

DAYCENT MODEL ASSESSMENT OF MANAGEMENT ON DECREASING NET GREENHOUSE GAS EMISSIONS FROM AGRICULTURAL SOILS IN THE USA GREAT PLAINS

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ABSTRACT

The DAYCENT ecosystem model was used to compare the effects of crop production management on net greenhouse gas fluxes (GHG_{net}) and crop yields for the dominant agricultural systems in the Great Plains of the USA. Improved management included conversion from intensive tillage to no-till cultivation and reduction of summer fallow periods by replacing winter wheat cropping with alternative rotations that are economically viable for different climate regimes within the Great Plains. N_2O emissions, CH_4 uptake, CO_2 fluxes, and the CO_2 costs of N fertilizer production were converted to a common unit of $\text{CO}_2\text{-C}$ equivalents and summed to obtain GHG_{net} . Under current management, DAYCENT calculates that the dryland agricultural soils in this region are GHG_{net} sources while irrigated alfalfa hay and corn are sinks. Simulations suggest that improved management can convert some cropped dryland soils to C sinks and decrease regional GHG_{net} by a $\sim 12 \text{ Tg CO}_2\text{-C yr}^{-1}$ while maintaining or increasing total crop yields for the agricultural land in the Great Plains.

1.0 INTRODUCTION

Agriculture is a primary source of anthropogenic N_2O and CH_4 emissions (Mosier and Kroeze, 2000; Baruah et al., 2002) and change of crop management has been suggested as a means to sequester CO_2 in soils (Lal et al., 1998). The effects of management change on non- CO_2 greenhouse gas fluxes must be included to appropriately assess the effects of different land management scenarios on net greenhouse gas (GHG_{net}) emissions (Roberson et al., 2000). Models are necessary to account for all the components of GHG_{net} and to estimate greenhouse gas fluxes on regional and national scales. Currently, simple models based on emissions factors are used to estimate GHG fluxes for regional and national assessments. For example, the IPCC assumes that 1.25% of N additions to soil are emitted as N_2O . More complex process based models that simulate plant growth and microbial processes that result in GHG emissions are potentially more reliable for assessments and comparing management scenarios because they account for effects of climate, soil type, cultivation, plant nutrient demand, and other factors on GHG fluxes.

The US Great Plains region includes all or parts of 10 states (Figure 1). The region is dominated by grassland vegetation and annual precipitation increases from ~35 cm in the western portion to ~100 cm near the eastern boundary. Mean annual temperature ranges from ~6°C in the north to ~13°C in the south. The majority of wheat (*Triticum aestivum*) grown in the US is in the Great Plains and significant proportions of alfalfa hay (*Medicago sativa* L), corn, (*Zea mays* L.), soybean (*Glycine max* Merr.), and cotton (*Gossypium hirsutum* L.) cropping occurs in the region. More than half of the cropped area in the Great Plains is for wheat, with spring wheat and winter wheat often grown in rotations with other crops in the northeast (ND, SD), continuous winter wheat in the moderately water stressed south central area (NE, KS, OK) and wheat/fallow rotations in the more water stressed western portion (CO, MT). The second and third most important crops are alfalfa hay and corn. Both of these crops are usually irrigated except in the wetter areas close

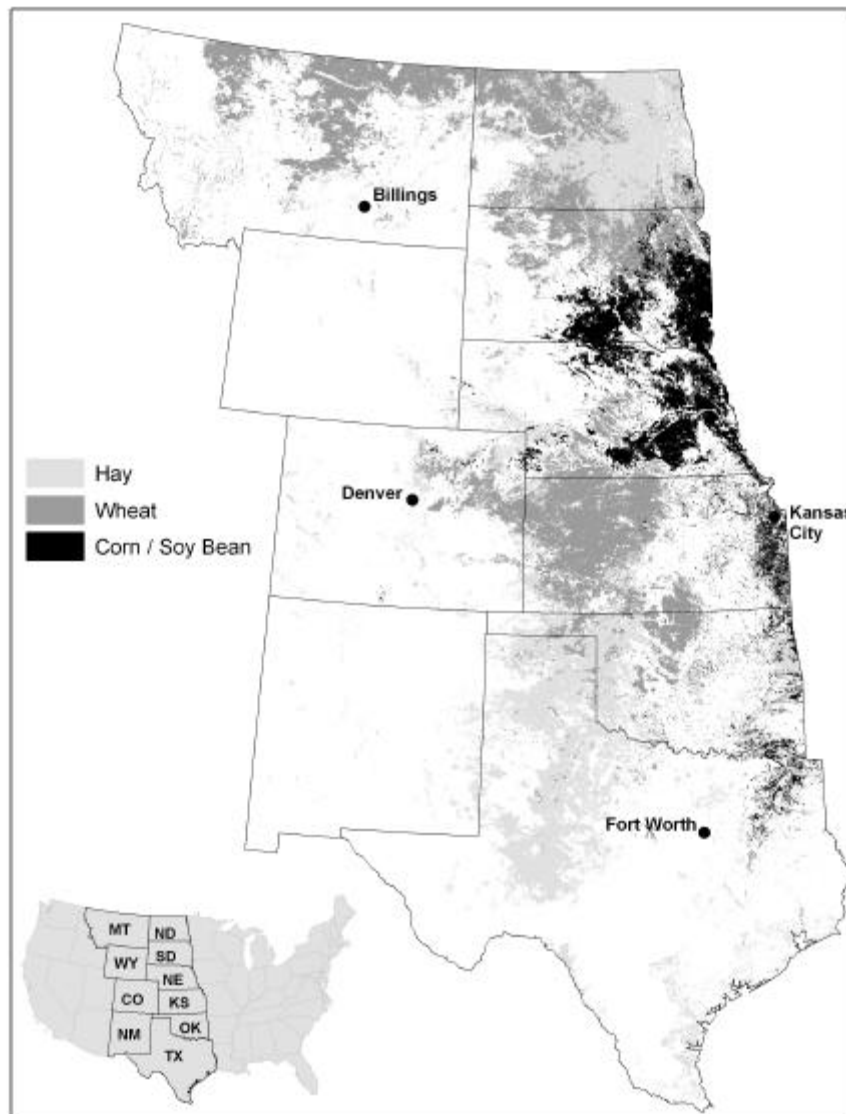


Figure 1. Distribution of common crops in the US Great Plains region.

to the eastern boundary. Wheat, alfalfa hay, and corn account for ~75% of the total cropped area in the Great Plains. Soy, cotton, barley, sunflower, potato, and sorghum cover most of the remaining area. Figure 2 shows the areas of the major crops represented in each state for these simulations.

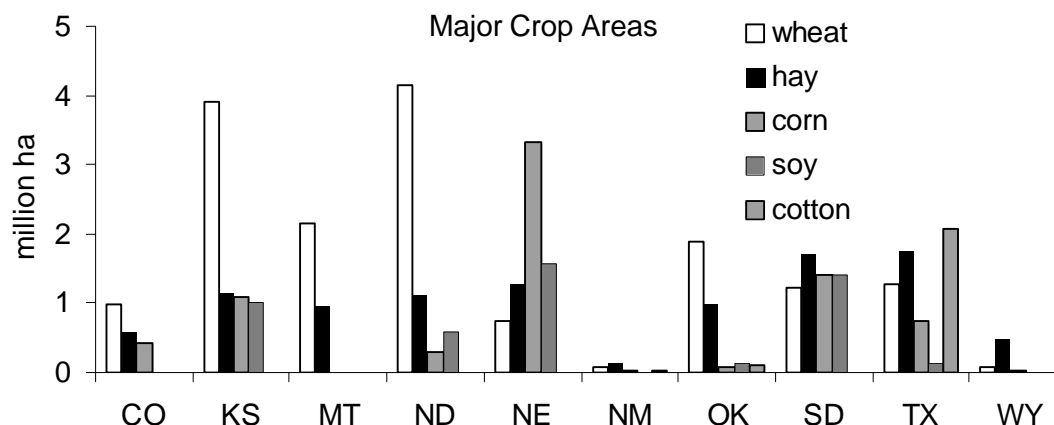


Figure 2. Major crop areas by state for the US Great Plains region; values are decadal averages from 1993-2002.

The DAYCENT terrestrial ecosystem model was used to estimate GHG_{net} emissions for cropped agricultural soils in the US Great Plains region. Emissions from animals and grazed land were not included. Simulated values for net CO_2 flux, direct and indirect N_2O emissions, and CH_4 uptake were compiled for the major crops in each state within the Great Plains. Model results were combined with area data for respective crops within each state and GHG_{net} was calculated. This set of simulations is similar to but more complete than those reported by Del Grosso et al. (2002a) because a larger portion of the Great Plains are considered, subdominant cropping rotations and indirect N_2O emissions are included, and total fluxes for the region are estimated.

2.0 DAYCENT MODEL DESCRIPTION

DAYCENT is the daily time step version of the CENTURY (Parton et al., 1994) biogeochemical model. DAYCENT (Del Grosso et al., 2001; Parton et al., 1998) simulates fluxes of carbon (C) and nitrogen (N) among the atmosphere, vegetation, and soil. Plant growth is controlled by nutrient availability and water and temperature stress. Nutrient supply is a function of soil organic matter (SOM) decomposition rates and external nutrient additions. Daily maximum/minimum temperature and precipitation, timing and description of management events (e.g. fertilization, tillage, harvest), and soil texture data are needed as model inputs. Key submodels include plant production, organic matter decomposition, soil water and temperature by layer, nitrification and denitrification, and CH_4 oxidation. Recent model improvements include the influence of solar radiation on potential plant growth rates and the ability to simulate the timing of seed germination as a function of

soil temperature and harvest date as a function of growing degree-days accumulated since germination. Comparison of model results and plot level data show that DAYCENT reliably simulates crop yields, soil organic matter levels, and trace gas fluxes for various native and managed systems (Del Grosso et al. 2002b). Recent regional simulations for the dominant cropping systems in the US showed a high correlation ($r^2 = 0.75$) between mean simulated and observed grain yields.

3.0 GREAT PLAINS REGIONAL SIMULATIONS

A sufficient number of crop rotations were simulated for each state in the Great Plains so that at least 85% of the harvested statewide crop area under current management was included. Crop area is defined as the mean harvested acres for 1993-2002 as reported by the US Department of Agriculture National Agricultural Statistics Service database (USDA-NASS <http://www.usda.gov/nass/>). For each crop rotation simulated in each state, N fertilizer additions were estimated from state and county level databases. State level soil type and computer generated climate data compiled for the EPIC model (Sharpley et al., 1990) were used to drive DAYCENT.

Two sets of simulations were performed, one which assumed traditional crop rotations and tillage practices (Business as Usual) and one in which improved management (IM) was substituted where possible. Improved management was defined as conversion to no till and reduction of the summer fallow period. For example, in drier regions of the Great Plains, winter wheat is the dominant crop. Winter wheat can be grown successfully in areas that experience summer drought but the disadvantage of winter wheat cropping is that the soil is kept fallow (vegetation free) during at least some of the summer months. Summer fallow and conventional tillage for weed control result in soils that are depleted in SOM.

In many areas where continuous winter wheat or wheat/fallow is the primary crop, alternative rotations that include summer cropping can be substituted. The water savings gained from no till can allow summer cropping to be alternated with wheat in multi year rotations. Irrigated alfalfa hay is an important crop in most of the Great Plains states but there is no improved management practice for this because soil is only cultivated every 4 years and there is no opportunity to reduce the summer fallow. No improved management was assumed for cotton because tillage is necessary for insect control. In general, we confined the improved management scenarios to crop rotations that have been shown to be economically viable or which are likely to be viable for the different states. We assumed that total cropped area and irrigated area are the same for BAU and IM. Table 1 lists the contrasting land use alternatives for the dominant BAU rotation that was eligible for IM in each state.

Before simulating different management scenarios, baseline conditions were established by simulating ~1850 years of native vegetation followed by ~130 years of agriculture that included historical rotations, progression of cultivars, changes in form and quantity of N amendments, and traditional tillage practices. From 1993-2002 BAU and IM simulations were conducted for each

region using the same baseline conditions. Yearly outputs for crop yields, net CO₂ flux, trace gas emissions, and N leaching were compiled. Non-CO₂ GHG fluxes were converted to CO₂-C equivalents by assuming that N₂O and CH₄ have 310 and 25 times, respectively, the warming potential of CO₂ on a per molecule basis. Indirect N₂O emissions were estimated by assuming that 1% of the NH₄ and NO_x volatilized will be converted to N₂O and that 2.5% of the NO₃ leached into groundwater will be denitrified to N₂O. We also assumed that the production of each gram of N fertilizer results in the emission of 0.8g CO₂-C due to energy consumption. State average values for harvested area and model-simulated values for the components of GHG_{net} during 1993-2002 were calculated. Then model outputs in units of gC m⁻² yr⁻¹ were multiplied by the respective crop areas to calculate a net flux for each component of GHG_{net} for each cropping system in each state. Lastly, the components were summed for all states to estimate GHG_{net} for the Great Plains under BAU and IM.

Table 1. Contrasting land-use scenarios for the dominant rotation that was eligible for improved management in each state in the US Great Plains. Rotations: w/f = wheat/fallow, c = irrigated corn, w = wheat, c/s = irrigated corn/soy, c/w/f/s = corn/wheat/fallow/soy, w/s/w = wheat/sunflower/wheat, w/m/f = wheat/millet/fallow, w/c/f = wheat/corn/fallow, c/w/s = corn/wheat/soy ct = conventional tillage, nt = no till

State	Business as Usual (BAU)				Improved Management (IM)			
	rotation	cult	fert (gN m ⁻² yr ⁻¹)	GHG _{net} (Tg C)	rotation	cult	fert (gN m ⁻² yr ⁻¹)	GHG _{net} (Tg C)
MT	w/f	ct	2.7	0.06	w/s/w	nt	2.9	-1.0
WY	w/f	ct	2.7	0.03	w/m/f	nt	7.5	0.02
CO	w/f	ct	2.7	0.12	w/c/f	nt	7.5	-0.32
NM	c	ct	15	0.007	c	nt	15	-0.01
OK	w	ct	8.1	0.05	c/w/s	nt	8.8	-1.8
KS	w	ct	8.1	-0.14	c/w/s	nt	8.8	-3.7
NE	c/s	ct	5.5	1.78	c/s	nt	5.5	-1.2
SD	c/w/f/s	ct	2.7	-0.08	c/w/s	nt	3.6	-1.15
ND	s/w	ct	6.7	-0.14	w/s/w	nt	6.7	-0.5

4.0 RESULTS

Figure 3a shows the components of GHG_{net} for the management scenarios considered on a per area basis and figure 3b has total regional fluxes. Both BAU and IM sequester CO₂-C in soil but IM stores approximately twice as much. BAU stores C because a large amount of area in the Great Plains that was C depleted from dryland wheat cropping was converted to irrigated alfalfa hay and corn cropping in the 1970's which led to C sequestration. BAU and IM show approximately equal amounts of N₂O emissions. The remaining components of GHG_{net} are relatively minor and BAU and IM do not show very great differences (Figure 3). DAYCENT analysis estimate that the US Great Plains is a carbon sink under BAU (GHG_{net} ~ 4 Gt CO₂-C yr⁻¹) but that the sink could be increased to ~16 Gt CO₂-C yr⁻¹ under improved management.

Table 1 includes GHG_{net} for the major contrasting cropping scenarios that are likely to be economically viable in different states. The largest potential for

GHG_{net} reduction is for continuous winter wheat cropping that could be converted to wheat/corn/soy rotations (OK, KS). Conversion of

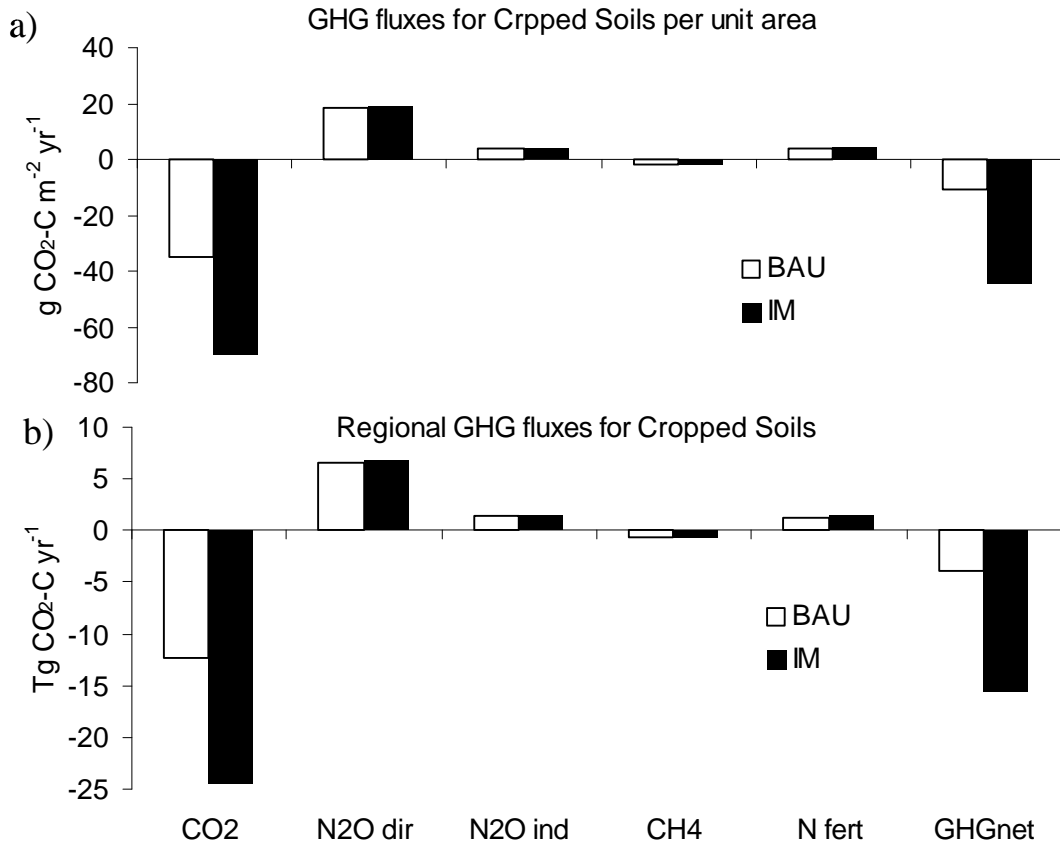


Figure 3. The components of GHG_{net} in CO₂-C equivalents on a per unit area (a) and regional (b) basis for DAYCENT simulations of the US Great Plains region. Scale is from the perspective of the atmosphere so negative values represent a GHG sink. Values are the annual mean for the decade of the 1993-2002.

wheat/fallow to a rotation that includes a summer crop every 3 years results in switching from a GHG_{net} source to a sink (MT, CO), as does conversion from conventional till to no-till corn/soy (NE). Although in some cases the improvement associated with IM was marginal, in no case did conversion to IM lead to higher GHG_{net}.

Overall grain yields tended to be slightly higher under IM as a result of two competing trends. Conversion to no till tended to decrease crop yields in some areas because soils warm more slowly and the growing season is shorter. However, reduction of summer fallow and partial replacement of wheat crops by higher yielding summer crops more than compensated for this and net yields were higher under IM. Overall, conversion to the suggested IM scenarios will not result in decreased yields although the risk of catastrophic crop failure may be increased.

5.0 DISCUSSION

Traditionally, winter wheat was the dominant crop in the Great Plains because it is tolerant of summer drought and soil water is conserved during the fallow season. However, wheat cropping leads to soils that are depleted in C. As irrigation became more available in the 2nd half of the 20th century, some areas that were previously used for dryland wheat cropping were converted to irrigated alfalfa or corn which increased SOM. But CO₂ sequestration upon conversion to irrigated cropping is at least partially compensated for by higher N₂O emissions under irrigation. To assess GHG_{net} under current management and to estimate GHG reductions that may be achieved under improved management DAYCENT simulations of alternative land management scenarios were performed for the Great Plains. DAYCENT results suggest that conversion to improved management could result in sequestration of ~12 Tg CO₂-C yr⁻¹. On one hand, this tends to be an over-estimate because the IM scenarios are already being used by some farmers. On the other hand, some improved management scenarios that may be feasible (nitrification inhibitors, precision fertilizer application, no till cotton) were not considered. Limitations of these simulations also include the coarse (state level) spatial scale and using generated instead of actual weather used to drive the model.

Differences in GHG_{net} between BAU and IM are driven primarily by differences in soil C sequestration. Conversion to no till cultivation and reduction of summer fallow leads to higher SOM for two reasons. No till reduces decomposing rates so soil SOM losses are lower while reducing summer fallow increases C inputs to SOM. Although N fertilizer additions tend to be higher under IM, regional simulated N₂O emissions were not higher (Fig. 3b). Some states showed increased N₂O emissions upon conversion to IM but this was compensated for by decreased N₂O emissions in other areas. Model results reinforce the idea that net GHG emissions are controlled by the interaction of crop rotation, N fertilizer additions, soil type, and climate patterns. Further simulations on smaller spatial scales driven with actual climate are needed to better estimate regional and national GHG fluxes. Future DAYCENT simulations that include the entire suite of potential managements options will be linked with economic models to perform cost/benefit analyses and identify optimal crop rotations, N amendments levels, nitrification inhibitor application rates, etc. for different agricultural regions in the USA.

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REFERENCES

- Baruah, K.K., Gogoi, N., Goswami, S, Barman, B. & Gupta, P.K. 2002. Plant and soil factors associated with methane emission from irrigated rice ecosystem in Assam. In: van Ham, J., Baede, A.P.M., Guicherit, R., Williams-Jacobs, J.G.F.M. (Eds.), *Proceedings of the Third International Symposium on Non-CO₂ Greenhouse Gases*, p 101-106. Millpress, Rotterdam, The Netherlands.
- Del Grosso, S.J., Parton, W.J., Mosier, A.R., Hartman, M.D., Brenner, J., Ojima, D.S. & Schimel, D.S. 2001. Simulated interaction of carbon dynamics and nitrogen trace gas fluxes using the DAYCENT model. In M. Schaffer, L. Ma, & S. Hansen (eds.), *Modeling Carbon and Nitrogen Dynamics for Soil Management*, p 303-332. Boca Raton, Florida: CRC Press.
- Del Grosso, S.J., Ojima, D.S., Parton, W.J., Mosier, A.R. & Peterson, G.A. 2002a. Regional assessment of net greenhouse gas fluxes from agricultural soils in the USA Great Plains under current and improved management. In: van Ham, J., Baede, A.P.M., Guicherit, R., Williams-Jacobs, J.G.F.M. (Eds.), *Proceedings of the Third International Symposium on Non-CO₂ Greenhouse Gases*, p 469-474. Millpress, Rotterdam, The Netherlands.
- Del Grosso, S.J., Ojima, D.S., Parton, W.J., Mosier, A.R., Peterson, G.A., Schimel, D.S. 2002b. Simulated effects of dryland cropping intensification on soil organic matter and greenhouse gas exchanges using the DAYCENT ecosystem model. *Environmental Pollution* 116: S75-S83.
- Lal, R., Kimble, J.M., Follett, R.F. & Cole, C.V. 1998. *The potential of U.S. cropland to sequester carbon and mitigate the greenhouse effect*. Chelsea, MI: Ann Arbor Press.
- Mosier, A.R. & Kroeze, C. 2000. Potential impact on the global atmospheric N₂O budget of the increased nitrogen input required to meet future global food demands. *Chemosphere-Global Change Science* 2: 465-473
- Parton, W.J., Ojima, D.S., Cole C.V., Schimel, D.S. 1994. A general model for soil organic matter dynamics: sensitivity to litter chemistry, texture and management. In, *Quantitative Modeling of Soil Forming Processes*, p 147-167. Madison, WI: Soil Science Society of America.
- Parton, W.J., Hartman, M.D., Ojima, D.S. & Schimel, D.S. 1998. DAYCENT: Its land surface submodel: description and testing. *Global Planetary Change* 19: 35-48.
- Robertson, GP, Paul, E.A., Harwood, R.R. 2000. Greenhouse gases in intensive agriculture: contributions of individual gases to the radiative forcing of the atmosphere. *Science* 289: 1922-1925.
- Sharpley, A.N., Jones, C.A. & Williams, J.R. 1990. The nutrient component of EPIC. Chapter 7, pp. 152-166 In A.N. Sharpley and J.R. Williams (eds.) *EPIC--Erosion/Productivity Impact Calculator: 1. Model Documentation*. U.S. Dept. Agric. Tech. Bull. No. 1768.