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Carbon and nitrogen environmental trade-offs of winter rye cellulosic biomass in the Chesapeake Watershed

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ABSTRACT

Cellulosic biomass from winter crops can complement maize stover harvested from maize (*Zea mays* L.) – soybean (*Glycine* max L.) rotations. In this study, we assessed on-field environmental impacts related to carbon (C) and nitrogen (N) by modeling representative agro-ecological conditions prevalent in the mid-Atlantic region of the United States. We used the biophysical model Cycles to simulate management scenarios for maize-soybean cropping systems that included winter rye (*Secale cereale* L.). The model was used to quantify changes in N losses via nitrate leaching (NO_3), emissions of nitrous oxide (N_2O) and ammonia (NH_3), changes in soil organic carbon, and carbon dioxide equivalent emissions per megajoule (CO_{2eq} MJ^{-1}). Including winter rye in the rotation reduced NO_3 leaching over a winter fallow control (77% on average), even when the winter rye was fertilized and regardless of whether stover, winter rye, or both cellulosic feedstocks were harvested. Applying fertilizer to winter rye did however increase NO_3 leaching as well as NH_3 and N_2O emissions. Model results consistently showed fertilizing the winter rye improved both biomass yield and soil C levels compared to unfertilized winter rye, regardless of location, soil, fertilizer type or stover harvest. While it is difficult to simultaneously reduce agricultural nitrogen losses, produce renewable energy and increase soil carbon, results can guide management of these trade-offs while tapping into an abundant energy resource and reducing greenhouse gas emissions.

1. Introduction

Winter cover crops are being re-conceptualized as biomass double crops, which can serve as food-neutral feedstocks for biofuels, bio-based chemicals and biomaterials. Examples relevant to temperate cropping systems include immature grasses such as triticale (× *Triticosecale*) (Heggenstaller et al., 2008) and winter rye (*Secale cereale* L) (Baker and Griffis, 2009) for cellulosic biofuels, or mature oilseeds like canola (*Brassica napus* L.) (Smith et al., 2007) and pennycress (*Thlaspi arvense* L.) (Moser et al., 2009) for biodiesel or aviation fuel. Only about 2% of the U.S. cropland is currently double cropped, mostly in systems with soybean (Borchers et al., 2014) and surveys indicate that producers are willing to plant more area with cover crops if the economic incentives to do so are in place (Singer et al., 2007).

Although cover crops have well documented environmental benefits for soil and water quality and other ecosystem services (Schipanski et al., 2014), environmental trade-offs can occur when these same winter crop species are monetized as double crops, e.g. when fertilizer is likely to be applied to increase yield, and aboveground biomass is harvested and sold. A dearth of data currently exists for double cropping systems on important metrics to quantify these trade-offs, such as the change in soil organic carbon (SOC), nitrogen (N) losses, and greenhouse gas (GHG) emissions.

Multi-cropping systems have been increasing internationally, generating the equivalent of 42 million ha of additional cropland productivity since 2000 (Langeveld et al., 2014). In the Chesapeake Watershed, the focus is still on maximizing production of summer annual crops, and most fields are left fallow during any given winter. However, over the last decade there has been an expansion of cover crop use, motivated in part by financial incentives from conservation programs for water quality and soil tilth benefits. These programs rarely cover the full cost of implementation, reducing farmer participation.

Bioenergy markets could provide additional economic incentives for winter crops and thus increase their acreage, but fertilizing to increase biomass yield and harvesting the aboveground biomass would change the carbon (C) and nitrogen (N) dynamics and presumably reduce environmental benefits. To shed light on our understanding of the environmental trade-offs of energy double crops relative to conventional practices of winter fallow or cover crops, deterministic biophysical models of the soil-plant-atmosphere continuum can be used to simulate

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C and N dynamics. These models make it possible to evaluate a range of scenarios for longer timescales than is possible with field experiments, and can be configured to analyze the effects of soil and climate on management scenarios (e.g. Meki et al., 2013; Bassu et al., 2014). Simulations of double cropping systems can provide important insights to farm operators and policy makers interested in establishing a viable bioenergy market with minimal impact on food production from existing cropland.

In this study, we employed an agroecosystem simulation model, Cycles, to assess the trade-offs of double cropping systems that include winter rye in rotation with corn and soybean. Cycles is a daily time step cropping system model based on modules developed in C-Farm (Kemanian and Stöckle, 2010) and CropSyst (Stöckle et al., 2003) to simulate the plant-soil-atmosphere system. We selected winter rye because of its robust germination and establishment, frost tolerance, and ability to accumulate large amounts of biomass during early spring before summer crops are planted (Feyereisen et al., 2013). A corn-soybean rotation was selected due to its large acreage and potentially underutilized winter fallow period (Feyereisen et al., 2013). Our objective in this study was to assess the on-field C and N impact of a fertilized and unfertilized double cropped system of winter rye in representative agro-ecological conditions prevalent in the Chesapeake Watershed. The environmental impact analysis was based on some of the environmental indicators for bioenergy sustainability recommended by McBride et al. (2011): nitrate leaching (NO_3 kg ha^{-1}), nitrous oxide emissions (N_2O kg ha^{-1}), ammonia volatilization (NH_3 kg ha^{-1}), carbon dioxide equivalent emissions per unit of energy grown (CO_{2eq} MJ^{-1}), and changes in SOC compared to a winter fallow period (kg C ha^{-1}). These outputs were selected because they reflect water quality, GHG emissions and soil quality impacts (McBride et al., 2011) and can provide guidance to manage trade-offs while tapping into a potentially low C emission energy source. While these environmental metrics have been investigated individually in systems across the Northeast and Midwest US (Feyereisen et al., 2006; Heggenstaller et al., 2008; Baker and Griffis, 2009; Thomas et al., 2013), comparative assessments of the trade-offs between these environmental impacts have not previously been done. The locations selected for the analysis span a range of growing season lengths in the Chesapeake Watershed: Rock Springs and Lebanon in PA, and Beltsville in MD.

2. Methods

2.1. Goal, scope and study site

This environmental trade-off analysis compared various biomass management scenarios in Rock Springs, PA (41° 12′ 12″N, 77° 11′40″ W), Lebanon, PA (40° 20′ 26″N, 76° 24′42″ W), and Beltsville, MD, (39° 2′ 5″N, 76° 54′28″ W) in the mid-Atlantic United States using the Cycles model. All three locations are within the boundaries of the Chesapeake Bay watershed, where nutrient contamination from agriculture is a major water quality concern.

Cellulosic biomass from double cropped winter and summer crops was generated from variations of a basic corn-soybean rotation. Management scenarios assessed the soil initial conditions (manured history or not), the biomass harvested (winter rye or corn stover) and the N fertilizer management applied to corn (manure or synthetic fertilizer), the details of which follow. Although this study did not consider downstream uses of the cellulosic biomass, both corn stover and winter rye are herbaceous grasses; winter rye would be harvested before seed maturity and is expected to be more easily converted to biochemical or biofuels than stover (Shao et al., 2015). Double-crop biomass harvesting strategies were compared to two "conventional" management practices in the region; *Winter Fallow* – nothing is planted in the winter, or *Winter Cover Crop* - a winter crop is planted, killed, and tilled into the soil in the spring.

Both past and present management decisions affect crop yield and environmental impacts. To understand the impact of historical land management representative of the dominant management practices in the region, two common initial soil conditions were simulated – soils with and without a history of manure application. Soils with or without a history of manure application are referred to as "High Organic Matter (HOM) Soil" or "Low Organic Matter (LOM) Soil", respectively. Three management schedules were designed to explore the effect of different strategies for cellulosic biomass harvest. The first schedule representing the conventional management practices was termed *Winter Fallow* and *Winter Cover Crop* where there was no harvest of any cellulosic biomass (neither rye nor stover). The second management schedule was termed *Rye Harvest* and used the winter crop as the source of cellulosic biomass every year after both corn and soybean summer crops. The third management schedule harvested corn stover in years when corn was grown and harvested winter rye after soybean; this was termed *Stover and Rye Harvest*. In the *Stover and Rye Harvest* schedule the winter crop acted as a cover crop "C supplement" in alternate years, and was not harvested the year after corn stover was harvested.

Finally, to shed light on the trade-offs between applying fertilizer to the winter crop to increase cellulosic biomass yield and the environmental impact, synthetic N fertilizer was applied at planting to the rye and termed *Fertilized Rye Harvest* and *Stover and Fertilized Rye Harvest*. Fertilizer rates for corn and soybean remained constant regardless or rye or stover harvest. These management scenarios are summarized in Table 1 and the model simulated tillage practices are summarized in Table 2. A schematic of the scenarios is illustrated in Fig. 1.

2.2. Soils

The soils in the three locations simulated are predominantly silt loam (Table 3). Soil profile data were downloaded from the USDA-NRCS National Soil Survey Center characterization database (NCSS,

Table 1
Summary of scenarios simulated. M = Total N mostly from manure (184 kg N ha^{-1}) with some synthetic fertilizer (67 kg N ha^{-1}); SF = all N from synthetic fertilizer. The rationale for N fertilization rates is discussed below.

Scenario	Description	N Fertilization			
		Corn		Winter Rye	
		M	SF	After corn	After soybean
		Total kg N ha^{-1}			
Winter Fallow	Fallow between summer crops of a corn-soybean rotation	252	186	–	–
Winter Cover Crop	Winter rye planted after corn and soybean, then killed and tilled-in the following spring	252	186	–	–
Rye-only Harvest	Winter rye harvested every year following corn and soybean	252	186	–	–
Stover and Rye Harvest	Winter rye harvested following soybean; corn stover harvested following corn	252	186	–	–
Fertilized Rye-only Harvest	N fertilizer applied at winter rye planting; harvest winter rye every year after corn and soybean	252	186	90	38
Stover and Fertilized Rye Harvest	N fertilizer applied at winter rye planting; harvest winter rye following soybean and corn stover following corn	252	186	90	38