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Research paper

Regional differences in impacts to water quality from the bioenergy mandate

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ABSTRACT

The bioenergy mandate under Energy Independence and Security Act (EISA 2007) will result in large scale land-use changes in the US if it is ever fully realized. Energy crops such as switchgrass (Panicum virgatum) and miscanthus (Miscanthus X giganteus) can grow well throughout the continental United States; however, most studies on the water quality impacts of land-use change from bioenergy policy are based in the Midwest. Insufficient research has been conducted to determine whether the results from the Midwest are applicable to other regions in the United States. This study compares water quality impacts of converting from corn to switchgrass in the Midwest (Upper Cedar watershed) and Southeast (Lumber watershed) with nitrogen loading to surface water as a proxy metric for overall water quality impacts using the Soil and Water Assessment Tool (SWAT). The analysis shows that the fraction of nitrogen runoff compared to the fertilizer applied is 36% in Upper Cedar as compared to 6% in Lumber. Existing management practices like tile-drainage and land-cover like riparian wetlands contribute to this difference in the baseline nitrate export from each watershed. The potential reduction in nitrogen loading per potential liter of ethanol to surface waters, which account for both nitrate export and productivities, from the baseline corn-soy to switchgrass is about 40% for the Upper Cedar watershed and around 80% for the Lumber watershed. Although, the trend in reduction is similar in both watersheds, this study shows that results extrapolated from the Midwest may not be representative of other bioenergy producing regions.

1. Introduction

Following concerns over energy security and efforts to reduce greenhouse gas emissions to mitigate climate change, the US Energy Independence and Security Act (EISA 2007) mandated the production of 136 billion L of biofuel a year to be used in the transportation sector by 2022. This includes 56.8 billion L of corn ethanol and 79.5 billion L of cellulosic and other advanced biofuel. The updated Billion-Ton Annual Supply Report (BT2), commissioned by the US Department of Energy (DOE) and Department of Agriculture (USDA), predicted that the production of biofuels to meet the mandate would result in a land-use change of 16–24 million hectares on agricultural and marginal land [1]. The BT2 analysis includes all states in contiguous US with significant quantities of feedstock coming from outside the Midwest. Such large scale land use change will significantly impact water resources, both in terms of quality and quantity.

The current knowledge about the impacts from the mandate comes from field studies [2–4], modeling studies at the field, farm and watershed scales [5–7] and system-wide studies in the Mississippi River Basin in the context of the Gulf of Mexico hypoxia [8,9]. The United States EPA [10], the National Research Council [11] and the Government Accountability Office [12] have extensively reviewed available literature on agricultural land-use change to evaluate the impacts of EISA 2007. These studies indicate that the nature and magnitude of the impact of agricultural land-use change on water quality depends on the prior land-use, crop type, climatological, topological factors and management practices [13–15]. While intensification of row crop agriculture for bioenergy feedstock cultivation will undoubtedly impair water quality, not all impacts from biofuels are negative or equal in magnitude. Studies have shown that growing perennial grasses in the place of corn/other row crops for cellulosic ethanol mitigates water quality

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impacts and improves soil quality [3,16,17].

The large scale studies that have evaluated the impacts of the mandate on water quality have been primarily in the context of the Gulf of Mexico hypoxia and therefore focus on land use change in the Mississippi River Basin (MRB). System-wide studies, which we define here as the studies that look at implementation of the 136 billion L EISA goal, have been generally assumed that all conventional and cellulosic ethanol in the US will be grown within the MRB. The challenge in conducting a large scale study is the uncertainty in predicting the future land-use in different parts of the US, therefore some system-wide studies address it in one of two ways; using deterministic models or physically based models coupled with agent based/economic models to model the future land use change [8] or employing scenario analysis to construct future landscapes [9,13]. Comparing these system wide studies show that the impacts from the mandate are scenario specific and goal-specific.

If all the production from EISA 2007 were to occur in the MRB, these studies indicate that the mandate may be unsustainable from a water and soil perspective. Perennials such as switchgrass and miscanthus have high, if not higher, productivity in the Southern and Southeastern parts of the United States [18–20]. There also has been recent interest in using marginal land in the Midwest and Northeast to grow alternative energy crops [21,22]. Therefore it is necessary to consider all major agricultural regions in the US to better understand how different land use changes in different regions will have different water quality impacts. Unfortunately, there are few studies that analyze the regions outside the Corn Belt and fewer still outside the MRB, either through modeling efforts or collection of field data and none that are at the system-wide scale to the best of our knowledge. Further, within the MRB there are far more modeled studies in the Corn Belt than other regions.

While the land-use change impacts, especially the conversion from a field crop to perennials, follow similar trends as in the Corn Belt, a comparison of relative differences between different regions has not yet been assessed. There are a number of field studies on small controlled plots [2,4,23] but fewer modeling studies outside the MRB specifically looking at water quality impacts from bioenergy conversion [3,24,25]. Of two recent studies looking at land-use change from cotton to switchgrass in the southeastern Coastal Plains in South Carolina and southern plains in Texas [3,24,26], only one looks at water quality impacts.

It is also more challenging to apply the methods used by the system-wide studies such as Donner and Kucharik [8] and Demissie et al. [13] to areas outside the Mississippi River Basin using physically based hydrological models such as the Soil and Water Assessment Tool (SWAT). Most hydrological models, including SWAT, were developed specifically for watersheds dominated by agriculture [27,28]. Many of the agricultural regions outside the Corn Belt are characterized by heterogeneous landscapes that are more difficult to model and are data-scarce. SWAT requires more calibration from the defaults when applied to watersheds with poorly drained soils and mixed land-use, wetlands or forests, as is often the case in the watersheds in Southeastern Coastal Plain [29–31]. Nutrient monitoring data is less frequently available in these regions, making model calibration difficult. Despite these challenges, a comprehensive analysis of the biofuel mandate should incorporate regional differences in expected water quality impacts based on region-specific parameters.

Although there have been studies that have compared differences in water quality impacts from the mandate between watersheds [7,32], this is the first study to our knowledge, that compares impacts between watersheds in two different regions. We demonstrate that there are significant regional differences in impacts to water quality for similar land-use transitions. The SWAT model was used to simulate the impacts of agricultural land management practices on nitrogen loading assuming a two-year corn-soy rotation replaced by switchgrass. The percentage difference in nitrogen loading per unit potential bioenergy produced between corn-soy rotation and switchgrass of an agriculture-dominated watershed in Iowa is compared to that of a more diverse watershed in North Carolina.

2. Data and methods

2.1. Study areas

The Upper Cedar River watershed in Iowa and the Lumber watershed in North Carolina were chosen to ensure that agriculture formed a significant portion of the land-use (Fig. 1). From a statistical evaluation looking at the percentage of each land cover class in watersheds in the Midwest (387 watersheds) and southeastern region (432 watersheds), these watersheds are representative of the regions as represented by Figures 1 and 2 in Supporting Information (Data S1).

The Upper Cedar Watershed (USGS HUC8 07080201, 4403 sq. km), located between 43° 45′ 16.3” N, 93° 14′ 47.1” W and 42° 43′ 15.5” N, 92° 22′ 1.8” W, is one of six subbasins in of the Cedar River Basin, a well-studied region with more than 81% agriculture [33]. Within Upper Cedar Watershed, more than 70% of the total land-cover is corn-soy rotation with extensive tile drainage (USDA CDL 2007), which is typical for the Midwest Corn Belt. The soils are primarily loamy derived from glacial till [34] and are mostly poorly drained. The annual precipitation is between 800 and 900 mm with the highest amount of precipitation occurring in the summer months [35].

The Lumber watershed (USGS 03,040,203, 4688 sq. km) in the Coastal Plain region of North Carolina and South Carolina, located between 35° 12′ 39.81” N, 79° 38′ 0.46” W and 34° 11′ 26.51” N, 78° 44′ 43.23” W is primarily wetland dominated (35%), with a large percentage of the land-use in forested land(26%) and agriculture (24%). The Coastal Plains are characterized by high annual precipitation (~1250 mm/year), sandy-loamy soils and high evapotranspiration during the hotter months [30]. The watershed is a part of the Coastal Plain and groundwater discharge in wetlands contributes a significant portion of streamflow to riverine transport.

The presence of tile drainage in one watershed and riparian wetlands in the other makes the study of these two watersheds an exceptionally contrasting one. Tile drainage in the Midwest has steadily increased the proportion of baseflow in the watersheds. It has been found that the increasing nitrate export to surface waters in Iowa is correlated to the base flow [36,37]. On the other hand, wetlands reduce nutrient export by settling nutrients, increasing their absorption into sediments, uptake through growth of biomass and presenting good conditions for denitrification [38]. Therefore, the results of this study could also offer insight into the range of reduction in nitrogen export from LUC.

2.2. The SWAT model

The Soil and Watershed Assessment Tool (SWAT) is a well validated, continuous time physically based hydrologic model that can simulate impacts of agricultural land management practices on sediment and nutrient loading [39]. SWAT delineates watersheds and the stream network based on the digital elevation model (DEM) input by the user or based on a pre-defined watershed. The watershed is further divided into sub-watersheds or subbasins. All processes in SWAT are simulated at the Hydrologic Response Unit (HRU) level, that represent unique soil, slope and land-use characteristics within each sub-watershed. The climate, land-use and