Spatio-temporal analyses of simulated biophysical processes in the Chippewa River Watershed-Minnesota

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Abstract

Intensive crop production in the Chippewa River Watershed (CRW) in West Central Minnesota have altered the dynamics and nature of water, sediments, and nutrients and resulted in biophysical changes within and beyond the watershed. Opportunities to improve the ecological functioning of managed and natural ecosystems in CRW include reducing soil erosion, runoff, and nutrient leaching. We hypothesized that increasing perennial land-use in managed ecosystems will improve environmental health through sustained carbon sequestration and concomitant reductions in soil erosion, runoff, and nutrient leaching. We calibrated, validated, and used a modular modeling framework to simulate the impact of 100 years each of historical and projected weather variables, in combination with soil data and current and alternative crop rotations, on biophysical processes of the predominant farming systems in 12 representative soil series located throughout the CRW. Different soil series, depending on their physical characteristics and position in the landscape, varied in their response to increasing the proportion of perennial, in the crop rotation, and in their buffering capacity to reduce the negative impact of projected climate change. Simulation results suggested that farmers in CRW can diversify current cropping systems, enhance the buffering capacity of their land, and help mitigate the impact of future climate change by adjusting land-use to accommodate more perennials in future crop rotations. This will help develop multifunctional production systems that can produce standard commodities as well as a wide range of other ecosystem services.

Keywords: alternative management, crop rotations, climate change, ecosystem services, spatial variation, variance components.

Introduction

Land use in Minnesota's Chippewa River Watershed (CRW) is predominately centered on commodity production systems that deliver corn, soybean, and livestock products for domestic consumption and for an expanding export market (Jordan et al. 2007). The current "leaky" land-use system (corn-soybean rotation, conventional tillage, N fertilizer) looses ~30% of the average 125 kg applied nitrogen per ha to subsurface drainage (Malone et al. 2007). The rise in intensive, homogeneous croplands, especially corn production systems, is responsible for a substantial proportion of the increase in NO_3-N values observed since the 1970s.

The CRW drains 5,387 km^2 of mixed natural and managed ecosystems in West Central Minnesota. Annual crops, predominantly grown in monocultures, occupy between 60 to 94% of the land area in the major agroecological regions of the watershed (Nangia et al. 2010). Recently, however, increased demand for domestic biofuels is expected to influence land-use options (Rayburn and Schulte 2009) and will impact several biophysical processes in managed and natural agroecosystems within the watershed. The CRW has high-value ecological features including seven major lakes, two state parks with prairie, forest and lake areas, numerous wildlife management and waterfowl production areas and 2,000 miles of intermittent and perennial streams (Boody et al. 2005, Jordan et al. 2007, Wymar 2007).

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Due to current land-use systems, the CRW faces a number of environmental challenges, including degradation of water quality, threats to biodiversity, and increased flooding, soil erosion and nutrient loss to both surface and underground water (Boody et al. 2005, Nangia et al. 2010). In addition to these environmental challenges, the impact of spatio-temporal climate variability in the watershed is likely to be intensified by climate change, which is predicted to disrupt many ecosystem functions, altering their capacity to provide goods and services and rendering them more susceptible to degradation (IPCC 2007, Friend 2010).

Earlier simulation models (Nicks et al. 1996) suggested that average annual percent change in precipitation, runoff, soil loss and crop yield, in response to projected climate change in six locations in MN, would increase by 16.1, 34.6, 22.5 and 58.6%, respectively. Similar projections in biophysical processes, except crop yield, were obtained (Wuebbles and Hayhoe 2004) using historical (20th century) and model data (21st century) in the Midwest. Earlier monitoring efforts in the CRW (Wymar 2007) resulted in establishing a water quality and quantity baseline, and concluded that increased perennials on the landscape is necessary to enhance environmental and economic agroecosystems services, promote conservation incentives, and develop viable markets for perennials and integrated crop-livestock production systems. Previous modeling predicted that land resources in the CRW can be multifunctional; they can provide a large number of functions related to social, economic and environmental prosperity and sustainability (Boody et al. 2005, Jordan et al. 2007)..

Given the complexity of the agroecosystem, and the spatio-temporal variability of the involved processes, modeling is needed (Hatfield et al. 2008) for assessing the impact of alternative agricultural management strategies. The strategies should include more permanent plant cover on the landscape and their impact on a number of biophysical processes (e.g., biomass and grain yield of crops, carbon sequestration in the soil, nitrogen loss, runoff, and soil erosion) in the watershed. The objectives of this research were to model the impact of targeted land-use changes on managed agroecosystems in 12 representative soil series located throughout the watershed and to develop guidelines for needed agricultural land-use changes to enhance ecosystem integrity and reduce the impact of soil and habitat degradation.

Methods

We utilized the Agricultural Production Systems Simulator (APSIM 7.3) that integrates modules of cropping, management, and biophysical processes within farming systems for improved decision support. It estimates crop productivity and potential impacts of farming systems at selected locations in the study area based on the site's soil properties and climate regimes (Keating et al. 2003). A database derived from on-station and on-farm research on traditional and alternative cropping systems, including perennial biomass crops, were utilized to calibrate the simulation model and sensitivity analysis was carried out for each crop in the crop rotations. The database included detailed quantitative measurements on crops, soils, nutrients, and weather variables (Jaradat and Weyers 2011).

Simulation scenarios

To conduct the simulations and subsequent multivariate statistical analyses, we used existing weather data on the past 100 years, as well as simulated changes in future temperature, precipitation, and CO_2 concentrations generated by the Coupled Global Climate Model (CGCM) 3.1 which was developed by the Canadian Center for Climate Modeling and Analysis, Canada (http://www.ec.gc.ca/ccmac-cccma/default.asp?lang=En). The IPCC A2 scenario was selected for simulations. This scenario is characterized by a high rate of growth in CO_2 emissions and most closely reproduced the actual emissions trajectories during the period since the scenarios were defined (2000-2008).

For each of the 12 locations, representing soil series, conventional management practices, as defined in Jaradat and Weyers (2011), and position in the landscape within the watershed (Fig. 1), we assessed the impact of current conventional (corn-soybean) and alternative [corn-soybean-wheat-alfalfa (1 to 5 years of alfalfa following three years of grain crops), and continuous alfalfa for 8 years] crop rotations on several crop and soil biophysical processes (Olmstead and Brummer 2008). Conventional tillage and local management practices were used in simulations along with 100-year historical weather data (rainfall, temperature and CO_2) and 100 years of projected weather data based on scenario A2 as predicted by CGCM 3.1 (IPCC 2007). Simulation data were subjected to principal components and variance components analyses using relevant modules in STATISTICA (StatSoft Inc. 2011).

Results

The 12 sites selected for the simulation study represented the predominant soil series, cropping systems and physiographic features in the watershed (Fig. 1). In addition, these locations represent different positions in the landscape with slopes ranging from 0.0 to 12%. The North-South and West-East spread of the 12 locations and their proximities/distances from water bodies, as well as their soil physical and chemical properties and soil profile characteristics captured the maximum diversity within the watershed and provided necessary data to validate the simulation results.

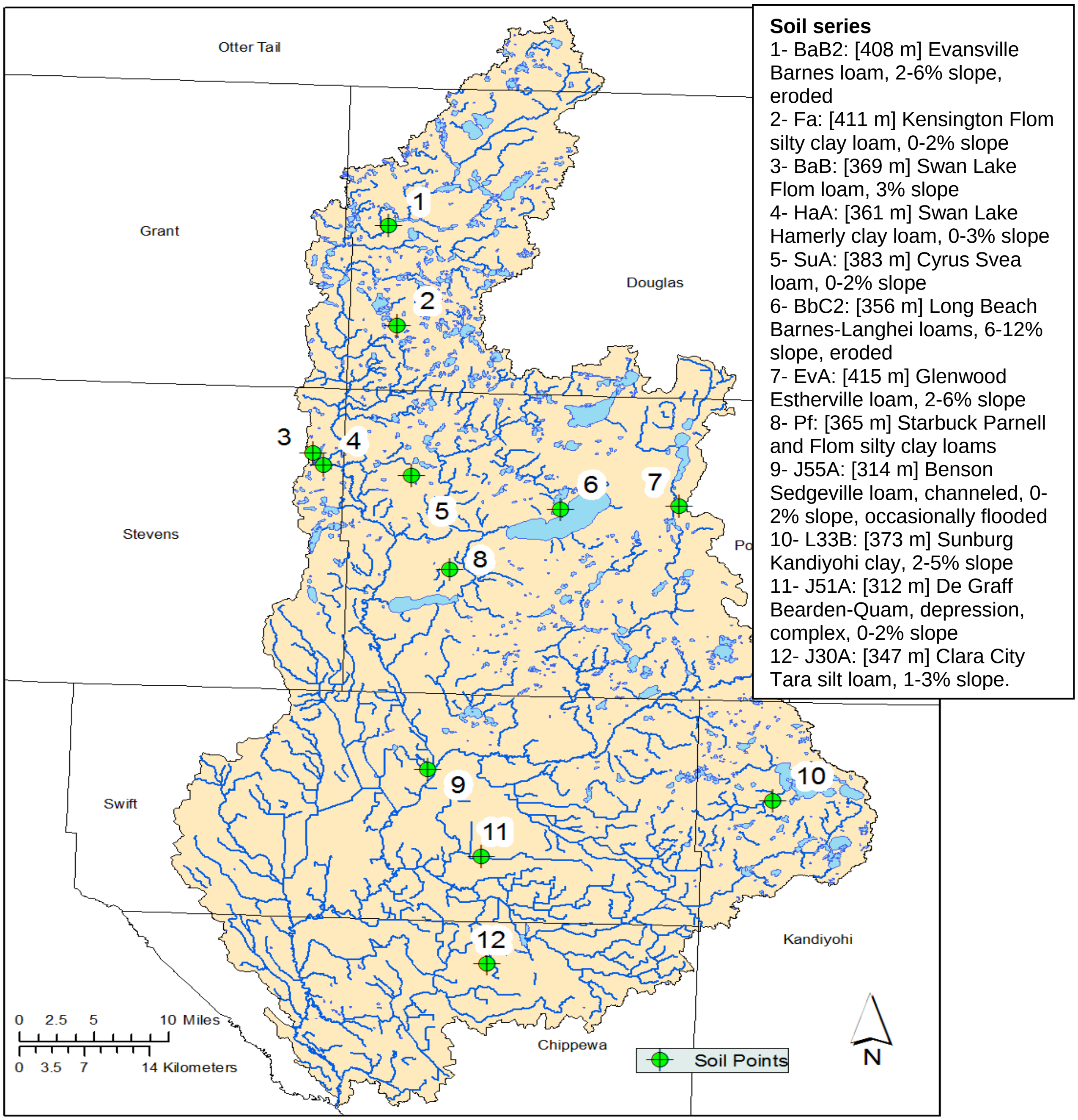

Figure 1. Map of the Chippewa River Watershed in West Central Minnesota showing the location, [elevation, m] and a brief description of 12 soil series used in the simulation study.

Multivariate relationships

A summary of all factors (past and future weather variables, soil series, and crop rotations) and variables (biophysical processes) used in the simulation study is presented in Fig. 2 in the form of loadings (i.e, correlations) on the first principal component (PC; i.e., latent variable). The calibration and validation phases of the PC analyses captured 0.63 and 0.52 of total variation in all factors and variables. The second, and orthogonal, principal component accounted for 0.22 and 0.18 of calibration and validation variances, respectively. The simulated biophysical processes based on past and future weather variables, contributed the most to both calibration and validation variances in PC1, followed by differences between soil series; whereas, differences between crop rotations contributed the least to PC1 and accounted for all variation in PC2.

Simulated biomass, grain yield (GY), and NH_4-N based on future 100-yr weather variables (F-, in Fig. 2), as predicted by the A2 climate change scenario, had positive loadings on PC1 and where significantly smaller in magnitude (0.89, 0.78, and 0.75, respectively) in comparison with those based on the past (P-, in Fig. 2) 100-yr of weather variables. However, the small positive change in soil carbon (4%), also with positive loading on PC1, was not significant. The remaining biophysical processes (i.e., NO_3-N, runoff, and erosion), as well as elevation of the soil series, exhibited negative loadings on PC1 and there were significant differences between simulated P-runoff and F-runoff (0.43 lower) and between P-erosion and F-erosion (0.26 lower) but not for NO_3-N.

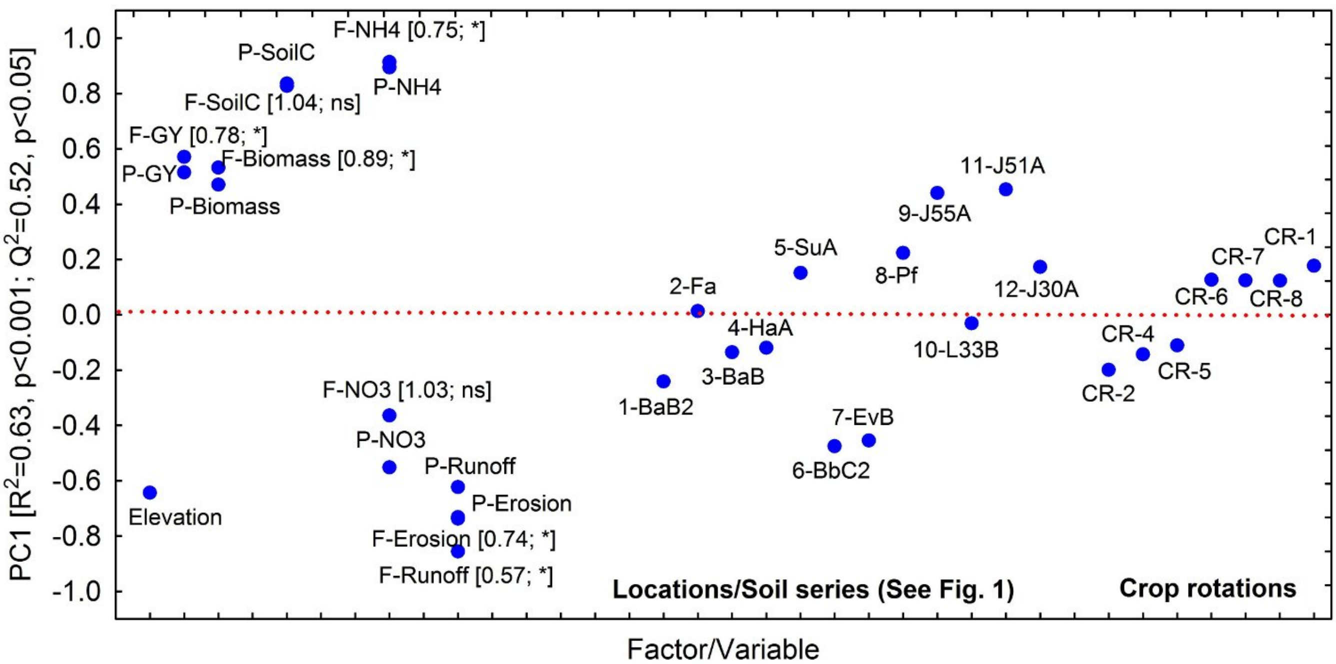

Figure 2. Loadings of factors and simulated (P=past 100 years; F=future 100 years) crop and soil variables derived from conducting seven crop rotation on 12 soil series in the Chippewa River watershed, on the first principal component (PC1); calibration (R^2), and validation (Q^2) variance accounted for by PC1, and results of mean separation between simulated variables. [Value following F- between brackets is fraction of its P-estimate; ns: not significant, *: significant at 5% level of probability]

Elevation of the soil series location ranged from 415 to 312 m above sea level. Elevation exhibited a strong negative loading on PC1 (-0.62), and was associated with larger NO_3-N loss, runoff, and erosion. The largest values of all three variables were associated with the soil series having the highest slope (6-BbC2 and 7-EvB; Fig. 1). Loadings of soil series on PC1 were negatively correlated with both latitude ($r=-0.62$; $p<0.01$), and elevation ($r=-0.67$; $p<0.01$) of their location; whereas, latitude and elevation of soil series location were positively correlated ($r=0.74$; $p<0.001$).

Five of the 12 soil series had positive loadings (0.2 to 0.4), two had almost 0.0 loadings and the remaining five soil series had negative loadings (-0.5 to -0.1) on PC1. The soil series with positive loadings (i.e., 5-SuA, 12-J30A, 8-Pf, and 11-J51A, in increasing order, Fig. 2) had larger values of biomass and grain yield, soil carbon and NH_4-N loss, and exhibited lower NO_3-N loss, runoff, and erosion. On the other hand, the soil series with negative loadings on PC1 (i.e., 4-HaA, 3-BaB, 1-BaB2, 7-EvB, and 6-BbC2, in increasing order; Fig. 2) had lower biomass and grain yield, lower loss of NH_4-N, but larger NO_3-N loss, erosion, and runoff, as compared with the first group of soil series.

Differences between crop rotations contributed the least to the variance accounted for by PC1; however, they fully contributed to PC2 which accounted for 0.22 and 0.18 of variation in the calibration and validation models. Continuous production of a perennial (alfalfa; CR-1) is expected to produce the largest biomass; whereas, the traditional 2-yr crop rotation of corn and soybean (CR-2) is expected to produce the least biomass and grain yield. The 4-yr crop rotation (CR-4) with one year of alfalfa is expected to produce less biomass and grain yield as compared with those crop rotation with 2, 3 4, or 5 years of alfalfa (i.e., CR-5, CR-6, CR-7, and CR-8, respectively), following three years of corn-soybean-wheat.

The plot in Fig. 2 indicated that the soil series with positive loadings on PC1 are expected to produce more biomass and grain yield when the frequency of the perennial crop exceeds 3 years (or ~40% of the duration of the crop rotation); whereas, those with negative loadings are expected to produce more grain or biomass if the perennial crop is included for one or two years in the crop rotation. The plot also indicated that the higher the frequency of the perennial crop, the lower the expected runoff, soil erosion, and the loss of NO_3-N.

Variance components

Sources of variation (Table 1) in this study were classified as fixed (crop rotation and crops within crop rotations) and random (soil series and the interaction of crop rotations with soil series. The classification made it possible to quantify the variance components that can be attributed to the random factors assuming that the soil series represented a random sample derived from the larger number of soil series present in the watershed.

Crop rotations, whether based on past or future weather conditions, differed significantly for all biophysical processes under study; however, crops within crop rotations differed significantly as to their biomass and grain yield under both simulation scenarios. The soil-related processes (soil carbon, NO_3-N, NH_4-N, runoff, and erosion) were not significantly impacted by differences between crops within crop rotations. Nevertheless, under the A2 climate change scenario, all variables except soil carbon differed significantly from those based on past weather variables (Fig. 2).

Variances accounted for by soil series in all biophysical processes were highly significant and ranged from 29% for NH_4-N to 74% for soil carbon based on past weather scenario, and from 32% for NH_4-N to 64% for runoff, based on the A2 climate change scenario. Variances accounted for by the interaction between crop rotations and soil series were highly significant, except biomass and grain yield based on past weather scenario, and grain yield based on the A2 climate change scenario. In general, these variances were smaller in magnitude as compared with those attributed to differences between soil series with three exceptions. Larger variance estimates due to the interaction between crop rotations and soil series were predicted for NO_3-N and NH_4-N based on past weather scenario, and for NH_4-N based on the A2 climate change scenario.

A number of biophysical processes are expected to be differentially impacted by future weather scenario depending on how the soil series may react to changes in future weather variables. More variation in NO_3-N (48 vs. 34%) and runoff (64 vs. 54%) will be accounted for by future weather scenario, and less variation in biomass (56 vs. 61%), soil carbon (62 vs. 74%), and erosion (45 vs. 52%) will be accounted for by future weather scenario. These projected changes may or may not be associated with changes in variances accounted for by the interaction between crop rotations and soil series. Variances accounted for by this interaction are expected to increase for soil carbon (12 vs. 23%), to decrease for NO_3-N (54 vs. 31%), NH_4-N (56 vs. 46%), and erosion (40 vs. 27%) due to the A2 climate change scenario.

Soil carbon is a variable of interest in studies involving crop rotations and their interaction with soil series and climate change scenarios. The simulation study suggested that there will be a slight increase (4%) in soil carbon sequestration due to increased CO_2 as projected by the A2 climate change scenario. Also, soil carbon is one of a few variables where soil series and their interaction with crop rotation accounted for large (86 and 85% based on past and future weather, respectively) portions of its variation. Therefore, matching crop rotations and soil series may constitute the most appropriate mitigation option in the future.

Table 1. Variance components and their level of significance accounted for by fixed factors, random factors and their interaction in two simulation scenarios involving 12 soil series and eight crop rotations in the Chippewa River Watershed, Minnesota.

Simulation	Variable	Fixed factor		Random factor	
		Crop rotation	Crops(Crop rotation)	Soil series	Crop rotation x Soil series
		Probability of F-value		Probability of z-value (% variance)	
Past 100 yr	Biomass	0.001	0.001	0.05 (61%)	0.21 (3%)
	Grain yield	0.005	0.05	0.02 (45%)	0.09 (6%)
	Soil carbon	0.0001	0.12	0.01 (74%)	0.05 (12%)
	NO_3-N	0.005	0.15	0.05 (34%)	0.01 (54%)
	NH_4-N	0.05	0.09	0.05 (29%)	0.01 (56%)
	Runoff	0.0001	0.07	0.02 (54%)	0.01 (32%)
	Erosion	0.0001	0.11	0.01 (52%)	0.01 (40%)
Future 100 yr	Biomass	0.001	0.001	0.01 (56%)	0.05 (5%)
(A2 scenario)	Grain yield	0.001	0.001	0.01 (45%)	0.14 (5%)
	Soil carbon	0.0001	0.10	0.001 (62%)	0.05 (23%)
	NO_3-N	0.001	0.07	0.02 (48%)	0.05 (31%)
	NH_4-N	0.001	0.09	0.05 (32%)	0.02 (46%)
	Runoff	0.0001	0.14	0.01 (64%)	0.05 (30%)
	Erosion	0.0001	0.22	0.02 (45%)	0.05 (27%)

Conclusions

Ecosystem services, whether provisioning, regulating, or supporting services, provided by the Chippewa River Watershed are being threatened by anthropogenic as well as climatic factors. The simulation results offer strategies to optimize site-specific crop rotations in this watershed. The simulated impact of increasing perennial land-use in managed ecosystems across the watershed on several biophysical processes suggested that farmers can help improve environmental health through sustained carbon sequestration and concomitant reduction in soil erosion, runoff, and nutrient leaching. Diversifying the corn-soybean crop rotations by including a perennial crop, especially in certain soil types and locations in the watershed, would offer farmers a way to mitigate negative environmental impacts caused by corn and soybean production while providing an additional source of income based on new regional markets for food and biomass from perennials and diverse crops. Adaptive management, where stakeholders contribute to optimize resource use and minimize anthropogenic and climatic impact on the production base within the watershed, is expected to help develop multifunctional production systems that can produce standard commodities as well as a wide range of other system services. This modeling effort will be extended to cover the whole watershed using GIS/GPS technologies and to predict how biophysical processes may respond to land-use changes and their impact on water quality. This study is part of a larger project intended to develop markets for perennial products, analyze the economic impact of land-use changes, and actively encourage farmers to consider implementing, and monitor the impact of, needed land-use changes on their farms.

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References

Boody, G., B. Vondracek, D.A. Andow, M. Krinke, J. Westra, J. Zimmerman, and P. We;lle. 2005. Multifunctional agriculture in the United States. BioScience 55:27-38.

Friend, A.D. 2010. Terrestrial plant production and climate change. Journal of Experimental Botany 61:1293-1309.

Hatfield, J., K. Boote, P. Fay, L. Hahn, C. Izaurralde, B.A. Kimball, T. Mader, J. Morgan, D. Ort, W. Polley, A. Thompson, and D. Wolfe. 2008. Agriculture. *In* The effect of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity in the United States. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. Washington, D.C. USA.

IPCC. 2007. Impacts, adaptations and vulnerability. *In* M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson, eds. Contributions of the working group II to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, U.K.

Jaradat, A.A., and S.L. Weyers. 2011. Statistical modeling of yield and variance instability in conventional and organic cropping systems. Agron. J. 103:673-684.

Jordan, N., G. Boody, W. Broussard, J.D. Glover, D. Keeney, B.H. McCown, G. Mclsaac, M. Muller, H. Murray, J. Neal, C. Pansing, R.E. Turner, K. Warner, and D. Wyse. 2007. Sustainable development of the agricultural bio-economy. Science 316: 1570-1571.

Keating, B., P. Carberry, G. Hammer, M.E. Robert, M.J. Robertson, D. Holzworth, N.I. Huth, J.N.G. Hargreaves, H. Meinke, Z. Hochman, G. McLean, K. Verburg, V. Snow, J.P. Dimes, M. Silburn, E. Wang, S. Brown, K.L. Bristow, S. Asseng, S. Chapman, R.L. McCown, D.M. Freebairn, and C.J. Smith. 2003. An overview of APSIM, a model designed for farming systems simulations. European Journal of Agronomy 18:267-288.

Malone, R.W., L. Ma, D.L. Karlen, T. Meade, D. Meek, P. Heilman, R.S. Kanwar, and J.L. Hatfield. 2007. Empirical analysis and prediction of nitrate loading and crop yield for corn-soybean rotations. Geoderma 140:223-234.

Nangia, V., P. Wymar, and J. Klang. 2010. Evaluation of a GIS-based watershed modeling approach for sediment transport. International Journal of Agricultural and Biological Engineering 3:43-53.

Nicks, A.D., R.D. Williams, and J.R. Williams. 1996. Regional analysis of erosion from agricultural fields using global change scenarios. In Erosion and sediment yield: Global and regional perspectives. Proceedings of the Exeter Symposium, July 1996. IAHS Publishers. No. 236, 1996.

Olmstead, J. and E.C. Brummer. 2008. Benefits and barriers to perennial forage crops in Iowa corn and soybean rotations. Renewable Agriculture and Food Systems 23:97-107.

Rayburn, A.P., and L.A. Schulte. 2009. Landscape change in an agricultural watershed in the U.S. Midwest. Landscape and Urban Planning 93:132-141.

StatSoft, Inc. 2011. STATISTICA (data analysis software system). Version 10. www.statsoft.com.

Wuebbles, D.J., and K. Hayhoe. 2004. Climate change projections for the United States Midwest. Mitigation and Adaptation Strategies for Global Change 9:335-363.

Wymar, P. 2007. Chippewa River Watershed Monitoring Summary 2007: Reading the Land in the River. Montevideo, MN: Chippewa River Watershed Project.