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Research paper

# Life cycle air quality impacts on human health from potential switchgrass production in the United States

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## ABSTRACT

Switchgrass is a promising bioenergy feedstock, but industrial-scale production may lead to negative environmental effects. This study considers one such potential consequence: the life cycle monetized damages to human health from air pollution. We estimate increases in mortality from long-term exposure to fine particulate matter ($PM_{2.5}$), which is emitted directly ("primary $PM_{2.5}$") and forms in the atmosphere ("secondary $PM_{2.5}$") from precursors of nitrogen oxides ($NO_x$), sulfur oxides ($SO_x$), ammonia ($NH_3$), and volatile organic compounds (VOCs). Changes in atmospheric concentrations of $PM_{2.5}$ (primary + secondary) from on-site production and supporting supply chain activities are considered at 2694 locations (counties in the Central and Eastern US), for two biomass yields (9 and 20 Mg $ha^{-1}$), three nitrogen fertilizer rates (50, 100, and 150 kg $ha^{-1}$), and two nitrogen fertilizer types (urea and urea ammonium nitrate). Results indicate that on-site processes dominate life-cycle emissions of $NH_3$, $NO_x$, primary $PM_{2.5}$, and VOCs, whereas $SO_x$ is primarily emitted in upstream supply chain processes. Total air quality impacts of switchgrass production, which are dominated by $NH_3$ emissions from fertilizer application, range widely depending on location, from 2 to 553 \$ $Mg^{-1}$ (mean: 45) of dry switchgrass at a biomass yield of 20 Mg $ha^{-1}$ and fertilizer application of 100 kg $ha^{-1}$ N applied as urea. Switching to urea ammonium nitrate solution lowers damages to 2 to 329 \$ $Mg^{-1}$ (mean: 28). This work points to human health damage from air pollution as a potentially large social cost from switchgrass production and suggests means of mitigating that impact via strategic geographical deployment and management. Furthermore, by distinguishing the origin of atmospheric emissions, this paper advances the current emerging literature on ecosystem services and disservices from agricultural and bioenergy systems.

## 1. Introduction

Bioenergy is increasingly being considered as a means of enhancing access to clean energy and ensuring energy security, which are fundamental constituents of human wellbeing [1]. Bioenergy feedstock production can also drive ecosystem change, affecting human wellbeing by altering the delivery of ecosystem services from the converted landscapes [2]. At the same time, bioenergy production and use can affect human health [3], another key constituent of human wellbeing [1]. A major concern for human health is mortality arising from long-term exposure to fine particulate matter ("$PM_{2.5}$", particles with a diameter $\leq 2.5$ μm) [4]. $PM_{2.5}$ can be emitted directly as "primary" $PM_{2.5}$ or can form in the atmosphere as "secondary" $PM_{2.5}$ through chemical reactions of other pollutants ("precursors"), chiefly ammonia ($NH_3$), sulfur oxides ($SO_x$), nitrogen oxides ($NO_x$), and volatile organic compounds (VOCs). Overall, the air quality effects of agriculture in the US negatively impact human health. For example, in the US, the agricultural sector contributes around half of the surface-level mass of anthropogenic $PM_{2.5}$ in the atmosphere [5], with agricultural sources of outdoor air pollution in the US estimated to have been responsible for around 16,000 premature deaths in 2010 [6].

In the US, the dominant prospective lignocellulosic feedstock for bioenergy is the perennial herbaceous crop, switchgrass (*Panicum virgatum*). It has many attractive attributes concerning feasibility; *e.g.*, high yield [7] [8], long stand life (~10 years [9]), and harvestable using conventional techniques [10]. Furthermore, owing to low agricultural inputs and perenniality, switchgrass has the potential to provide other valuable ecosystems services such as soil erosion control

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[11], carbon sequestration [12] [13], habitat provision for biodiversity [14] [15] [16] [17], and reduction of water pollution [11]. Still, switchgrass production, and potentially the production of any bioenergy feedstock, can affect air quality, from both biogenic [18] [19] [20] and anthropogenic emissions [21] [22] [23].

The aim of this study is to evaluate the potential air quality effects of switchgrass production in the US through an ecosystem services framework. Some previous research has investigated the effects of switchgrass production on air quality, but much of that work either has not been carried to the end point of estimating impacts on human health and wellbeing [21] [24], has not been at a sufficiently high resolution to demonstrate potential impacts of geographic variability in production [22], or has not included biogenic emissions alongside anthropogenic emissions [21]. Within an ecosystem services framework, the emissions considered in this study entail a trade-off. While these emissions are the outcome of acquiring a provisioning ecosystem service (*i.e.*, switchgrass feedstock) that enhances human wellbeing through energy security and access [1], they can negatively affect another constituent of human wellbeing, namely health. Some authors refer to such processes as "ecosystem disservices" [25] [26] [27].

We first describe potential yield, fertilization, and location scenarios for growing switchgrass (Section 2.1), ultimately describing impacts for 2694 locations (counties in the Central and Eastern US), 2 yields, 3 fertilization rates, and 2 fertilizer types. We examine such a range of production locations and practices because there is considerable uncertainty as to where and how switchgrass might be grown in the US [28]. Only ~11 Gg of switchgrass were produced in 2012 (for comparison, corn grain: ~260 Tg $y^{-1}$) [29]. Next, we construct a life cycle inventory of emissions of $PM_{2.5}$ and its precursors for switchgrass production, normalized to 1 Mg (dry basis) of switchgrass (Section 2.2). We then model the resulting annual average changes in concentrations of total $PM_{2.5}$, both primary and secondary, and estimate the subsequent monetized mortality impacts for each of these scenarios (Section 2.3). Section 3 outlines the main results of the life cycle assessment (LCA) study for the US. Section 4 puts these findings into perspective, comparing them with other studies and discussing them within the context of ecosystem services.

## 2. Methodology

### 2.1. Growing scenarios

The air quality impacts of switchgrass on human health depend on many parameters, including the following:

- Yields can vary widely in a given location owing to genotype or environmental conditions. Genetic engineering, cross-breeding and improved management practices might increase future yields [30], which, all else being equal, might reduce the negative air quality impacts of biomass production.
- Higher N fertilization results in higher emissions, both from fertilizer production and use. Emissions also depend upon fertilizer type and timing of application, among other factors. Precision agriculture or high N use efficiency cultivars could reduce emissions [31].
- All else being equal, health impacts are generally greater if emissions occur near a densely populated area [32].

Because of the importance and uncertainty of these variables, we consider multiple scenarios for each. A "baseline scenario" was chosen, at a yield of 20 Mg $ha^{-1}$ switchgrass, and 100 kg $ha^{-1}$ N applied as urea (see 2.1.3). "Low" and "high" scenarios for fertilization rate were chosen at 50 kg $ha^{-1}$ and 150 kg $ha^{-1}$ N respectively. Application of N in the form of urea ammonium nitrate (UAN) was also considered. A "low yield" scenario was chosen at 9 Mg $ha^{-1}$ switchgrass.

This paper considers scenarios for all combinations of the chosen biomass yield, N fertilizer rate, and N fertilizer type. These variables are strongly coupled [33] [34] [35], and work has been done to model how they relate to each other [33] [36] [37]. We examine them across a wide range of locations in the Central and Eastern US.

#### 2.1.1. Biomass yield

"Low" and "high" yield scenarios are taken as 9 Mg $ha^{-1}$ and 20 Mg $ha^{-1}$ dry switchgrass respectively. This choice of yields was informed by the following studies. Wullschleger et al. [33] compiled 1190 yield observations from 39 US field trials, concluding that the mean (± standard deviation) yield was 8.7 ± 4.2 Mg $ha^{-1}$ for the upland ecotype and 12.9 ± 5.9 Mg $ha^{-1}$ for the lowland ecotype. EPA's yield range for perennial grasses [28] is higher, from 7.6 to 22.2 Mg $ha^{-1}$ (national average: 20.4 Mg $ha^{-1}$), whereas DOE reports a range of 9.2–18.0 Mg $ha^{-1}$ national average (13.5 Mg $ha^{-1}$).

#### 2.1.2. Nitrogen fertilizer rate

Although switchgrass can be grown without N fertilization, its profitable production in monocultures likely requires N application [38]. The N fertilization rate in the baseline scenario is 100 kg $ha^{-1}$ $year^{-1}$ of N. "Low" and "high" fertilization scenarios are chosen at 50 kg $ha^{-1}$ $year^{-1}$ and 150 kg $ha^{-1}$ $year^{-1}$, respectively.

N fertilization guidelines are commonly derived from expected yields, and reported per unit mass of switchgrass produced. Argonne's GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) Model has a default fertilization rate of 8 kg $Mg^{-1}$ of N per unit mass of dry switchgrass. Iowa State Extension describes 5 kg $Mg^{-1}$ N for the Liberty cultivar [39], which is also recommended by Penn State Extension for switchgrass cultivars in general [40]. For the Great Plains and Midwest, Mitchell et al. recommend 10 kg $Mg^{-1}$ of N when harvested in the growing season, or 6–7 kg $Mg^{-1}$ if harvesting after a killing frost [41].

#### 2.1.3. Nitrogen fertilizer type

Because switchgrass is a perennial crop, there is aboveground biomass throughout most of its stand life, which contraindicates fertilization methods involving injection, subsurface banding, or incorporation [42]. The choice of N fertilizer type is therefore limited. Urea, ammonium nitrate, and a solution mix of both are possible options. Enterprise budgets from Oklahoma State University [43] and several field plot studies [44] [45] [46], suggest the use of urea, whereas GREET [47] [48] and Mississippi State University [49] suggest ammonium nitrate. However, the use of pure ammonium nitrate has strongly declined in recent years [50].

There are two reasons to justify the consideration of UAN solution as a fertilizer in this study. First, a recent study compiling the emissions inventory of switchgrass [21] states that this is likely to be the primary fertilizer used. Second, urea can have 15% N loss by volatilization, compared to 8% for an UAN solution [51]. Large-scale switchgrass farmers might act to be more efficient in N-use, so as to be more cost-efficient [52]. We consider both urea and UAN for scenarios in our analysis. This is because of the uncertainty in whether switchgrass farmers will prefer urea or UAN as discussed above, and the fact that the large difference in volatilization rate for these fertilizer types leads to a large difference in $NH_3$ emissions.

#### 2.1.4. Location

We constrain growing locations to US states on and east of the 100th meridian west, which is the historic range of switchgrass [53], comprising 2694 counties in the Central and Eastern US. Research efforts have been made to determine the land available for switchgrass production at subcounty resolution. However, many of these depend on some specification of "marginal" land, whether this be idle, fallow, or abandoned land [54], polluted land [55], unproductive cropland [31], or conservation land [56]. As many of these studies differ in crucial assumptions regarding where switchgrass will be profitable or high-yielding [35] [57], for the sake of generality, the centroid of each