman	460-550 (high)	CT	WW-SB-SW	1,8
2			RT	WW-SB-SW	2,9
3			NT	WW-SB-SW	3,10
4	St John	380-460 (middle)	CT	WW-SB-SF	4,11
5			NT	WW-SB-SF	5,12
6	Lind	<380 (low)	CT	WW-SF	6,13
7			RT	WW-SF	7,14

*CT: conventional tillage; RT: reduced tillage; NT: no tillage

** WW: winter wheat; SB: spring barley; SW: spring wheat; SF: summer fallow

*** Scenarios 1-7 with allocation to WW and 8-14 consider whole rotation

For the different scenarios, CropSyst provided estimations of yields, residue production and fate, SOC storage changes, and N_2O emission resulting from both nitrification and denitrification. The model does not consider methane fluxes. It was assumed that there was no significant difference for methane emissions between CT and NT (Jacinthe and Lal, 2005; Mosier et al., 2006; Omonode et al., 2007) especially considering the low temperatures prevailing most of the year in the area of study.

LCA Inventory

The inventories of the LCA scenarios in Table 25.1 were evaluated from average yearly results of the simulated upper and lower SOC oxidation limits. Two inventories were built for each simulation scenario. The first inventory was for the evaluation of emissions and GWP allocated to WW as the main product (commodity). The sequestered carbon and N_2O emissions were allocated to WW years as weighted averages of the simulated rotations. For the sequestered carbon, the weight was based on the ratio of residue production in the year of WW production to the total residue production in all years of the rotation. The weights for the N_2O emissions were based on the ratio of N fertilizer applied for WW to the total applied during the whole rotation. Fuel consumption was evaluated based on equipment use during the WW season. Emmissions from fertilizer production were calculated based on amounts of N, P and S fertilizers applied to WW.

The second inventory calculated the emissions and GWP per unit land area (Mg CO_2e ac^{-1} yr^{-1}) considering the entire rotation cycle. Accordingly, emissions were calculated from the cumulative simulation results dividing the difference between end-point (at year 30) and the initial values by the simulation period (i.e. 30 years). Emissions from fertilizer production were assessed for each rotation. Fuel consumption was evaluated from all equipment used during the rotation and averaged for each year.

Emissions from fertilizer production were evaluated according to IFA (2009). Emissions from fuel consumption were evaluated stoichiometrically from the consumption of diesel assuming 99% conversion effeciency to CO_2 (US EPA, 2005).

LCA Computations

The LCA computational framework by Heijungs and Suh (2002) was implemented in Matlab to automate the LCA computation for the GWP evaluation in the eco-sphere. The required LCA computation was simplified by scoping the LCA to the single impact category of climate change. The simplified computations are presented by equations (1) to (3). The inventory of the cropping system was arranged into two matrices A and B. Rows (i_1) of matrix A presents $n_1=5$ economic flows of wheat, fuel and N, P, S fertilizers. Rows (i_2) of matrix B presents $n_2=4$ environmental interventions of CO_2 and N_2O flows in addition to the yield of biomass residues and land use. The columns of both matrices (j) present the $n_1=5$ production/consumption processes of wheat, fertilizers and fuel. The demand vector f was set to the base of the functional unit, i.e., per Mg WW_{dg} or per ha. Equation (1) determined a scale vector s. Equation (2) determined the vector g of the total interventions. The characterization matrix Q was reduced to one row, i.e. presenting one impact category, estimating the total GWP. Characterization was only needed for N_2O and was taken as 298 kg CO_2e/kg N_2O (IPCC, 2007).

$$s = A^{-1} f \tag{1}$$

$$g = Bs \tag{2}$$

$$GWP = Qg \tag{3}$$

Contribution analyses were performed by the elemental operations in Equation (4) to determine the contribution of each process and intervention to the GWP.

$$GWP_{i_2,j} = Q_{i_2}.B_{i_2,j}.s_j \qquad i_2 = 1:n_2;\ \ j = 1, n_1 \tag{4}$$

Carbon Credit Economics

Currently traded carbon credits do not account for reduced fuel use or other emission reductions (CCX, 2009). The CCX project boundary is the physical boundary of the farm field. Therefore, when carbon credits are calculated from the output of the LCA analysis, they will be specified according to their respective life cycle domain (Fig. 25.1) as eco-sphere carbon credits or value-sphere carbon credits. Value-sphere carbon credits for the NT and RT scenarios were calculated according to Equation (5) based on reduced emissions relative to CT Mg CO_2e. The carbon credit value was assumed to be $6 per Mg CO_2e based on the CCX 2009 average market value. This price was reduced by 10% to account for auditing fees. Profit from carbon credits was compared with the returns to risk obtained from the detailed budget for each scenario (Painter, 2009).

$$CC_{value-sphere} = CC_{market-price}(1-f).(E_{total,CT} - E_{total,NT}) \quad (5)$$

Where:

$CC_{value-sphere}$: the US $ value of the reduced emmission considering emmission sources in the LCA system boundary

$CC_{market-price}$: the market price of Mg CO_2e

f: ratio of the auditing fee to the carbon credit

$E_{total,CT/RT/NT}$: total emissions in Mg CO_2e within the LCA system boundary of conventional, reduced or no-till operations

Results

Techno-sphere Emissions

Simulated sequestered carbon and cumulative N_2O emissions are presented in Figure 25.2. Results are shown for seven simulation scenarios applying the lower SOC oxidation limit in CT. Thus, differences in sequestered carbon between CT and other scenarios represent the minimum estimated for converting to RT or NT. Carbon sequestration under CT shows little change over the 30 year simulation time and extends steadily from the 1000 year initialization. In general, the NT carbon sequestration was higher than RT and CT. The amount of sequestered soil carbon started to level off for the highest rainfall zone by the end of the simulation period at year 30. Starting the simulation from the stabilized content for CT at 40.9 Mg C ac^{-1}, the NT began to level off at 42.5 Mg C ac^{-1} storing 1.6 Mg C ac^{-1} in 30 years. In the intermediate rainfall zone, the sequestered carbon did not level off by the end of the simulation and the stored carbon in 30 years was about 0.8 Mg C ac^{-1}. The initial state of soil carbon for this middle rainfall zone was less than half that for the high rainfall zone. As shown from the sawtooth pattern, the sequestered carbon dropped during the fallow years and was higher during the years of crop production. For the low rainfall zone only RT is typically used by farmers, and the simulation showed 0.6 Mg C ac^{-1} stored within the simulated period of 30 years. The cumulative N_2O results were linearly increasing in all tillage, rainfall and rotation scenarios. Results are presented by cumulative emissions less initial state to show the slight emission differences with tillage. Simulations of N_2O emissions for CT were higher in the high rainfall zone compared to NT and RT but relative emissions decreased as rainfall declined.

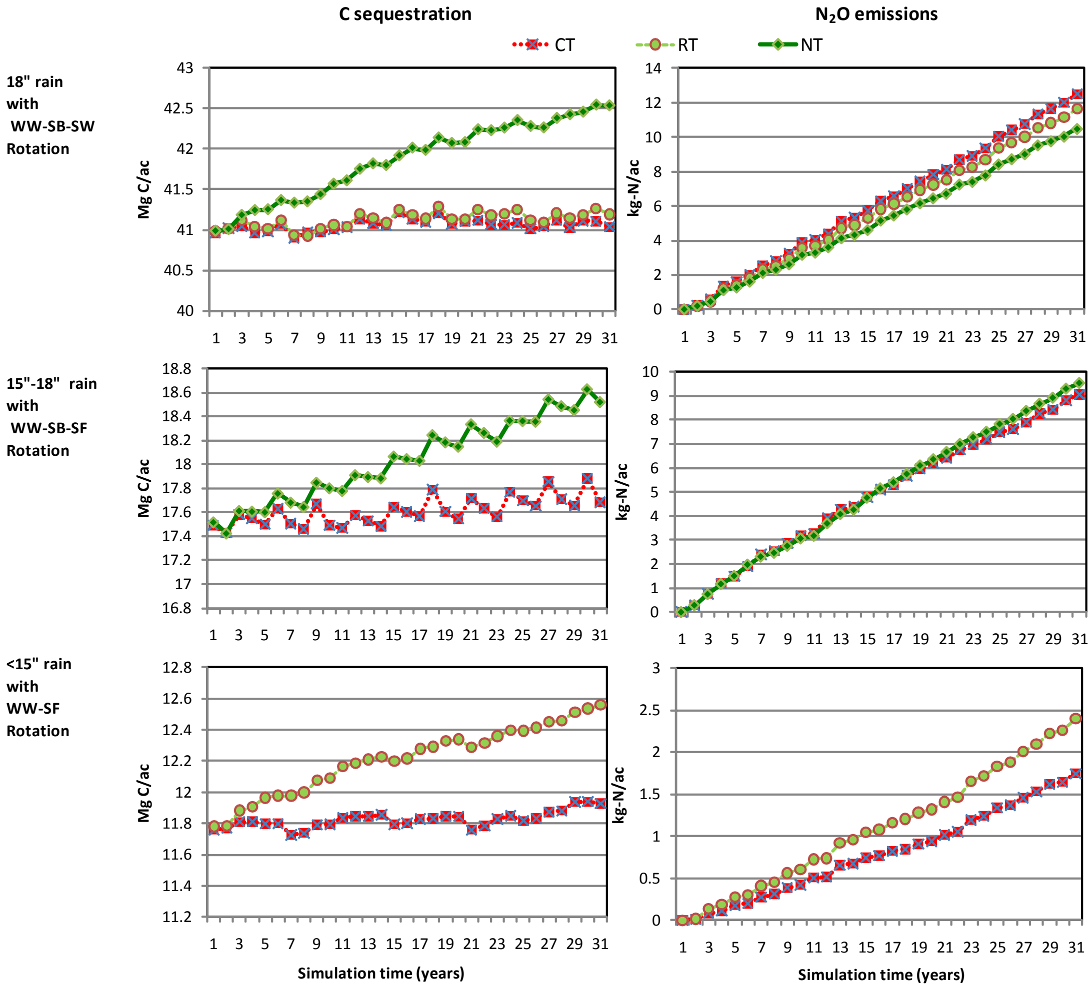

Figure 25.2. Sequestered carbon and cumulative N_2O emissions from different tillage operations, rainfall zones and crop rotations

Eco-sphere Total Emissions

Figure 25.3 shows emission results in LCA scenarios 1-7 with GWP allocated to WW grain. The GWP (Mg CO_2e/Mg WW_{dg}) decreased with RT and NT in all rainfall zones. Sequestered carbon provided the main offset to total emissions and increased with tillage reduction. The amount of sequestered carbon allocated to WW increased with lower precipitation (Fig. 25.3) because in the rotations at lower precipitation, more of the residue produced was produced by winter wheat. But C sequestration per unit area of land decreased with lower precipitation (see Figure 25.4). The allocated N_2O emissions decreased in the lower rainfall areas as less N fertilizers were used. Emissions from fertilizer production were nearly similar in all scenarios, indicating that the amount of N, P, and S added were relative to expected WW yields. Emissions from fuel consumption were slightly decreased with tillage reduction due to fewer field operations. Field operations for WW were relatively higher in middle and low rainfall zones.

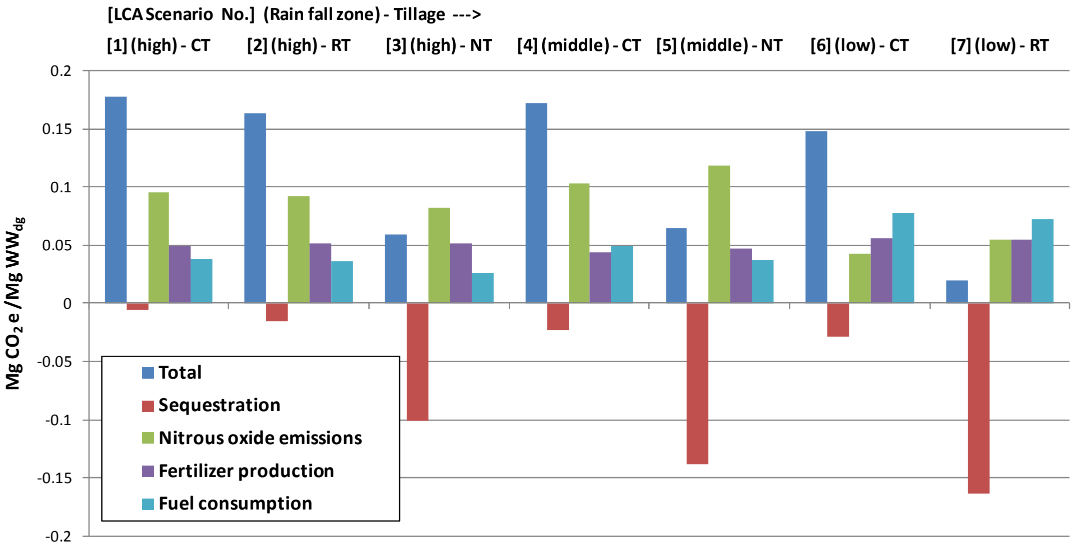

Figure 25.3. GWP allocated to WW (Mg CO_2e/Mg WW_{dg}) for different tillage operations and rainfall zones

Figure 25.4 shows the GWP ac^{-1} yr^{-1} considering all crop rotations and operations. Results in Figure 25.4 confirm that emission reduction by RT and NT is mainly due to sequestered carbon. Relatively less carbon is sequestered by NT and RT with lower precipitation because of the effect of rotation intensity (lower residue inputs) and C losses in the fallow years. Although fewer inputs such as fertilizer and fewer machinery operations are used, the decline in C sequestration in lower rainfall zones overwhelms these small reductions.

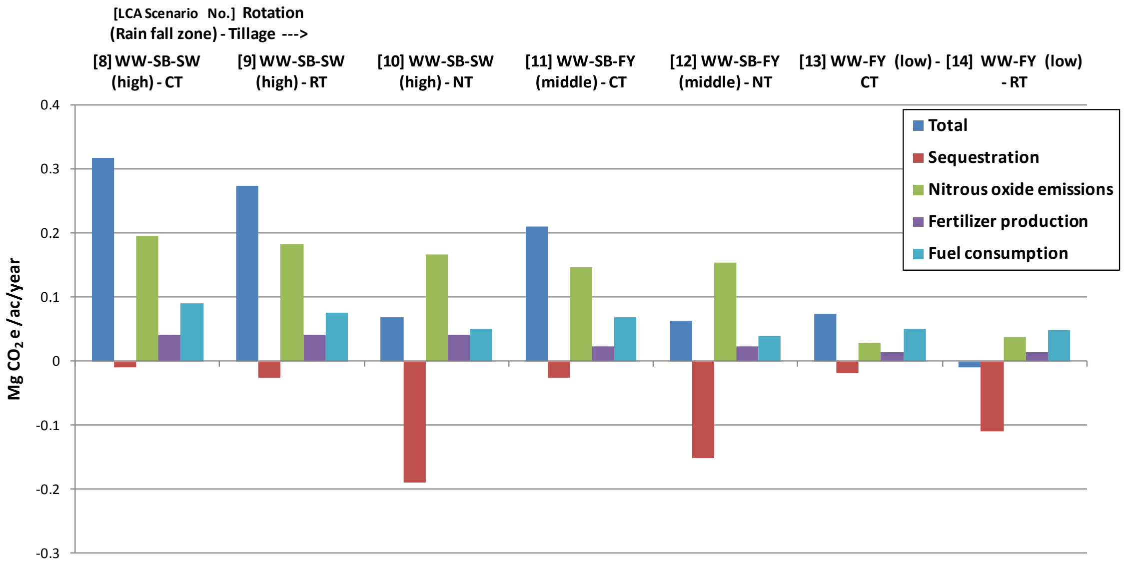

Figure 25.4. GWP per acre per year for different crop rotations, tillage and rainfall zones

Value-sphere Carbon Credit

Figure 25.5 shows the value of value-sphere carbon credit allocated to WW by converting to RT and NT, and the savings/extra cost of reducing tillage. All NT and RT achieve value-sphere carbon credit (based on \$5.40 /Mg CO_2e) of about 0.6-0.7 \$/Mg WW_{dg} with the exception of RT in the high rainfall zone, which is about 0.07 \$/Mg WW_{dg}. In the high rainfall zone, the value-sphere carbon credit represents additional profit, as the RT and NT systems are more profitable than CT. The WW value-sphere carbon credit for NT and RT in middle and low rainfall areas is far from breakeven as reduced tillage systems are less profitable than CT under the assumption of equivalent yields.

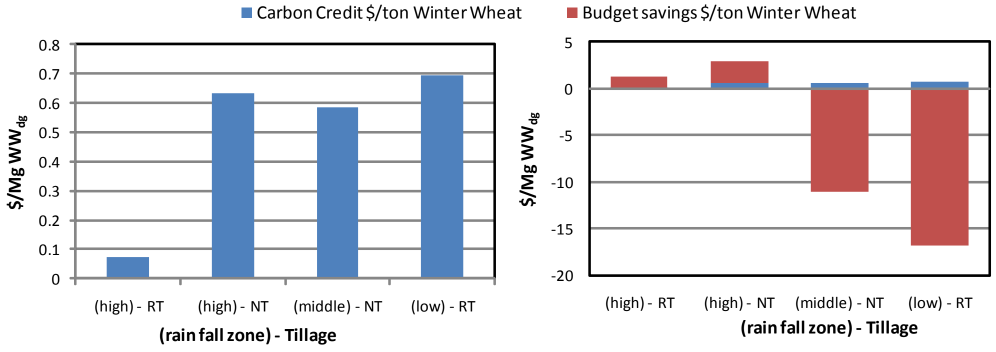

Figure 25.5. WW carbon credit from tillage reduction and comparison with whole operations budgets.

These results were confirmed by evaluating the value-sphere carbon credit per unit area of land (\$ ac^{-1} yr^{-1}) over the entire rotation cycle in Figure 25.6. On a per unit area basis, however, the effect of the fallow year significantly reduced the value-sphere carbon credit in middle and low precipitation zones.

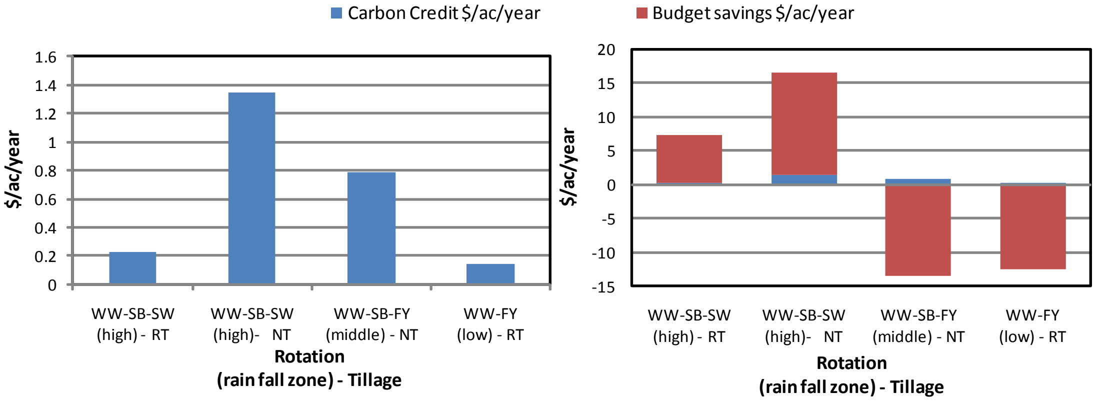

Figure 25.6. Carbon credit per acre from tillage reduction and comparison with whole operations budgets.

Discussion

Converting from CT to NT reduces GHG emissions and GWP in all studied locations of WW production in the dryland region of eastern Washington. The simulation and LCA results indicated that carbon sequestration is the main contributing mechanism to achieve these emission reductions. From the simulations in Figure 25.2, soil carbon sequestration results were 54, 27, 20 kg-C ac^{-1} yr^{-1} in high, middle and low rainfall zones, respectively. An increase in rainfall intensity increases crop yield and carbon sequestration due to the increased portion of the biomass recycled to the soil. Thomson et al. (2002) showed that WW yield in this region increases proportionally to the rainfall. In addition to rainfall, many other factors interact non-linearly and influence emissions by the cropping system. The contributions of on- and off-farm GHG sources to GWP varied among the analyzed scenarios. On-farm N_2O emissions contributed 60-70% of the GWP ac^{-1} yr^{-1} in high and middle rainfall scenarios and 30-40% in low rainfall scenarios. The remaining contributions to GWP were mainly due to off-farm emissions from fertilizer production and emissions from fuel consumption and equipment use. Therefore, it is necessary to expand the system boundary and account for emissions using the broader concept of LCA to compare GWP from different cropping scenarios.

Evaluating LCA scenarios using two different functional units leads to a better understanding of the interacting factors and sources of emissions. Although the use of additional functional units increases the LCA iterative computations, these computations are necessary to analyze the nonlinear cropping system and to avoid any interpretation errors due to the linearity assumption of LCA methodology (ISO, 2006[a,b]). Using per unit land area and per Mg of dry grain represent complementary analyses with respect to the multifunctional role of agricultural activity (Charles et al., 2006).

The allocation of emissions to the WW dry grain yield as the main product using the functional unit of Mg CO_2e/Mg WW_{dg} assists in the analyses of emissions (Figure 25.3) by rainfall, fertilizer application and use of agriculture machinery in different locations. In the high rainfall zone, sequestered carbon in NT reduced emissions by 0.095 Mg CO_2e/Mg WW_{dg}. The corresponding reduction in total emissions (the difference in total emissions between CT and NT) was 0.118 Mg CO_2e/Mg WW_{dg}. This difference is higher even than C-sequestration because N_2O emissions and use of equipment are both lower in the high rainfall zone NT compared to CT. Although sequestration in the intermediate rainfall NT and low rainfall RT contributed more to emission reductions (0.114 and 0.134 Mg CO_2e/Mg WW_{dg}, respectively), total emissions offset these reductions due to more N_2O emissions compared to CT. The corresponding reductions in total emissions were 0.108 and 0.129 Mg CO_2e/Mg WW_{dg} respectively, for the intermediate rainfall NT and low rainfall RT compared with CT emissions.

Using the LCA results presented here for the average yearly emission from the whole crop rotation per unit area as the functional unit would allow a fully-disclosed determination of the GWP offsets and the corresponding carbon-market credit for converting to NT. But, "At this time CCX does not allow for the crediting of reduced fuel use or other emission reductions that may be occurring . . .," (CCX, 2009). The CCX project boundary is specifically defined as the physical boundary of the farm field. The LCA approach provides a more complete picture of GWP than is provided by SOC sequestration alone. As shown in Figure 25.4, the increased frequency of fallow years decreases carbon sequestration. However, total emissions are reduced due to reduced use of fertilizer and equipment in the whole rotation. Converting to NT in the high and intermediate rainfall zones and to RT in low rainfall zone achieved CO_2e savings of 0.249, 0.146 and 0.083 Mg CO_2e ac^{-1} yr^{-1}. These estimated values, based in part on soil carbon storage to a depth of 30 cm, are below the U.S. average SOC sequestration rates of 0.545 Mg CO_2e ac^{-1} yr^{-1} (West and Marl, 2002), and they are below values from a global analysis of SOC sequestration rates by West and Post (2002). Part of the reason our CO_2e savings are below those just cited is that LCA considers a wider range of the carbon costs/benefits of farming than just SOC. Additional considerations exist. West and Post (2002) give average sequestration rates of 0.47 Mg CO_2e ac^{-1} yr^{-1} for all wheat systems, 0.37 Mg CO_2e ac^{-1} yr^{-1} for continuous wheat systems, and 0.03 Mg CO_2e ac^{-1} yr^{-1} for wheat-fallow systems. However, most of the data they compiled are from shallow soil layers, so the data are likely biased in favor of NT systems as discussed by Stöckle et al. (this report). CropSyst estimations based only on the top 15 cm of soil give values of 0.33 (lower oxidation boundary) and 0.38 (higher oxidation boundary) Mg CO_2e ac^{-1} yr^{-1}, in reasonable agreement with West and Post (2002).

In all LCA scenarios, emission of N_2O was the second most important mechanism influencing GWP from agriculture land after carbon sequestration. Simulations did not show substantial differences between CT and NT. Literature reports are mixed concerning NT compared to CT N_2O emissions. Other simulation studies are contradictory regarding the long-term effect of NT management on N_2O emissions.

Del Grosso et al. (2002) predicted a gradual increase in N_2O because of the increase in soil N with continuous NT while Six et al. (2004) predicted that N_2O emissions would initially increase and then decrease gradually due to soil aggregation and improved aeration in NT soils. Halvorson et al. (2008) compared measurements of GHG emissions from NT and CT cropping systems and concluded that crop rotation and N fertilizer application rate had a larger effect than tillage system on N_2O emissions.

Under the LCA analysis, the potential NT CO_2e would represent additional profit (if they could be traded) in the high rainfall zone where NT also improves soil conservation and reduces the use of machinery. In middle and low rainfall zones, NT requires additional costs compared to CT. The additional costs far outweigh simulated or currently designated CO_2e savings. These costs are mainly due to the expense of the chemical treatment required to fight weeds and pests that spread during the fallow years. CT systems use less costly mechanical tillage. Interestingly, RT and NT adoption is lower in the high rainfall zone than in the intermediate rainfall zone, where considerable adoption is underway. We postulate that the assumption of equivalent yields is to blame for these counter-intuitive results. In the intermediate rainfall zone, where moisture is limiting, spring grain yields often respond well to increased seed zone moisture. In the higher rainfall zone, growers worry that colder, wetter soils will lower yields. In addition, farming is more profitable in this higher rainfall zone, so farmers have less incentive to change.

Conclusions

A complete, LCA-based view of the CO_2e savings from tillage reduction expands the evaluation of emissions on the larger ecological scale, and expands the economic analyses on the scale of local farm budgets. Crop system models estimate the emissions from agricultural lands providing insight to major changes that accompany tillage reduction.

Eco-sphere emissions due to fertilizer production and equipment use comprise 30-70% of the cropping system emissions. Therefore, it is necessary to use the Life Cycle Assessment (LCA) methods to expand the cropping system boundaries to evaluate emissions associated with agricultural inputs in addition to direct land emissions. Standard implementation of LCA assumes linearity of the systems under study, which is not the case in cropping systems. Several LCA iterations and scenarios should be considered for the interpretation of emissions from nonlinear systems. Analyzing the emissions from winter wheat cropping was successful by considering different locations and operations of the cropping systems, and by assuming allocations and functional units for different emissions.

Allocation to WW using a functional unit per Mg of dry grain revealed that carbon sequestration in RT and NT was the main emission reduction mechanism. Allocation to the whole rotation showed the impact of tillage reduction and fallow years on the potential earnings from CO_2e savings. Tillage reduction was economically feasible in high rainfall zones, assuming that yields are unchanged. In lower rainfall zones, reduced tillage is less profitable than CT, assuming equal yields, even with potential earnings from value-sphere carbon credits, based on 2009 carbon credit levels of $6 per Mg CO_2e. Profit-maximizing NT farmers in these lower rainfall regions may make up cost differences with yield gains. NT farmers across the entire region may be placing values on environmental and longer-term economic benefits from reduced soil erosion and improvements in soil quality.

Acknowledgements

This research was supported in part by a grant from the Paul G. Allen Family Foundation.

References

Alluvione, F., Halvorson, A.D., Del Grosso, S.J., 2009. Nitrogen, tillage, and crop rotation effects on carbon dioxide and methane fluxes from irrigated cropping systems. Journal of Environmental Quality, 38(5), 2023-2033.

CCX, 2009. Offset project protocol: agricultural best management practices – continuous conservation tillage and conversion to grassland soil carbon sequestration, Chicago Climate Exchange, Inc., Chicago, USA.

Charles, R., Jolliet, O., Gaillard, G., Pellet, D., 2006. Environmental analysis of intensity level in wheat crop production using life cycle assessment. Agriculture, Ecosystems & Environment, 113(1-4), 216- 225.

Chatskikh, D., Olesen, J.E., 2007. Soil tillage enhanced CO2 and N2O emissions from loamy sand soil under spring barley. Soil and Tillage Research, 97(1), 5-18.

Das, A., Kandpal, T.C., 1998. Indian fertilizer industry: assessment of potential energy demand and emissions. International Journal of Energy Research, 22(5), 383-397.

Del Grosso, S.J., D.S. Ojima, W.J. Parton, and A.R. Mosier. 2002. Simulated effects of tillage and timing of N fertilizer application on net greenhouse gas fluxes and N losses from agricultural soils in the Midwestern USA. p. 23–29. In Van Ham, Baede, Guicherit, and Williams-Jacobse (ed.) Non-CO2 Greenhouse Gases; Proc. NCGG 3. Maastricht, the Netherlands, 21–23 Jan. 2002. Millpress, Rotterdam. ISBN 90-77017-70-4.

Dutaur L., and. Verchot L.V., 2007. A global inventory of the soil CH4 sink. Global Biogeochemical Cycles. 21, GB4013, doi:10.1029/2006GB002734.

Finnveden G. et al., 2009. Recent developments in Life Cycle Assessment. Journal of Environmental Management, In Press, Corrected.

Finnveden, G. et al., 2009. Recent developments in Life Cycle Assessment. Journal of Environmental Management, In Press, Corrected.

Follett, R.F., 2001. Soil management concepts and carbon sequestration in cropland soils. Soil and Tillage Research, 61:77–92.

Guinee, J., 2002. Handbook on life cycle assessment operational guide to the ISO standards. The International Journal of Life Cycle Assessment, 7(5), 311-313.

Halvorson, A.D., Del Grosso, S.J., Reule, C.A., 2008. Nitrogen, tillage, and crop rotation effects on nitrous oxide emissions from irrigated cropping systems. Journal of Environmental Quality, 37(4), 1337-1344.

Hammer, G., Kropff, M., Sinclair, T., Porter, J., 2002. Future contributions of crop modelling from heuristics and supporting decision making to understanding geneticregulation and aiding crop improvement. European Journal of Agronomy, 18, 15-31.

Heijungs, R., Suh, S., 2002. The computational structure of life cycle assessment, Kluwer Academic Publishers, ISBN 1-4020-0672-1

Hofstetter, P., Baumgartner, T., Scholz, R., 2000. Modelling the valuesphere and the ecosphere: Integrating the decision makers' perspectives into LCA. The International Journal of Life Cycle Assessment, 5(3), 161-175.

IFA, 2009. International Fertilizer Industry Association - Fertilizers, Climate Change and Enhancing Agricultural Productivity Sustainably, First edition, IFA, Paris, France

IPCC, 2007. Climate Change 2007: the physical science basis. Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change, Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.), Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996 pp.

ISO, 2006[a]. ISO 14040 International Standard. In: Environmental Management –Life Cycle Assessment – Principles and Framework. International Organisation for Standardization, Geneva, Switzerland.

ISO, 2006[b]. ISO 14044 International Standard. In: Environmental Management –Life Cycle Assessment – Requirements and Guidelines. International Organisation for Standardisation, Geneva, Switzerland.

Jacinthe, P.A., and Lal. R., 2005. Labile carbon and methane uptake as affected by tillage intensity in a Mollisol. Soil and Tillage Research, 80:35–45.

Koga, N., Tsuruta, H., Tsuji, H., Nakano, H., 2003. Fuel consumption-derived CO2 emissions under conventional and reduced tillage cropping systems in northern Japan. Agriculture, Ecosystems & Environment, 99(1-3), 213- 219.

Kroeze, C., Mosier A.R., and Bouwman L., 1999. Closing the global N2O budget: A retrospective analysis 1500–1994. Global Biogeochemical Cycles, 13:1–8.

Margni, M., Rossier, D., Crettaz, P., Jolliet, O., 2002. Life cycle impact assessment of pesticides on human health and ecosystems. Agriculture, Ecosystems & Environment, 93(1-3), 379- 392.

Mileusnic, Z.I., Petrovic, D.V., Đevic, M.S., 2009. Comparison of tillage systems according to fuel consumption. Energy, In Press, Corrected.

Minamikawa, K., Yagi, K., Nishimura, S., 2009. Agriculture and Global Warming: Their Interaction and Other Problems of Sustainability. Journal of Developments in Sustainable Agriculture, 4(1), 79-81.

Mosier, A.R., Halvorson, A.D., Reule, C.A., Liu, X.J., 2006. Net global warming potential and greenhouse gas intensity in irrigated cropping systems in northeastern Colorado. Journal of Environmental Quality, 35, 1584-1598.

Omonode, R.A., Vyn, T.J., Smith, D.R., Hegymegi, P., Gál, A., 2007. Soil carbon dioxide and methane fluxes from long-term tillage systems in continuous corn and corn-soybean rotations. Soil and Tillage Research, 95(1-2), 182-195.

Painter K., 2009. Crop Rotation Budgets - Dryland Grain Producing Region of the NW Wheat & Range Region, http://www.uidaho.edu/~kpainter

Paltsev S., Reilly J. M., Jacoby D. H., Gurgel A. C., Metcalf G. E., Sokolov A. P. and Holak J. F., 2007. Assessment of U.S. Cap-and-Trade Proposals- MIT Joint Program on the Science and Policy of Global Change, Report No. 146 http://mi t .edu/globalchange/

Sainju, Jabro, Stevens, 2008. Soil Carbon Dioxide Emission and Carbon Content as Affected by Irrigation, Tillage, Cropping System, and Nitrogen Fertilization. Journal of Environmental Quality, 37(1), 98-106.

Six, J., S.M. Ogle, F.J. Breidt, R.T. Conant, A.R. Mosier, and K. Paustian. 2004. The potential to mitigate global warming with no-tillage management is only realized when practiced in the long term. Global Change Biology, 10:155–160.

Stöckle, C. O., S. Martin and G. S. Campbell. 1994. CropSyst, a cropping systems model: water/nitrogen budgets and crop yield. Agricultural Systems 46:335-359.

Stöckle, C.O., Donatelli, M., Nelson., R. 2003. CropSyst, a cropping systems simulation model. European Journal of Agronomy, 18:289-307.

Stöckle, C., Higgins, S., Kemanian, A., Nelson, R., CropSyst, Huggins, D., Marcos, J., 2010. Simulation of the effect of climate, tillage and rotation on the potential for carbon sequestration and on nitrous oxide emissions in Pacific Northwest agriculture (in preparation)

Thomson, A.M. et al., 2002. Elevation dependence of winter wheat production in easternwashington state with climate change: a methodological study. Climatic Change, 54, 141-164.

UNFCCC, 2008. Kyoto Protocol reference manual, ISBN 92-9219-055-5

US EPA, 2005. Emission facts-average carbon dioxide emissions resulting from gasoline and diesel fuel, Office of Transportation and Air Quality, EPA420-F-05-001.

West, T.O., Marl, G., 2002. A synthesis of carbon sequestration, carbon emissions, and net carbon flux in agriculture: comparing tillage practices in the United States. Agriculture, Ecosystems & Environment, 91(1-3), 217- 232.

West, T.O., Post, W.M., 2002. Soil Organic Carbon Sequestration Rates by Tillage and Crop Rotation: A Global Data Analysis. Soil Science Society of America Journal, 66(6), 1930-1946.