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Research paper

Improving water quality in the Chesapeake Bay using payments for ecosystem services for perennial biomass for bioenergy and biofuel production

Peter B. Woodbury [a, *], Armen R. Kemanian [b], Michael Jacobson [b], Matthew Langholtz [c]

[a] *Soil and Crop Sciences, 1017 Bradfield Hall, Cornell University, Ithaca, NY 14853, USA*
[b] *The Pennsylvania State University, University Park, PA, USA*
[c] *Oak Ridge National Laboratory, Oak Ridge, TN, USA*

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ABSTRACT

Replacing row crops with perennial bioenergy crops may reduce nitrogen (N) loading to surface waters. We estimated the benefits, costs, and potential for replacing maize with switchgrass to meet required N loading reduction targets for the Chesapeake Bay (CB) of 26.9 Gg^{-1}. After subtracting the potential reduction in N loading due to improved N fertilizer practices for maize, a further 22.8 Gg reduction is required. Replacing maize with fertilized switchgrass could reduce N loading to the CB by 18 kg ha^{-1} y^{-1}, meeting 31% of the N reduction target. The break-even price of fertilized switchgrass to provide the same profit as maize in the CB is 111 $ Mg^{-1} (oven-dry basis throughout). Growers replacing maize with switchgrass could receive an ecosystem service payment of 148 $ ha^{-1} based on the price paid in Maryland for planting a rye cover crop. For our estimated average switchgrass yield of 9.9 Mg ha^{-1}, and the greater N loading reduction of switchgrass compared to a cover crop, this equates to 24 $ Mg^{-1}. The annual cost of this ecosystem service payment to induce switchgrass planting is 13.29 $ kg^{-1} of N. Using the POLYSYS model to account for competition among food, feed, and biomass markets, we found that with the ecosystem service payment for switchgrass of 25 $ Mg^{-1} added to a farm-gate price of 111 $ Mg^{-1}, 11% of the N loading reduction target could be met while also producing 1.3 Tg of switchgrass, potentially yielding 420 dam^3 y^{-1} of ethanol.

1. Introduction

Producing perennial biomass feedstocks for bioenergy can have environmental benefits at the watershed scale. Such benefits are additional to other economic and greenhouse gas benefits of bioenergy production. If paid for, such additional environmental benefits, or ecosystem services, could increase the financial return to growers and increase investments in bioenergy industries and total bioenergy production. This is particularly important when low fossil fuel prices put downward pressure on alternative energy sources, including bioenergy.

Ecosystem services are the benefits that humans derive directly and indirectly from nature [1, 2]. When such services are classified and quantified, payments can be allocated to internalize what are otherwise economic and financial externalities. Such "payments for ecosystem services" (PES) can support increased social welfare and improve decision-making about investments in new industries and land management practices.

One important environmental benefit of producing perennial bioenergy feedstocks compared to annual row crops is reduced nitrogen (N) leaching to surface and ground waters. For example, such reductions could occur if maize (*Zea mays* L.) area is replaced by switchgrass (*Panicum virgatum* L.) because switchgrass systems use N much more efficiently than maize due to having extensive root systems during all seasons that take up mineral N and store it in plant tissues [3]. Thus perennial crops such as switchgrass lose much less N to the environment, including leaching to streams and rivers which pollutes the coastal zone with excess N loading. This

Abbreviations: BMP, Best Management Practice, the best practices achievable on farms using current technologies, information and equipment; Bay, Chesapeake Bay; CBW, Chesapeake Bay Watershed.

* Corresponding author.
E-mail addresses: pbw1@cornell.edu (P.B. Woodbury), kxa15@psu.edu (A.R. Kemanian), mgj2@psu.edu (M. Jacobson), langholtzmh@ornl.gov (M. Langholtz).

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opens the possibility for switchgrass and other perennial biomass crops to be used synergistically to produce a suite of ecosystem services in watersheds including reducing nutrient pollution from agriculture.

Nutrient loading to coastal zones is a global issue that causes environmental problems such as damage to populations of aquatic plants and animals and increasing harmful and toxic algal bloom [4]. The Chesapeake Bay (henceforth "Bay") and its watershed (CBW) are emblematic of these issues (e.g. Ref. [5]. Despite decades of analyses and management, reductions in nutrient loading have not met the targets required to improve water quality [6]. States within the CBW are under increasing pressure to find feasible and cost-effective methods to reduce N loading (e.g. Ref. [7]. Replacing some maize fields with switchgrass that can be used for energy production could thus reduce N loading downstream to the coastal zone. Such reduced N loading can contribute to provision of multiple ecosystem services by healthy coastal zones including food production and recreation.

We estimate the potential benefit of replacing maize area with switchgrass to reduce inorganic N loading to surface waters in the CBW. Specifically, we estimate the total area and cost required to use this approach to meet the Bay nutrient reduction targets set for 2025, and the degree to which the goals could be met given the available land base and the area suitable for improved management practices to reduce N loading. Finally, we estimate the extent to which growers might be induced to grow switchgrass in place of maize while accounting for national demand for food and feed crops based on an economic model and our estimate of the payment of ecosystem services that could be available to reduce N loading to the CBW. Our analysis is intended to support strategic decision-making about the extent to which PES could both improve water quality and produce products such as ethanol to help meet society's demand for transportation fuels.

2. Methods

The analysis has six main steps to determine:

1) N loading from maize to fields in the CBW;
2) N loading reduction from replacing maize with switchgrass;
3) N loading reduction from adding winter rye (*Secale cereale* L.) to maize systems;
4) switchgrass price with and without payment for N loading reduction;
5) payments for N loading reduction; and
6) potential future area of switchgrass using economic modeling.

To accomplish these steps, our approach was to use the best available estimates of each parameter required in the calculations based on existing literature and supplemented by model results. A description of these steps follows in Sections 2.1–2.6 and summarized in Table 1.

2.1. Nitrogen loading from maize

Nitrogen loading depends in particular on N fertilizer rate, timing, and harvest removal. Therefore, we estimated N fertilizer rates and subsequent N loading to the Bay from current average maize management business as usual (M+BAU) and also from best management practice maize management (M+BMP).

Most of the maize production in the CBW occurs in Pennsylvania. While average N fertilizer application rates per state are available, these data are not adequate to determine representative N application rates for a given field due to crop rotations, manure use, local yield potential and other practical considerations. To estimate N fertilizer application rates by growers, we used data from on-farm research trials in the region, modified to reflect average maize yields in Pennsylvania. Specifically, we used data from an on-farm research study for maize grain production without manure at 50 site-year combinations from 2011 to 2013. From this study, the average N fertilizer rate was 228 kg ha^{-1} y^{-1} (Table 1, [8,9]). The average maize yield in these trials was 11.7 Mg ha^{-1} (15.5% moisture on green weight basis), which was higher than the average of 9.4 Mg ha^{-1} in Pennsylvania in 2015. We adjusted the N fertilizer rate by the ratio of the average yield in Pennsylvania to that in the 50 trials (i.e. 9.4/11.7) for a final estimate of 184 kg ha^{-1} y^{-1} (Table 1). Henceforth, this estimate of current average practice for maize will be referred to as M+BAU.

The on-farm trial mentioned above indicated that there is substantial room for improvement in N management and grower profit in maize production. Thus, we estimated the average N fertilizer rate using best management practices (BMP) from an online tool called "Adapt-N". This tool uses soil and management practice data to recommend the minimum side-dress N rate that will enable a target high yield based on the recent weather at the field location [10]. Based on the study mentioned above, the Adapt-N rate averaged 160 kg ha^{-1} y^{-1} for 50 trials (site x year) in NY [8,9]. Yet, on-farm yield in plots that followed Adapt-N recommendations were not lower than those with the higher average grower rate of 228 kg ha^{-1} y^{-1} [8, 9). Thus, we adjusted the N fertilization rate using the ratio of yield in Pennsylvania to that in the 50 trials (9.4/11.7) for a final estimate of 129 kg ha^{-1} y^{-1}, henceforth referred to Scenario M+BMP (Table 1). This recommendation is about 25% lower than the rule of thumb of approximately 22 kg of N per Mg of expected grain yield recommended by Pennsylvania State Extension [11]. For comparison, for New York State in 2007, we estimated previously an average recommended fertilizer rate for grain maize of 129 kg ha^{-1} y^{-1} [12,13], but because yields have increased since 2007, the Adapt-N recommendation represents an improved efficiency. This reduction in N rate increased average grower profits by 91 $ ha^{-1} because yields were not decreased (Table 1, [9]. This reduction in N rate will also reduce N loading to surface and groundwater compared to current average management practices.

To estimate changes in N loading to the CBW coastal zone we must estimate (a) the N amount leaching below the rooting zone, (b) the N amount reaching streams via interflow and surface flow, and (c) the N amount reaching the coastal zone after transport and processing in streams and rivers. The amount of N leaching below the rooting zone was modeled for the 50 site-year combinations discussed above using Adapt-N. For the average grower fertilizer rate, the average N leaching below the rooting zone was 44.8 kg ha^{-1} y^{-1}. This leaching rate is close to the surplus N obtained by subtracting the N in the harvested grain from N in fertilizer and other inputs. This rate was adjusted downward as described above based on the lower average yields in Pennsylvania compared to those in the on-farm trials, resulting in an adjusted value of 36.2 kg ha^{-1} y^{-1}.

Losses of N due to denitrification in the subsurface soils during transport below the rooting zone to the stream were calculated using the difference between basin-wide N inputs and measured concentrations of N in rivers near the coastal zone weighted by the flow. The Susquehanna River Basin is the dominant source of water and nutrients to the CBW. For the Susquehanna Basin, we assumed that the fraction of N entering the Bay from the river was 0.21 of that entering the entire watershed as calculated by Woodbury et al. [14]. We assumed that this input/output ratio can be multiplied by the N fertilizer rate to estimate the fraction of the N that would end up as N loading to the coastal zone. Losses in the riverine system have been estimated using the SPARROW model, and the average N delivery ratio of the river system within the basin is 0.98 (Table 1,