The Impact of Crop Price on Nitrous Oxide Emissions:

A Dynamic Programming Approach

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ABSTRACT: The use of N fertilizer in agriculture is a major source of Nitrous Oxide, an important greenhouse gases. Market-based instruments, such as incentives or taxes, may help reduce Nitrous Oxide emission by changing Nitrogen application rate. Using a dynamic programming approach, we found that changing corn price or fertilizer price have effects on both farm profit and Nitrogen application rate. However, farm profit and Nitrogen rate always change in the same direction when affected by either input or output prices. Furthermore, as the corn price is relatively higher than the fertilizer price, changing the corn price is more effective in influencing Nitrogen rate, and thus Nitrous Oxide emission. This analysis can provide policymakers with useful information when designing Market-based tools to help reduce Nitrous Oxide emissions and mitigate global warming.

Key words: Nitrous Oxide Emissions, Dynamic Programming, Agricultural Prices

INTRODUCTION

Nitrous oxide (N_2O) is an important greenhouse gas. Although its concentration in the atmosphere is much less than carbon dioxide, its global warming potential is about 298 times stronger (Myhre et al., 2013). Agriculture is a major source of N_2O emissions, accounting for 75% of the overall U.S. N_2O emissions (US EPA, 2012). The use of Nitrogen (N) fertilizer in agriculture is likely to keep rising due to increasing demands for food and biofuel production, posing a threat to our efforts to mitigate global warming; therefore how to reduce N_2O emissions from agricultural sector becomes a pressing issue.

However, it may not be economically sound to reduce N fertilizer use due to its important role in agricultural productivity. Furthermore, in many regions, N fertilizer is relatively inexpensive compared to crops, so agricultural producers may apply more N fertilizer than necessary (Good and Beatty, 2011). One of the motivations is to reduce the risk of rising N fertilizer demand due to unexpected weather variations. One way to reduce N fertilizer rate without sacrificing economic returns is implementing crop rotation. Compared to continuous cropping, crop rotation helps maintain or improve productivity with lower N fertilizer application (Berzsenyi et al., 2000; Meyer-Aurich et al., 2006). However, agricultural producer's decision of implementing a crop rotation is mostly driven by the expected economic return. For instance, when corn price soars, producers may switch from corn-soybean rotation to continuous corn cropping for short term returns. Since switching to continuous cropping reduces corn yield, producers may at the same time increase N fertilizer application in order to maintain crop yield. Increasing climate variability is expected to induce more volatile crop yields and prices, which motivates the producers to skip crop rotation more frequently and thus apply more N fertilizer.

If policymakers can use market-based instruments (MBIs), such as agricultural incentives or N taxes, to encourage producers to implement crop rotation, N fertilizer application rate and N_2O emission could be reduced. Therefore, it becomes important to investigate the relationship between agricultural prices and N_2O emissions so that policymakers can have a better idea about how much direct N_2O emissions can be reduced through certain MBIs. In this study, we simulate how agricultural price affects direct N_2O emissions through its impact on producers' planting decision (crop rotation or continuous cropping) and N fertilizer rate decisions using an improved dynamic programming model of crop rotation (corn-soybean), while most of the previous studies only empirically estimated the price elasticity of N fertilizer demand.

The rest of the paper proceeds as follows. The next section describes the methods that we used to optimize N input, calculate emission factor and damage cost. Then we present the simulation result of the optimized farm profit and the environmental cost of N loss. Then the final section concludes.

METHODS

A Crop Rotation Model

Cai et al. (2013) developed a crop rotation model to optimize planting decisions in response to crop yield and price volatility. By maximizing net present value of the expected current and future farm profits for a five-year period, a modified Bellman equation (Bellman, 1957) helps optimize planting decisions, using a corn-soybean rotation as an example. It is found that agricultural producers are more likely to choose a crop rotation scheme when the yield differences between crop rotation and continuous cropping are higher, and when the profitability of corn and soybeans are similar. However, Cai et al. (2013)'s model is not able to indicate N usage since the model assumes a fixed N fertilizer application rate when the producers change planting decisions, which is unrealistic since the producers may increase N fertilizer application rate to maintain crop yield when switching from crop rotation to continuous cropping.

A Modified Model

To improve Cai et al. (2013)'s crop rotation model, now we allow the producer (assumed to be a price-taker and five-year profit-maximizer) to optimize both crop choice and N fertilizer application rate so that the model is able to simulate the change in N_2O emissions in response to crop price changes. In addition, since N input is now a variable cost, we also simulate producers' response when N price changes. Figure 1 shows how we improve Cai et al. (2013)'s model.

We assume that the producer can plant corn or soybeans on two equal-sized tracts of land. Only one crop is allowed on each parcel of land. Thus we have three planting scenarios: corn-corn, soybean-soybean, and corn-soybeans for each season. The producers make two planting decisions in the beginning of each season: first, the producer determines the economically optimal N fertilizer rate for each of the possible crop choices, based on expected input and output prices, and crop yield responses to N application rate. Second, the producer determine the crop choice that maximizes the net present value of current and future profit over a five-year period, assuming that the optimal N fertilizer application rate is used for each crop choice. Overall, the model uses the Bellman equation to optimize the five-year sequential decisions with a balance of an immediate profit against expected future profits.

Yield response and Optimal N Rate

To calculate the optimal N rate, we need a yield response function that represents how corn/soybeans yields vary with alternative N rates. We follow the function form with the quadratic-plateau yield response relationship (Cerrato and Blackmer, 1990; Sawyer et al., 2006):

$$Yield = \begin{cases} \alpha + \beta_1 * N + \beta_2 * N^2, & if\ N \le -\dfrac{\beta_1}{2*\beta_2} \\ \alpha - \dfrac{\beta_1^2}{4*\beta_2}, & if\ N > -\dfrac{\beta_1}{2*\beta_2} \end{cases} \tag{1}$$

where N is the N application rate, α , β_1, and β_2 are the coefficients of yield response curves. Assuming that the producer does not apply excess N rate, the farm profit function will be:

$$\pi = P_{output} * Y - P_{input} * N \tag{2}$$

where π is the farm profit, Y is the crop yield, P_{output} is the crop output price, P_{input} represents input price. Here we assume that the price of N fertilizer is the only input price. Substituting Equation 1 into Equation 2, we have

$$\pi = \begin{cases} P_{output} * (\alpha + \beta_1 * N + \beta_2 * N^2) - P_{input} * N, & (N \le -\dfrac{\beta_1}{2*\beta_2}) \\ P_{output} * (\alpha - \dfrac{\beta_1^2}{4*\beta_2}) - P_{input} * (-\dfrac{\beta_1}{2*\beta_2}), & (N > -\dfrac{\beta_1}{2*\beta_2}) \end{cases} \tag{3}$$

After we obtain the coefficients in Equation 1, [1] the optimal N rate which maximizes the farm profit can be calculated based on the first-order condition:

$$\pi' = P_{output} * (\beta_1 + 2 * N * \beta_2) - P_{input} = 0$$

[1] For the purpose of simplicity, we only estimate the quadratic part of the equation.

$$N = \frac{P_{input} - \beta_1 * P_{output}}{2 * \beta_2 * P_{output}} \tag{4}$$

Emission Factor and Damage Cost

Next, we determine the proportion of N fertilizer released to the environment (emission factor). Crop varieties, fertilizer types, soil types, soil temperature and humidity, and management practices can all affect N_2O emissions. In this study, we use emission factors suggested by IPCC (1996), where 1.3% of N is emitted as N_2O, and 40% of N is lost to the environment in forms such as nitrate (NO_3^-), nitrogen oxides (NO_x), and ammonia (NH_3). Compton et al. (2011) further assign the damage cost to N released in different forms. For instance, N released as N_2O has a damage cost of three dollars per kilogram of N (2005 U.S. dollar). The detailed emission factors and damage costs for various forms of released Nitrogen are listed in Table 1 (Zhang et al., in review).

RESULTS

Yield Response and Optimal N rate

We first estimate the yield response to N application rate based on 24 years of trials conducted in Iowa.[2] Two yield response functions – corn in continuous corn, and corn in crop rotation – were estimated with the function form of Equation 1 using a pooled OLS regression (results not shown). Yield response curves illustrated in Figure 2 are based on these estimated coefficients. In Figure 2, as expected, we observed that rotational corn has higher yield as

[2] Data are kindly provided by Antonio Mallarino and Ken Pecionovsky.

compared to continuous corn. We also found that rotational corn reaches its maximum yield level with a lower N rate than continuous corn.

Based on the estimated coefficients in Equation 1, the optimal N rates for continuous corn or rotational corn under certain input and output prices can then be calculated using Equation 4. Since we have the estimated coefficients $\beta_2 < 0$, and $\beta_1 > 0$, the optimal N rate decreases as input prices increase, and increases as output prices increase.

The Impacts of Crop Prices

For a producer who wants to maximize net present value of farm profit for the next five years, our simulation results show that higher corn price encourages more continuous corn cropping and thus increase N_2O emissions during a five-year period. When the corn price stays at current levels,[3] five-year planting decisions will be a mixture of crop rotation and continuous cropping. If the corn price is reduced by 16% from current levels, while holding soybeans price and fertilizer prices fixed, a profit maximizing producer will switch to crop rotation for each of the five years, and thus N application rate will drop to a lower level. Based on Figure 3 (A), it is observed that, even if price changes stays within a range (phase) that does not lead to a planting decision change, higher N price still lead to higher optimal N rate. Overall, profit and N rate changes in the same direction. Therefore, to keep N rate at the lower level, sacrificing a portion of profit is unavoidable. If corn price could be reduced by 83% from the current level, N level would be zero, since the producers would be planting only soybeans for the whole five-year period. While this scenario may be good for the environment, producers sacrifice a lot in terms of profit. Besides, under this scenario producers will only produce soybeans, leading to an

[3] "Current level" refers to the current USDA projection of corn prices for the next five years.

undersupply of corn that may have other negative effects on society. Thus we may want to find a balance where N rate is not too high and profit levels are acceptable to the producers.

The Impacts of N Fertilizer Prices

In Figure 3 (B), it is observed that higher fertilizer price tends to reduce optimal N fertilize rate and N_2O emissions. However, compared to changing the corn price, it is found that even if we change N fertilizer price by increase 50% or decrease it by 50% (the same range of corn price change that we investigated), producers have a relative inelastic response in planting decisions – producers only switch between continuous corn, and a mixture of continuous corn and crop rotation. This inelastic response largely comes from the relatively inexpensive N fertilizer price compared to the corn price. Thus changing it has a smaller effect on planting decisions. However, increasing N price still has effect on reducing N rate, although it is not as effective as corn price change.

DISCUSSION

It should be noted that, in Figure 3, we should only focus on whether or not profit and cost change in the same direction and by how much, but not their relative magnitude or their differences. Their relative magnitude is largely affected by our baseline corn price and N fertilizer price. Moreover, the calculation of total cost from Compton et al. (2011) is considered as a preliminary estimation, thus it should be viewed with caution.

Although changing corn price is likely to have larger effects on N application rate as compared to that of N tax, this doesn't imply that we should always choose to change the corn price. It is possible that changing the same range of corn price is less implementable than changing the N fertilizer price.

Even without implementing MBIs to reduce N loss or nitrous oxide emissions, the crop prices and N prices are affected by many factors, such as food and biofuel demand, extreme weather, international trade and so on. However, these exogenous factors are unlikely to adjust the crop price and N price to value where N rate is not high and the profit is acceptable as indicated in Figure 3. Therefore the implementation of MBIs is challenging and need to take into consideration of these exogenous factors that can influence output and input prices.

Also, whether changing corn price, or N tax, or both should consider cost efficiency, which means that the marginal cost of doing so should be equal for the whole society in order to minimize the total cost. Implementation of a cost effectiveness scheme instead of net benefit is due to the difficulty in comparing the benefit to the cost in reducing N emission from agricultural sector.

CONCLUSIONS

In this paper, we simulated the effects of market-based instruments on producers' planting decisions and in turn N releases to the environment. This is based on an improved crop rotation model from Cai et al. (2013). Overall, we found that changing corn price or fertilizer price have effects on both farm profit and N rate. However, profit and N rate always changes in the same direction when affected by either input or output prices. Furthermore, as corn price is relatively higher than fertilizer price, changing corn price is more effective in influencing N rate, and thus N_2O emission. This analysis can provide policymakers with useful information when designing MBIs to help reduce agricultural N_2O emissions and mitigate global warming.

Overall, we intend to provide a framework showing the tradeoffs between farm profit and the environmental cost related to N loss. For its application to a specific region, the emission factors and damage cost should be made more specified.

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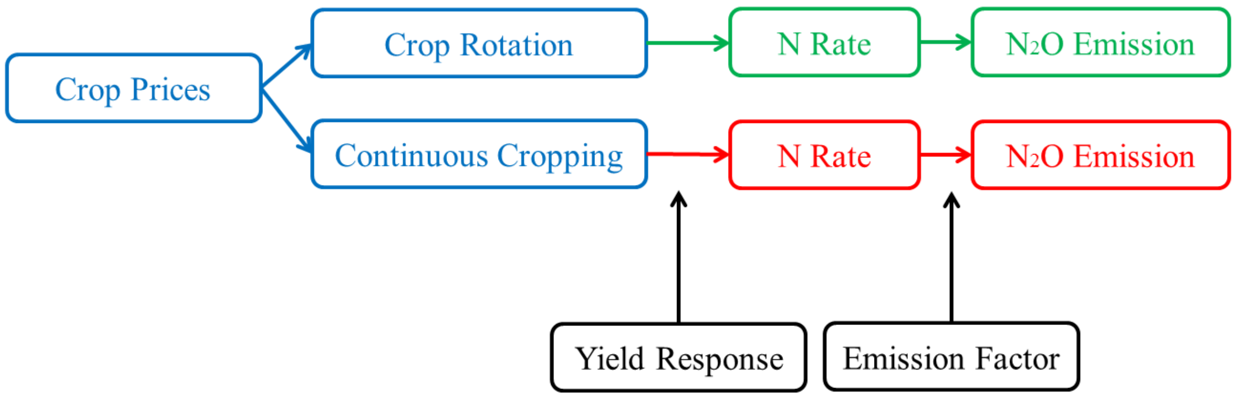


Figure 1. The diagram shows how we improve Cai et al. (2013)'s model. Cai et al. (2013) are represented by blue boxes, while we extend it with variable N rate.

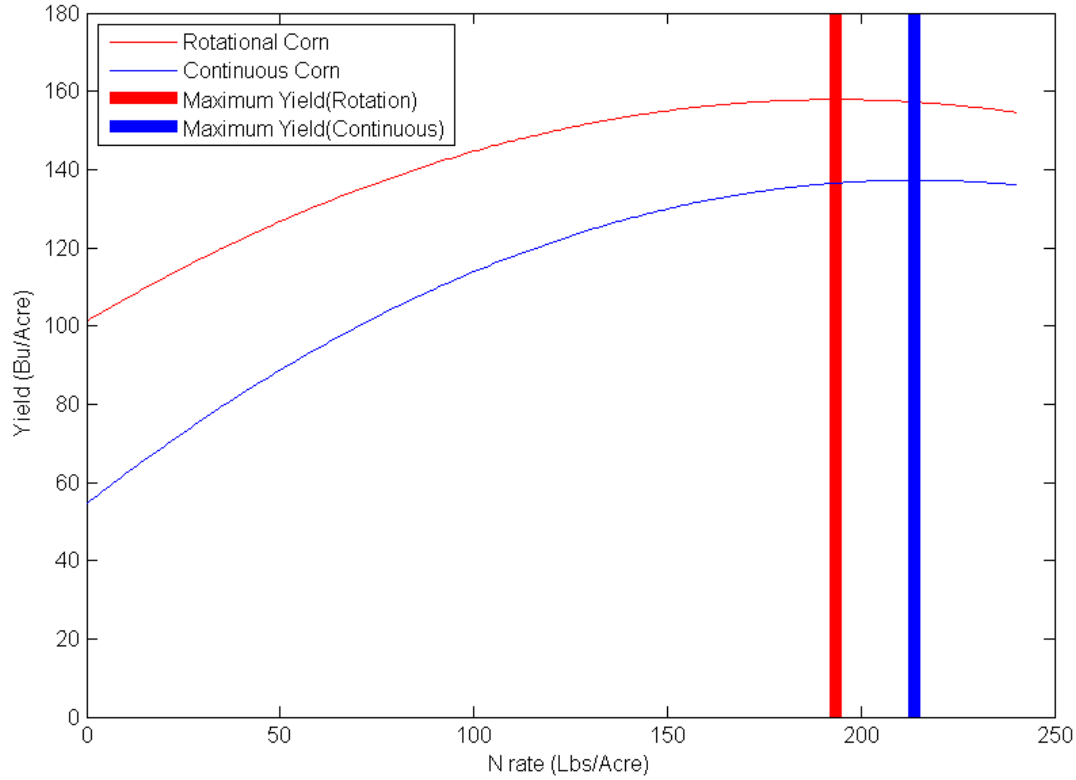
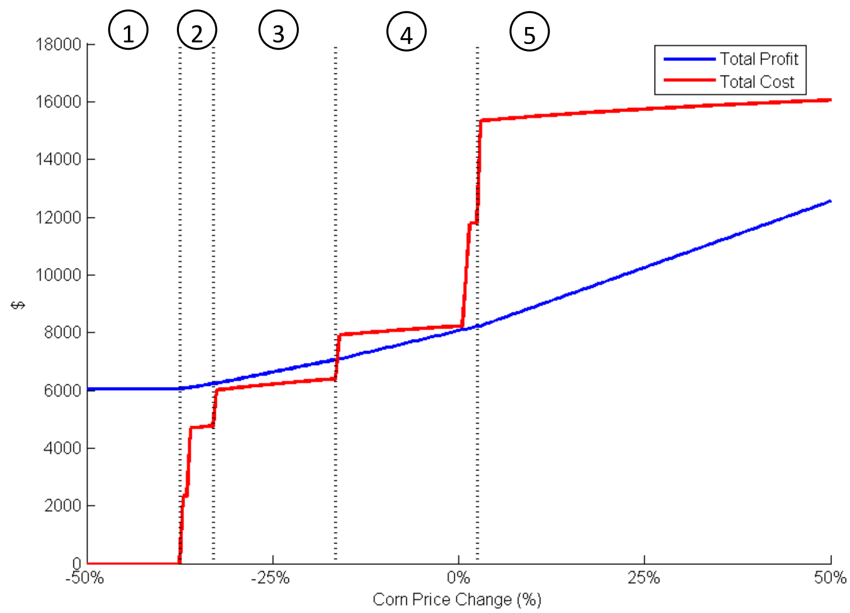


Figure 2. Yield response curve to different N application rate.

(A)



(B)

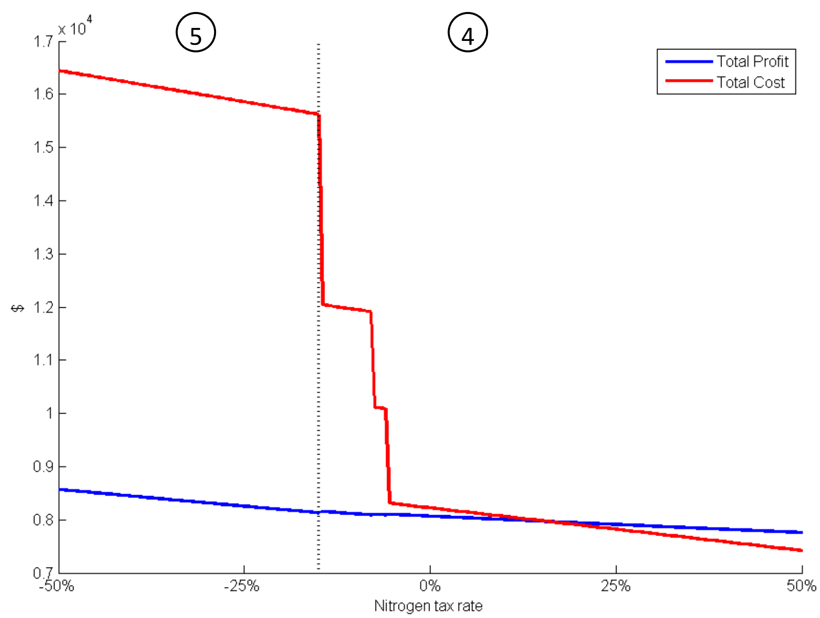


Figure 3. Profit and cost. (A) changing corn price from current level. (B) changing N tax rate from current level. Phase 1: Continuous soybeans. Phase 2: Continuous Soybean and crop rotation. Phase 3: Crop rotation. Phase 4: Continuous Corn and crop rotation. Phase 5: Continuous Corn.

Table 1. Emission factors and damage costs of four forms of reactive N (Zhang et al., in review).

Reactive N (Nr) species	IPCC emission factor (EF_i) (IPCC, 2006)	Fraction of N_{exc} emitted as Nr ($Frac_i$)	Damage cost estimation (2005 USD kg N^{-1}) (Compton et al., 2011)
N_2O	0.013*	0.03	3
NO_3^-	0.3	0.73	57
NO_x	0.05	0.12	23
NH_3	0.05	0.12	4

*Include direct and indirect emissions from n fertilization in cropland.