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# Validation of an agroecosystem process model (AGRO-BGC) on annual and perennial bioenergy feedstocks

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ABSTRACT

Corn (*Zea mays* L.) residues and perennial $C_4$ grasses are two Midwest bioenergy feedstock candidates due to their compatibility with agricultural infrastructure and potential for ecosystem service delivery. We validated the ecosystem process model AGRO-BGC by comparing model estimates with empirical observations from corn and perennial $C_4$ grass systems across Wisconsin and Illinois under no-tillage, nitrogen fertilized, and unfertilized management. Validation parameters included soil organic carbon (SOC), total soil nitrogen (N) to 1.2 m, aboveground net primary productivity (ANPP), net ecosystem productivity (NEP), and leaf area index (LAI). We parameterized AGRO-BGC to represent ecophysiological characteristics of corn and perennial prairie grasses, and constructed scenarios to represent corresponding edaphic, climate, and management conditions. Unfertilized annual model estimates had normalized mean average errors relative to field measurements of 0.3, 23, and 4 t ha$^{-1}$ for ANPP, SOC, and N, respectively. Fertilized simulations erred from observations by 0.6, 29, 5 t ha$^{-1}$ for ANPP, SOC, and N, respectively.

We also estimated long-term implications of varying residue removal rates on SOC. Model estimates compared to field data tested the hypothesis that long-term increased residue removal decreases SOC. Field observations showed 0.17, 0.09, and a −0.17 t C ha$^{-1}$ yr$^{-1}$ change for control, harvest, and bare grass residue removal treatments, respectively. Simulated SOC loss was greatest for the most intensive residue removal scenarios (−0.48 and −0.68 t C ha$^{-1}$ yr$^{-1}$ for corn and grass, respectively), compared to no-harvest scenarios that increased SOC by 0.05 t C ha$^{-1}$ yr$^{-1}$ for both corn and grass. AGRO-BGC estimated a 0.07 t C ha$^{-1}$ yr$^{-1}$ loss under corn residue harvest, while estimating 0.09 t C ha$^{-1}$ yr$^{-1}$ loss for grass. Results suggest long-term increased corn and grass residue harvest (beyond grain) for biofuel feedstock will decrease SOC and soil productivity by approximately 15% in corn and 21% in grass systems over 47 years.



## 1. Introduction

Agricultural residues are estimated to provide 350 million dry tons of bioenergy feedstock, 70% of which could come from corn (*Zea mays* L.) stover or corncob biomass. These residues are poised for bioenergy feedstock because of their ample supply, low cost, and widespread availability in the Upper Midwest (Perlack and Stokes, 2011). The 2007 Energy Independence and Security Act (EISA) set forth provisions to promote the use of renewable energy through the Renewable Fuels Standard (RFS). This mandate calls for the production of 36 billion gallons per year (BGY) of renewable fuels by 2022, 16 of which are to come from cellulosic biofuels and 14 BGY from advanced biofuels (Perlack and Stokes, 2011).

The USDA estimates that crop yields will increase by 9.5% over the next ten years, generating the potential for increased amount of crop residues available for allocation to bioenergy production (Perlack and Stokes, 2011). While the production potential of crop residues is great, there is still uncertainty around how much residue

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can be harvested to meet bioenergy feedstock demands without decreasing long-term soil productivity (Mann et al., 2002; Lal, 2005; Blanco-Canqui and Lal, 2007; Wilhelm et al., 2007; Cruse and Herndl, 2009; Surendran Nair et al., 2012).

Changing land cover from natural vegetation to agriculture results in an initial, large loss of $CO_2$ from the soil to the atmosphere (Schlesinger, 1997). Continued cultivation results in chronic low-levels of $CO_2$ released to the atmosphere due to reduced inputs of plant detritus and increased decomposition rates compared with pre-cultivation vegetation conditions (Jenkinson and Coleman, 1994). Carbon release is further intensified by current competing agricultural practices that include harvest for livestock bedding, silage, and manure-stover slurry, in addition to the potential harvest for bioenergy feedstock. When left on the field, residues provide erosion protection and carbon (C) and nitrogen (N) inputs to soils. Some research suggests that long-term removal of residues will create plant nutrient deficiencies unless N is replaced by alternative inputs (Wilhelm et al., 2004; Lal, 2005). Another concern is that residue removal will decrease soil organic matter (SOM) stocks in agroecosystems (Lal and Pimentel, 2007), which would likely result in decreased nutrient content, diminished biological activity, and degraded soil structure. The removal of crop residues can alter these processes by changing energy balances and leaving soil surfaces exposed to wind and water impacts. These can significantly degrade soil quality and contribute to soil loss, which is detrimental to agricultural systems and environmental quality.

One major uncertainty surrounding bioenergy feedstock production is the long-term sustainability of soil fertility, and the amounts of crop residues that can be sustainably harvested from agroecosystems to meet US bioenergy needs. Field studies provide useful insights into the short-term effects of different management practices on soil productivity, however SOC and N are slow to respond to external change (Jenkinson and Coleman, 1994) and empirical data on long-term residue manipulation studies for agroecosystems are rare, particularly for bioenergy feedstocks. An alternative is to employ a long-term SOC dataset from an annually managed experimental prairie site as a proxy to explore the effects of residue manipulations in agroecosystems. Using ecosystem process modeling tools such as AGRO-BGC (Di Vittorio et al., 2010) validated with empirical field data can help elucidate the long-term implications of residue management policies (Peckham and Gower, 2011). We applied AGRO-BGC to a Wisconsin system to estimate the effects of residue harvest over the long term.

The application of ecosystem process models, such as AGRO-BGC, BIOME-BGC, CENTURY and AGRO-IBIS (Parton et al., 1987; Kucharik, 2003; Wang et al., 2005; Di Vittorio et al., 2010; Peckham and Gower, 2011), on natural and managed ecosystems improves understanding of the functions and dynamics of complex ecosystems. They improve understanding of the magnitude and variability of management effects over time scales (i.e. multiple decades) that are rarely captured by existing empirical research studies (Peckham and Gower, 2011). Interactions among management practices, erosion, SOM, nutrients, and crop or biomass yields are complex, and the use of AGRO-BGC can assist in clarifying these interactions over the long-term.

The ability to simulate the dynamics of an annual cropping system is constrained by our understanding of underlying agroecosystem dynamics, access to accurate climate and edaphic information, and our ability to assign correct ecophysiological values to vegetation subroutines of models. AGRO-BGC simulates C, N, and water cycles, and their interactions, and allows users to simulate ranges of irrigation inputs, annual seed planting, fertilizer application, and harvest practices (Di Vittorio et al., 2010). The predecessor of AGRO-BGC, BIOME-BGC, has been validated extensively against eddy covariance flux tower data (Turner et al., 2005) and against long-term empirical field data sets across evergreen and deciduous forests (Turner et al., 2002; Peckham and Gower, 2011). Both models have been validated in perennial grass systems and BIOME-BGC has been validated in an annual corn cropping system in China (Wang et al., 2005), but neither has been applied to annual corn cropping systems in the Upper Midwest under the context of bioenergy feedstock production.

The two objectives of this research were to (i) validate AGRO-BGC by comparing simulated results with empirical observations from multiple agricultural field sites across Wisconsin and Illinois, and to (ii) use the model to explore long-term implications of residue removal on soil productivity. Metrics of evaluation included comparing model estimates of state variables and magnitude of fluxes with field measurements. Because agroecosystems are highly modified through varying management practices and desired production outputs, a realistic and robust ecosystem process model should be able to capture the effects of these practices on soil dynamics.

## 2. Materials and methods

We modeled C and N dynamics for one experimental agricultural system in south central Wisconsin, for one active farm in central Illinois, and for two perennial grassland systems (i.e. prairie restorations) also in south central Wisconsin. The experimental agricultural system was in continuous corn production, while the farm validation site was in annual soybean (*Glycine max*) – corn crop rotation. The prairie sites consisted of mixed perennial grasses. All AGRO-BGC simulations were conducted as either continuous corn or perennial grass ecosystems, and detailed information on modeling phase characteristics is in Section A of the Supplementary Information.

### 2.1. Validation site descriptions

Validation field sites were selected to evaluate the model's performance in four specific areas: seasonal phenology (i.e. how well the model captures maxima, minima, and changes throughout the growing season), carbon allocation (i.e. how accurately the model distributes carbon to above ground plant pools), how well the model estimates carbon pools and fluxes, and how accurately the model captures the above soil and plant variable responses to repeated annual harvests (Table 1).

The pre-settlement dominant land cover type in Southern Wisconsin was a mixture of prairie and oak (*Quercus* spp.) savannah (Cottam and Loucks, 1965). Following settlement, arable land was put into agriculture production for growing wheat (*Triticum aestivum*), oats (*Avena sativa*), tobacco (*Nicotiana tabacum*), and hops (*Humulus lupulus*), or put into pasture for livestock or dairy. The late 1800s brought about annual row crop production, particularly corn and soybeans (Schaefer, 1922).

The Arlington (AG) dataset provides a robust quantitative assessment of C stocks and fluxes in a corn agroecosystem, particularly metrics for productivity including SOC, total soil N, and ANPP (Kucharik et al., 2001; Brye et al., 2002). The Arlington dataset also provides a robust water budget to supplement the C simulations, including estimates of evapotranspiration (ET; Brye et al., 2000). This site is situated in the University of Wisconsin-Madison's Arlington Agricultural Research Station in Arlington, WI (Latitude: 43.283, Longitude: −89.366). The AG site was on a Plano silt loam (fine-silty, mixed, superactive, mesic Typic Argiudoll) that developed in loess over glacial till (Brye et al., 2002). The corn study, established in the spring of 1995, consisted of four replicate test plots (9.1 m × 12.2 m) of continuous corn under various management practice combinations, with an annual fall grain harvest and crop residues left on the field. Specific management practices