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Biomass supply and nutrient runoff abatement under alternative biofuel feedstock production subsidies

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ABSTRACT

The objective of this paper is to design two types of subsidies for biofuel feedstock production and water quality improvement and to analyze how each subsidy affects biomass supply and the abatement of nutrient runoff associated with the conversion of cropland to biomass production. Per-hectare (per-ha) subsidy was designed as a system that pays producers for each ha of cropland converted to switchgrass production and per-megagram (per-Mg) subsidy was a system that pays producers for each Mg of switchgrass produced. This study focuses on Oostanaula Creek watershed in East Tennessee. The analysis used a dynamic programming model coupled with a Soil and Water Assessment Tool (SWAT) simulation model to predict profit-maximizing fertilizer application rates, crop yields, and nitrogen (N) runoff for a biofuel feedstock (switchgrass) and a conventional crop (corn) across 28 different landscapes in the watershed. A Monte Carlo analysis was conducted to simulate the impact of stochastic N fertilizer and corn prices and yields on subsidies over a ten-year planning horizon. A per-ha subsidy system is more cost effective and feasible than a per-Mg system because the former has significantly lower subsidy than the latter for each kilogram (kg) of N reduction and for each Mg of switchgrass harvested. Converting all of the cropland from corn to switchgrass over ten years results in 124,084 dry Mg of switchgrass and 23% reduction in nitrogen runoff for the per-ha system and 122,347 dry Mg of switchgrass and 3% reduction for the per-Mg subsidy system.

1. Introduction

The United States (U.S.) government has attempted to support growth in the production of transportation fuels from renewable resources (i.e., biofuels) by adopting a Renewable Fuel Standard (RFS). The RFS – adopted as part of the Energy Policy Act of 2005 and later revised by the Energy Independence and Security Act of 2007 – requires that U.S. annual production of biofuels reach 136 billion liters by the year 2022 (National Research Council, 2011). The RFS requires that 79 of these 136 billion liters be advanced biofuels derived from non-grain sources, and that at least 61 of the 79 billion liters of advanced biofuels are produced using cellulose, hemicellulose, or lignin renewable biomass which come from switchgrass, corn stover, wheat straw, and forest residues (Epplin et al., 2007; De La Torre Ugarte et al., 2007). Biofuel production has increased from under 15 billion liters in 2005 to over 53 billion liters in 2013 (U.S. Energy Information Administration, 2014). Meeting the advanced biofuel requirement will require dramatic increases in the production of cellulosic feedstock through large-scale changes in land use (Thomson et al., 2009).

The land needed to produce cellulosic feedstock will likely originate from the conversion of: (i) idle cropland including land enrolled in the Conservation Reserve Program (CRP) (Lubowski et al., 2006); (ii) conventional cropland (Song et al., 2011); or (iii) non-cropland. Projections by the U.S. Department of Agriculture (USDA) suggest that half of cellulosic feedstock to meet the RFS requirement will be grown in the southeastern U.S. because of favorable growing conditions (USDA, 2010).

To the extent that active cropland is dedicated to biofuel feedstock production, there is potential for both increased biofuel production and reduced sediment and nutrient runoff from these lands by selecting switchgrass as the dedicated energy crop (Liebig et al., 2005; De La Torre Ugarte et al., 2007; Hellwinckel et al., 2010). Switchgrass is a perennial

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Abbreviations: US-EIA, U.S. Energy Information Administration; CRP, Conservation Reserve Program; USDA, U.S. Department of Agriculture; SWAT, Soil and Water Assessment Tool; US-EPA, U.S. Environmental Protection Agency; EQIP, Environmental Quality Incentives Program.

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warm-season C4 plant with a strong, deep, and extensive root system that can hold and prevent soil erosion and filter nutrient loads (McLaughlin and Walsh, 1998; Simpson et al., 2008; Zhou, 2011; Zhou et al., 2015). As a result, switchgrass has often been planted as field edges and waterways to protect water quality (Nelson, et al., 2006). Switchgrass typically requires less fertilizer than conventional agricultural crops (Ranney and Mann, 1994; McIsaac et al., 2010), which also helps to decrease nutrient runoff (Nelson, et al., 2006; Parrish and Fike, 2005; Rinehart, 2006).

Furthermore, Babcock et al. (2007) found that the conversion of land from annual row crops to switchgrass production could significantly reduce nutrient loading of nitrate by 44%, total nitrogen by 53%, and phosphorous by 83% into waterways for Maquoketa River Watershed in Iowa (Zhou et al., 2015). Costello et al. (2009) estimated that producing cellulose biomass instead of corn for ethanol production decreased nitrate runoff by 20% in the Mississippi and Atchafalaya River Basins (Zhou et al., 2015). Using the Soil and Water Assessment Tool (SWAT) biophysical simulation model (Santhi et al., 2001), Nelson et al. (2006) estimated that producing switchgrass instead of corn–soybean–wheat or sorghum–soybean–wheat rotation would reduce sediment loading by 99%, surface runoff by 55%, N in surface runoff by 34%, and edge-of-field erosion by 98% (Zhou et al., 2015). Switchgrass edge-of-field breakeven price was estimated to range from \$40 Mg^{-1} with no N applied to \$24 Mg^{-1} with 224 kg N ha^{-1} applied because yield predicted by SWAT increased as N increased and average annual cost ranged from about 190 \$ ha^{-1} with no N applied to around 345 \$ ha^{-1} with 224 kg N ha^{-1}.

Reducing water quality degradation caused by agricultural production is also an important policy goal. Agriculture was the single most prevalent pollutant source in the U.S., contributing to over 209, 214 impaired river or stream kilometers (U.S. Environmental Protection Agency, 2009). Agriculture's extensive contribution to water quality degradation was explained, in part, by the extent to which agricultural production was exempt from the Clean Water Act regulations relative to other sources of water pollution (Zhou, 2011; Zhou et al., 2015).

In the absence of regulation, a common approach to reducing the adverse impacts of agricultural production on water quality is to offer agricultural producers subsidies that incentivize the adoption of emissions-reducing best management practices (Johansson et al., 2004; USDA-Environmental Quality Incentives Program, 2014). For example, the CRP pays farmers to convert erodible land to perennial grassland to reduce soil erosion and nutrient emissions (Johansson et al., 2004).

Subsidies designed to support ecosystem service provision through land use conversion have typically been paid through contracts that most closely resemble a lease. These programs typically consist of fixed, periodic payments over a fixed time period, typically on a per-ha basis. In some instances, contracts were awarded on a competitive basis where differences in the extent or quality of ecosystem services generated following conversion were one factor used to differentiate competing bids (Engel et al., 2008). However, these systems could be designed to pay on the basis of the quantity or quality of ecosystem services provided. For example, Antle et al. (2003) compared the cost-effectiveness of a per-ha payment for soil carbon sequestration to a contract of per-Mg payment system based not on area enrolled but on the amount of carbon sequestered. Their research concluded that per-Mg payment was more cost effective than per-ha payment because the latter were as much as five times more costly than the former. This research extends the comparison between these two payment systems to the context of biofuel feedstock production and to two dimensions, biomass supply and nutrient runoff abatement.

The objective of this paper is: 1) to design two types of subsidies – one based on per-ha of land converted and one on per-Mg of feedstock produced – for incentivizing feedstock production and water quality improvement; and 2) to analyze how each subsidy affects biomass supply and the abatement of nutrient runoff associated with the conversion of cropland to feedstock production. The amount of subsidy needed to induce cropland owners in the Oostanaula Creek watershed in East Tennessee to produce switchgrass instead of corn and the associated differences in N runoff – or the level of runoff abatement associated with converting cropland from corn to switchgrass production – were estimated using a dynamic programming model to profit-maximize fertilizer application rates incorporated with N carryover and runoff rates predicted by SWAT simulation model for 28 different landscapes in the watershed. A Monte Carlo analysis was conducted to simulate the impact of stochastic N fertilizer and corn prices and yields on subsidies over a ten-year planning horizon. Supply curves were derived for switchgrass production and N abatement for per-ha and per-Mg subsidy systems, respectively.

This study develops a modeling framework for nutrient dynamics incorporating runoffs for production of a conventional crop versus a bioenergy crop for profit-maximization and also demonstrates a subsidy program to reduce nutrient runoff through incentivizing farmers to produce the bioenergy crop in cost-effectiveness with spatial heterogeneity.

2. Data and methods

2.1. HRU determination

The Oostanaula Creek watershed is typical of the ridge-and-valley region of the Southeast US (Hagen and Walker, 2007), covering 182 km^2 (Tennessee Department of Environment and Conservation, 2002) of which hay is grown on 30%, forest accounts for 40%, and crop land takes up 6%. Carryover and runoff rates of the crop land including 28 unique combinations of slope, soil type and land use, or what are known as hydrological-response units (HRUs) delineated in SWAT, were obtained from ten years of simulation runs of the SWAT model calibrated for the Oostanaula Creek watershed (Zhou, 2011; Zhou et al., 2015). Average soil N carryover rates for the HRUs for the watershed were 0.05 year^{-1} for corn and 0.07 year^{-1} for switchgrass and average N runoff rates were 0.12 year^{-1} for corn and 0.11 year^{-1} for switchgrass.

2.2. Data

Switchgrass yield data was obtained from an N fertilization experiment on well-drained upland conducted at the University of Tennessee Milan Research and Education Center at Milan, TN (35°56′N, 88°43′W) from 2005 to 2011. The soil type was primarily Grenada silt loam, very suitable for row crop production. The experimental design was a randomized complete block with a strip-plot arrangement of treatments and four replications. The switchgrass was established in 2004. In 2005, the blocks were split into strips. The annual N fertilization rates were 0, 67, 134, and 202 kg ha^{-1} from 2005 to 2011. The N source was ammonium nitrate (34-0-0).

Corn yield data was collected from an N fertilization experiment conducted from 2006 to 2011 at the same site as the switchgrass experiment. The soil type was predominantly Grenada silt loam, which is very good for corn production. Corn was planted in a 76-cm row spacing under no-tillage in April. Each plot was 4.5 m wide and 9 m long. The experimental design was a randomized complete block with four replications. The annual N fertilizer rates were 0, 62, 123, 185, and 247 kg ha^{-1}. N fertilizer was uniformly spread to the soil surface as ammonium nitrate (34-0-0). All N applications occurred within a week after planting.

Annual price data on N from 2001 to 2011 and corn from 1980 to 2012 were obtained from USDA-National Agricultural Statistics Service (NASS) (2012). Nominal prices were converted to real prices using the U.S. Bureau of Economic Analysis (EBA) producer price index (U.S. EBA, 2012). In the absence of an active market for switchgrass, a single farm-gate price of \$53 dry Mg^{-1} for switchgrass was used as the price a biorefinery would be willing to pay for switchgrass less any costs