Supplementary data for “Nitrogen fertilization challenges the climate benefit of cellulosic biofuels”

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### Supplementary tables

**Table S1.** Model comparisons for the response of annual N$_2$O emissions to N fertilization rate. AIC = Akaike information criterion and BIC = Bayesian information criterion. In this comparison the best model has the lowest criteria; % AIC and % BIC represent the percentage increases for the linear models compared with the better exponential models that are indicated with “√”.

| Year   | Model     | R$^2$ | AIC  | % AIC | BIC   | % BIC |
|--------|-----------|-------|------|-------|-------|-------|
| 2009   | Linear    | 0.88  | -3.02| 52%   | 1.37  | 173%  |
|        | Exponential | 0.90  | -6.3 | √     | -1.87 | √     |
| 2010   | Linear    | 0.84  | 43.7 | 90%   | 48.1  | 76%   |
|        | Exponential | 0.91  | 23.0 | √     | 27.4  | √     |
| 2011   | Linear    | 0.86  | 54.0 | 121%  | 58.4  | 103%  |
|        | Exponential | 0.94  | 24.4 | √     | 28.7  | √     |
| All 3 yr | Linear   | 0.73  | 176  | 13.5% | 184  | 12.9% |
|        | Exponential | 0.75  | 155  | √     | 163  | √     |

**Table S2.** Model comparisons for the response of annual N leaching to N fertilization rate. See Table S1 legend for further information.

| Year   | Model     | R$^2$ | AIC  | % AIC | BIC   | % BIC |
|--------|-----------|-------|------|-------|-------|-------|
| 2009   | Linear    | 0.60  | 174  | 1%    | 178  | 1%    |
|        | Exponential | 0.65  | 172  | √     | 176  | √     |
| 2010   | Linear    | 0.73  | 182  | 4%    | 185  | 4%    |
|        | Exponential | 0.80  | 175  | √     | 178  | √     |
| 2011   | Linear    | 0.65  | 190  | 15%   | 194  | 14%   |
|        | Exponential | 0.87  | 166  | √     | 170  | √     |
| All 3 yr | Linear   | 0.64  | 547  | 4%    | 554  | 4%    |
|        | Exponential | 0.74  | 525  | √     | 532  | √     |
Table S3. Estimation of CO₂-equivalent emissions associated with switchgrass for cellulosic biofuel crop production. GWI = Global warming impact.

| GWI component          | Mg CO₂e ha⁻¹ yr⁻¹ | Data source                              |
|------------------------|-------------------|------------------------------------------|
| Seeds                  | 0.014             | See footnote b                           |
| Planting               | 0.013             | Gelfand et al 2013                       |
| N fertilizer production| 4.5 × X × 0.001    | Robertson et al 2000                     |
| N fertilizer application| 0.026             | Gelfand et al 2013                       |
| Harvesting (baling)    | 0.019             | Gelfand et al 2013                       |
| Direct N₂O emissions   | Field data        | This study                               |
| Indirect N₂O emissions| Leaching N × 0.75% | This study and IPCC 2006 N₂O indirect emission factor (De Klein et al 2006) |
| CH₄ uptake             | Field data        | This study                               |
| SOC change             | Field data        | This study                               |
| Fossil fuel offset credits| Field data and GREET | This study                        |

*a* Phosphorus and potassium fertilizers were not applied in our study, nor were herbicides, insecticides or lime.

*b* Calculation for seed production (Mg CO₂e ha⁻¹ yr⁻¹):

Switchgrass seeds production energy, 43.8 MJ kg⁻¹, was based on the analysis of Schmer et al. (2008). In order to convert energy (MJ kg⁻¹ yr⁻¹) to carbon emissions (Mg CO₂e ha⁻¹), we assumed that energy used in seed production consisted of a 50%, 20%, and 30% mix of fuel oil, natural gas, and electricity, respectively (Börjesson 1996). We also used energy conversion factors of 0.094 kg CO₂e MJ⁻¹ (Farrell et al 2006), 0.056 kg CO₂e MJ⁻¹ (Farrell et al 2006), and 0.21 kg CO₂e MJ⁻¹ (EPA 2014) for the conversion of gasoline, natural gas and electricity to carbon emissions, respectively. As a result:

Fuel: 43.8 MJ kg⁻¹ × 50% × 0.094 kg CO₂e MJ⁻¹ = 2.06 kg CO₂e kg⁻¹
Natural Gas: 43.8 MJ kg⁻¹ × 20% × 0.056 kg CO₂e MJ⁻¹ = 0.49 kg CO₂e kg⁻¹
Electricity: 43.8 MJ kg⁻¹ × 30% × 0.21 kg CO₂e MJ⁻¹ = 2.73 kg CO₂e kg⁻¹

Total carbon emissions (kg CO₂e kg⁻¹) = Fuel + natural gas + electricity = 5.28 kg CO₂e kg⁻¹

The seeding rate in our study is 7.84 kg ha⁻¹. Therefore,

Total carbon emissions (Mg CO₂e ha⁻¹) = 5.28 kg CO₂e kg⁻¹ × 7.84 kg ha⁻¹ × 0.001 Mg kg⁻¹ = 0.04 Mg CO₂e ha⁻¹

Since it is a perennial grass, switchgrass does not need to be seeded annually. Therefore, we averaged this value over the study period (3 yr), i.e., 0.014 Mg CO₂e ha⁻¹ yr⁻¹.

*c* Based on Robertson et al. (2000), 4.5 kg CO₂e released per kg of N produced and transported to field crops; X is the N fertilization rate (kg N ha⁻¹ yr⁻¹); 0.001 is the conversion factor from kg to Mg.

*d* Leaching N data from the field experiment in this study.

*e* GREET (Huo et al 2009) was used to calculate fossil fuel offset credits for different yields from each N treatment, with all farming inputs set to 0 as noted in Methods. Offset credits include co-product credits, which for lignocellulosic biomass includes lignin, used to generate electricity.
Supplementary references

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### Supplementary figures

| N fertilizer rate (kg N ha\(^{-1}\) yr\(^{-1}\)) |
|-----------------------------------------------|
| 0 kg N ha\(^{-1}\) yr\(^{-1}\)                |
| 28 kg N ha\(^{-1}\) yr\(^{-1}\)               |
| 56 kg N ha\(^{-1}\) yr\(^{-1}\)               |
| 84 kg N ha\(^{-1}\) yr\(^{-1}\)               |
| 112 kg N ha\(^{-1}\) yr\(^{-1}\)              |
| 140 kg N ha\(^{-1}\) yr\(^{-1}\)              |
| 168 kg N ha\(^{-1}\) yr\(^{-1}\)              |
| 196 kg N ha\(^{-1}\) yr\(^{-1}\)              |

**Figure S1.** Mean daily N\(_2\)O emissions May to December for the first three harvest years (2009-2011) following establishment in 2008 across the eight fertilization treatments. Error bars omitted for clarity (n=4 replicate chambers per treatment).
Figure S2. Relationship of daily N_{2}O emission to soil water content (water-filled pore space) at 0–25 cm depth across several levels of soil inorganic nitrogen (KCl-extractable NO_{3}^{-} + NH_{4}^{+}) during the first three harvest years (2009-2011). Bands show 95% confidence intervals around linear regression fits to the data (data points not shown); all fits are significant at $\alpha=0.05$.

Figure S3. Average daily CH_{4} uptake rates in each switchgrass N fertilization treatment for May to December for the first three harvest years (2009-2011). Error bars represent standard errors of the mean (n=4 replicate plots). There are no significant differences among treatments ($\alpha=0.05$).
Figure S4. Soil carbon concentrations at depths of 0-25, 25-50, and 50-100 cm across the N fertilization gradient. Error bars represent standard errors based on n=4 replicate plots. Bars to the left of the dashed line represent samples taken in 2012 versus those taken at the outset of the experiment in 2008 (to the right side of dashed line). There are no significant differences among treatments (α=0.05).