ANALYZING SOIL NITROGEN MANAGEMENT WITH DYNAMIC SIMULATION EXPERIMENTS

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ABSTRACT

Biogeochemical cycles are among the nine planetary boundaries, which are threatened by human activity. The planetary safe boundary for nitrogen fixation is already surpassed. Modern agriculture depends on nitrogen fertilizers produced by fixing inert atmospheric N_2 gas into ammonia through Haber-Bosch process. Because only a fraction of the inorganic nitrogen fertilizers applied on farmlands are assimilated by crops, inorganic N in soil solution is lost to the atmosphere and oceans, contributing to global climate change, water pollution and eutrophication. There is worldwide evidence indicating that nitrogen fertilizers are overused beyond profit maximizing levels, leading to dramatically low nitrogen use efficiencies. Studies addressing fertilizer application rates consider the economic factors, or environmental and technological determinants that influence farmers' behavior. Among the technological determinants, soil analysis for residual N is widely suggested. In this study, we focus on the problem of residual nitrogen accumulation on farmlands, its perceptions by farmers and consequences on fertilizer application rates. The methodology is dynamic simulation modeling and decision experimentation. It is argued that, outcome feedback on annual farm profits, although it is weak, helps subjects adjust their fertilizer rates. On the other hand, in real life, because information feedback is obscured by various confounding factors, regular information on residual N can be used as a guideline for informing farmers' decisions.

Keywords: soil nitrogen cycle, corn growth, fertilizer rates, dynamic simulation, decision experimentation

I. INTRODUCTION

Industrial processes to reduce N_2 to NH_4^+ for producing crop fertilizers and implementation of new agricultural practices have an enormous impact on the global nitrogen cycle. Canfield, Glazer et al. 2010 provide the following facts:

> During 2008 alone, the Haber-Bosch process of NH_4^+ production supplied 9.5×10^{12} mol N … [which is about 57% of the natural rate of terrestrial N fixation] … From 1960 to 2000, the use of nitrogen fertilizers increased by around 800%, with wheat, rice and maize accounting for about 50% of current fertilizer use. For these crops, the nitrogen use efficiency is typically below 40%, meaning that most applied fertilizer either washes out of the root zone or is lost to the atmosphere by de-nitrification before it is assimilated into biomass … One potential consequence of increased fixed nitrogen use is increased fluxes of riverine nitrogen to coastal zones, leading in turn to enhanced biological productivity, increased coastal anoxia, detrimental impacts on water quality and increased fluxes of N_2O to atmosphere.

There is worldwide concern on fertilizer application rates and its impact on economics and environment. The analysis of the decisions on fertilizer use mainly considers factors about farmers' capacity to access fertilizers, agro-climatic conditions, farm characteristics and farmer characteristics. In controlling application rates, the role and importance of education, improved rural extension services, the role of on-site demonstrations in controlling excessive application rates are widely emphasized (Zhou, Yang et al. 2010).

Many studies exploring the determinants of farmers' fertilizer decisions are built on large databases and regression analysis. However, few of the identified factors have policy relevance in controlling fertilizer rates. Very few studies take into account the residual nitrogen that accumulates in the soil profile over cropping seasons. Agronomic studies reveal an increase in nitrate accumulation in the soil profile with increasing levels of nitrogen applications. Yadav, Peterson et al. 1997 demonstrates that, both the recommended rates and farmers' use of nitrogen can exceed profit maximizing levels, when the residual nitrogen is not taken fully into account.

I.1. Problem

There is worldwide evidence indicating that in conventional agriculture, chemical fertilizers are overused, excessive nitrogen is leached and consequently, freshwater systems are nutrient loaded and eutrophied (Yadav et al. 1997). However, there are impediments to implementation of standard economic policies. Firstly, increasing fertilizer prices for creating disincentives for farmers is not a popular, hence politically viable strategy since many medium and small scale farmers already live on considerably low profit rates. Secondly, taxing the amount of fertilizer that has leached from the farmlands is technologically as well as politically not feasible, because nutrient load from farmlands is a dispersed non-point pollution which is difficult and expensive to measure and monitor. Thirdly, enforcing regulations for fertilizer quotas is difficult due to monitoring problems. Fourthly, fertilizer application on farmlands hardly possesses the characteristics of a common pool resource problem, because the farmlands are individually owned but the receiving medium is public, which has ill-defined boundaries and beneficiaries. Hence, community self-management for appropriate fertilizer rates is difficult to implement.

Acknowledging such difficulties, agricultural experts are in well agreement that farmers' education is the leverage in restraining fertilizer use to the detriment of the environment. In this paper, it is argued that, soil nutrient management is a case for stock-flow complexity. In the dynamic environment of soil N management, farmers' task is to keep soil nutrients at appropriate levels in consecutive seasons so as to promote biomass growth and increase farm profits. A conventional way of managing soil nutrients is to apply chemical fertilizers. While increased fertilizer rates increase soil nutrients and promote crop growth, fertilizer overuse can lead to irrational costs. Excessive environmental damage is a direct consequence.

With this perspective, fertilizer application and soil nutrient management is conceptualized as a dynamic decision making (DDM) problem. In DDM literature, there is rich experimental evidence pointing to systematic misperceptions of stocks and flows, underestimation of delays, ignorance of feedbacks and nonlinearities. Many studies reveal that, flawed mental models and misperceptions lead to overconsumption and overutilization of resources, even in cases where appropriate economic incentives are provided (Moxnes 2002; Sterman and Seweeney 2006, Moxnes and Saysel 2009).

In this research, inspired by the previous work on DDM and environmental resources management, we test whether the stock-flow complexity and weak information feedback leads to fertilizer overuse. For this purpose, a dynamic simulation model integrating soil N cycle and corn growth is created. After that, the model is used as the basis of a computer simulation game for experimentation on farmers' behavior.

II. THE SIMULATION MODEL

The simulation model is a compartmental model of soil N cycle and corn growth. N assimilation (uptake by corn) is the sole endogenous model factor stimulating growth of corn (Fig. 1., N assimilation loop reinforcing the growth of corn) and depleting mobile N (Fig. 1., the N depletion loop, controlling the growth of corn).

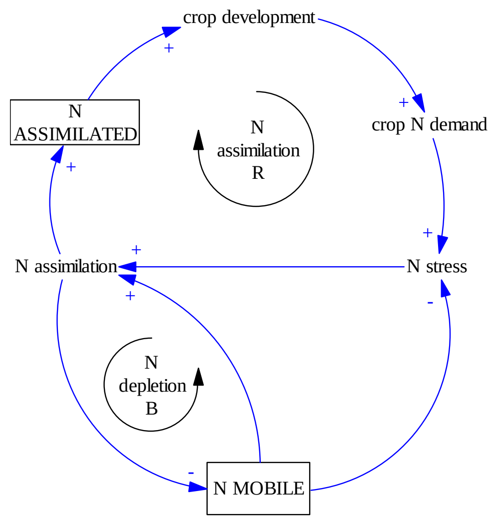


Figure 1. N assimilation and depletion

Model N cycle in the form of a model equilibrium diagram is depicted in Fig. 2. Soil inorganic N is classified under nitrate (NO_3^-) and ammonium (NH_4^+). Inorganic (mobile) N immobilizes into organic (immobile) N, while organic N mobilizes into NH_4. There is a constant return of organic N either from decomposing detritus or from humus. NH_4^+ is lost through volatilization and NO_3^- is lost through de-nitrification and leaching. Volatilization and de-nitrification are the sources of NH_3 and NO (N_2O) respectively, where the latter is a potent greenhouse gas. Leaching is the source of NO_3^- in freshwaters which is a potent contaminant. N fixation from the atmosphere and deposition by rainfall is omitted. All N transfers between stock variables are first order linear formulations with specific transfer constants. When the soil is intact, i.e. there is not cultivation and fertilizer application, model equilibrium is created (Fig. 2). Flows are in kg-N/days and stocks are in kg-N. The stock-flow structure is built on textbook knowledge on soil N cycle available in Foth 1990, pp. 186-197; Evangelou, 1998, pp. 323-364; and Stevenson and Cole 1999, pp. 141-226.

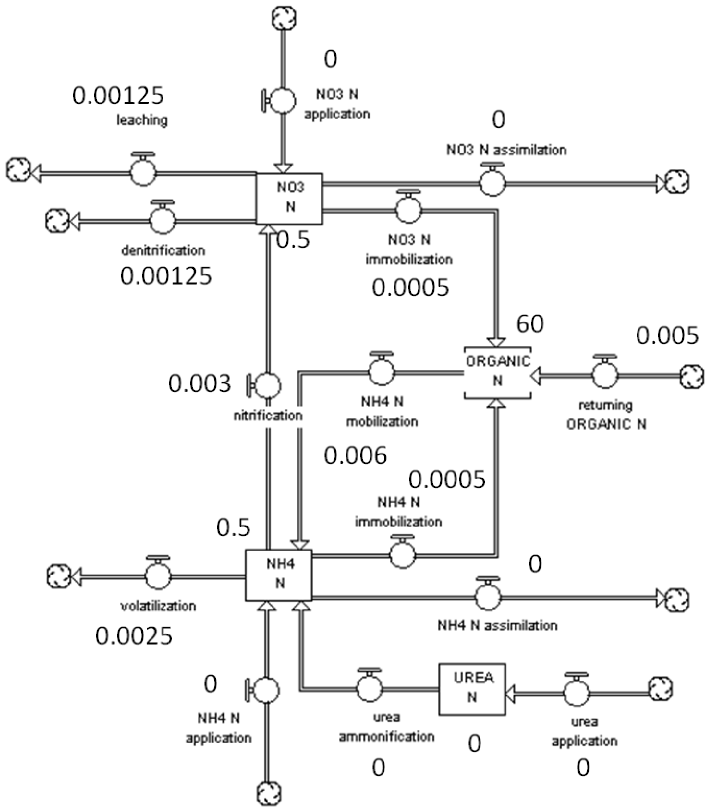


Figure 2. Soil N cycle equilibrium diagram.

Crop development model is depicted in Fig. 3. Stage of development is the accumulation of average daily temperatures above a threshold value and when it reaches at specified levels, a particular stage in development is complete (Thornley and Johnson 1990, p. 141). This empirical observation called *day-degree hypothesis* is used by agronomists to calculate critical stages in corn development (Abendroth, Elmore et al. 2011). Seed biomass increases with sowing of seeds. After a few days delay, seeds germinate and partition into root and canopy. Root, canopy and kernel growth are formulated with logistic functions less their respective decays. For each crop partition, there is a biotic potential that can be reached under ideal conditions. Moreover, growth in roots and kernel depends on canopy biomass and their staging is switched on with respect to the growth degree-days. The only a-biotic factor influencing growth is N nutrient availability. Important formulations are described below and all model equations are available with supplementary material.

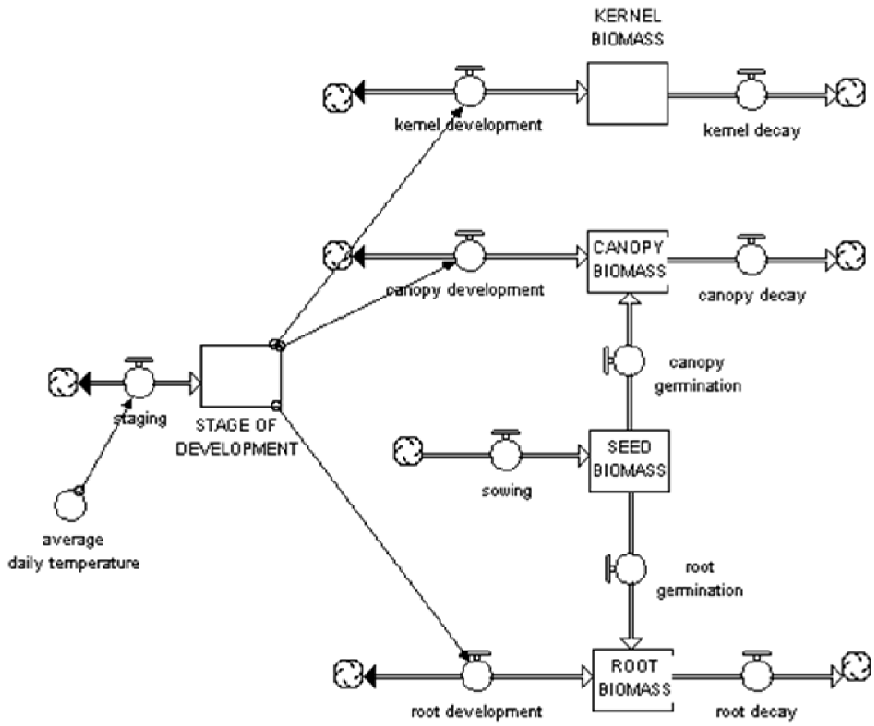


Figure 3. Crop development.

Crop N demand is formulated as proposed in M.H. Jeuffroy 2002:

*Crop N demand = total biomass * (max N percent – actual N percent) / day + net biomass growth * critical N percent* {kg-N/day} Eq. 1

Maximum N percent is the maximum concentration that can be stored by the plant and critical N percent is the concentration below which the plant's development is impaired. They are identified according to the empirical relationship:

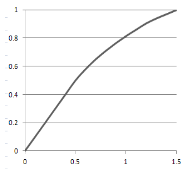
$$N\ percent = a * total\ biomass^{-b} \quad \text{Eq. 2}$$

where *a* and *b* are empirical coefficients.

Professional crop growth simulators use Michaelis-Menten type relationships for plant N uptake (Ma, Ahuja et al. 2009). According to such formulations, as soil N available in transpiration stream increases, fractional uptake asymptotically reaches at some specified maximum, however cannot exceed crop N demand. We follow a similar approach by a fuzzy minimum formulation. N uptake is the minimum of soil N available and crop N demand:

NO_3-*N assimilation=available* NO_3-*N*N stress multiplier* {kg-N/day} Eq. 3

Available NO_3-*N =* NO_3-*N/*NO_3-*N minimum uptake time* {kg-N/day} Eq. 4

N stress multiplier=f(N stress) 

{dimensionless} Eq. 5

N stress=crop N demand/N available {dimensionless} Eq. 6

N available=Available NO_3-*N+available* NH_4-*N* Eq. 7

These calculations are replicated for NH_4-*N assimilation*.

Effect of assimilated N on crop development is formulated as suggested in Jeuffroy, Ney et al. 2002:

canopy development=canopy normal growth fraction(1-CANOPY BIOMASS/canopy biotic potential)*canopy staging switch*CANOPY BIOMASS*N growth multiplier* {kg dry biomass/day} Eq. 8

N growth multiplier=(actual N percent-min N percent)/(critical N percent-min N percent) {dimensionless} Eq. 9

*actual N percent=N ASSIMILATED/TOTAL BIOMASS*100* {dimensionless} Eq. 10

Min N percent is the concentration below which the plant cannot survive, which is identified according to the empirical relationship in Eq. 2.

Model calculates total leached (TLN), denitrified and volatilized nitrogen amounts as well as nitrogen use efficiency (NUE), described by Mosier, Syers et al. 2004; p. 279 as the apparent recovery efficiency:

$NUE=(U_N-U_0)/F_N$ {kg-dry kernel biomass increase/kg-N applied} Eq. 11

where U_N is the plant N uptake at a certain level of fertilizer N applied, U_0 is the plant N uptake without any fertilizer application and F_N is the fertilizer application rate.

Other measures include farm revenue from crop yield, fertilizer application variable costs and annual farm profits (all in TRL).

Typical model responses to various fertilizer application rates for indirect structure validation are illustrated in Figure 4-5. Seeds are sown on the 15^{th} day and the crop is harvested on the 135^{th} day. The growing season is 120 days (four months). Biomass and growth curve patterns fit the description in various agronomic studies. Crop N percentage patterns can be verified for example by Jeuffroy, Ney et al. 2002. In Figure 4, there is a minor loss in soil organic content because mobilization is larger than total immobilization. Urea is constant because urea fertilizer rate is 0. Mobile nitrogen (NH_4 and NO_3) declines towards a new equilibrium because its uptake, immobilization and loss (volatilization, de-nitrification and leaching) exceed mobilization of soil organic N.

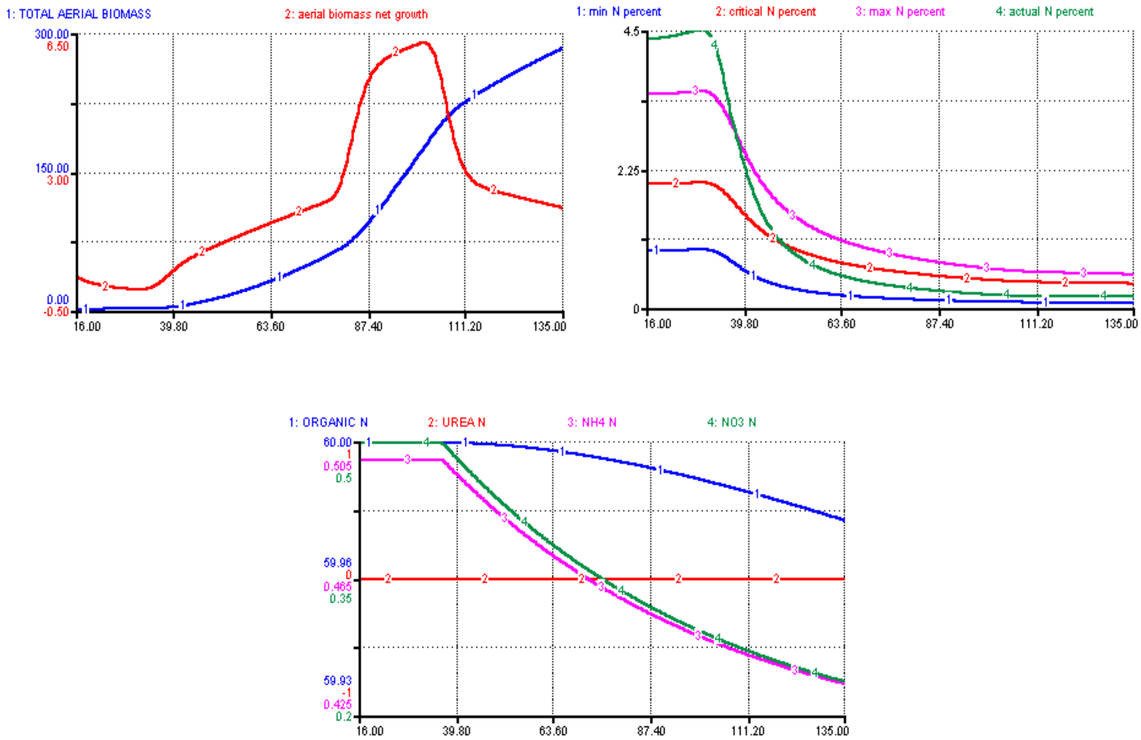


Figure 4. Model response to zero fertilizer application (time axis in days, biomass in kg-dry matter, all N in kg-N).

In Figure 5, fertilizer application stimulates biomass growth. Actual N percent reaches at maximum N percent indicating that the N deficiency is overcome. Organic N increases by immobilization of N sourced from urea fertilizer, urea and inorganic forms of N peak after application dates and then decline through uptake, immobilization and losses.

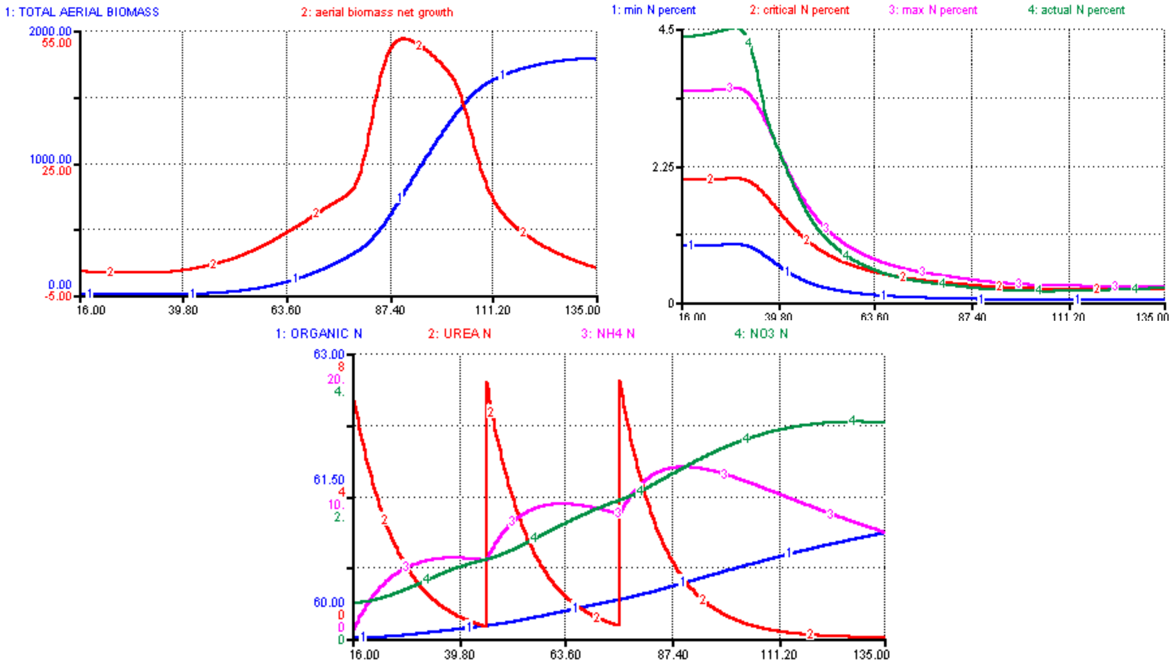
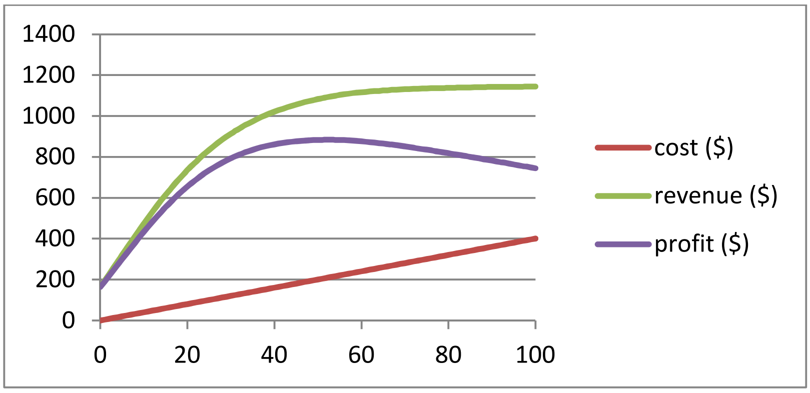


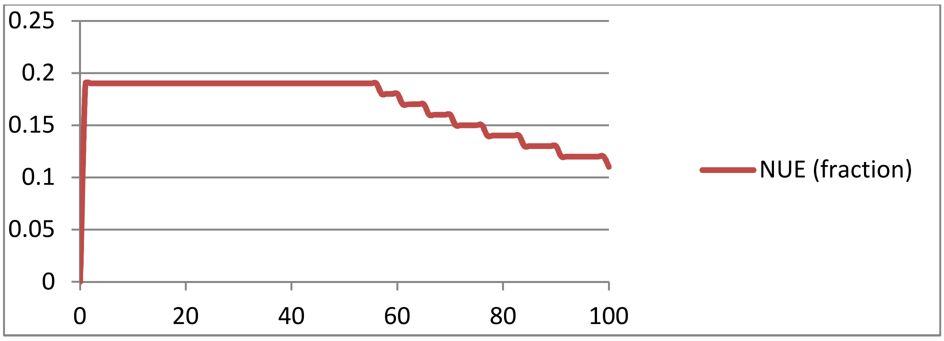
Figure 5. Model response to urea fertilizer application. Urea application rates are 15, 15, 15 kg-urea on the 0^{th}, 45^{th} and 75^{th} days.

III. EXPERIMENTAL PROCEDURE

III. 1. Task structure

Because nitrogen accumulation (residual nitrogen) develops over several cropping seasons, the game is designed as a perennial fertilizer application and corn cultivation game that lasts for ten consecutive years. Corn is sown on the 15^{th} day and harvested on the 135^{th} day of each year, which lasts for 360 days. The players are asked to decide on their annual fertilizer application rates so as to maximize their annual farm profits. Because the game lasts for ten consecutive years, soil residual nitrogen levels change and influence optimal fertilizer application rates. However, as the game starts, the players are suggested to start with what is optimal for the starting year. For the initial residual N concentration equal to 1 kg-N, the response of farm revenue (harvest x 1 TRL), fertilizer cost, farm profit, nitrogen use efficiency (NUE) and total nitrogen leached (TNL) to fertilizer application are depicted in Figure 6.





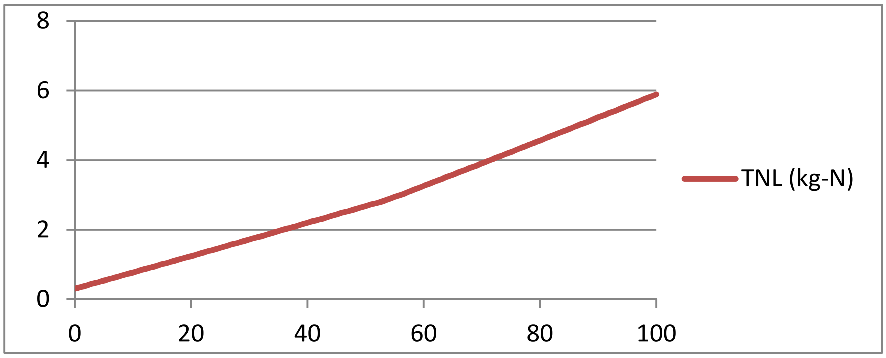


Figure 6. Model response to fertilizer rates (kg-urea) at residual N=1 kg-N at t=0.

It is observed that fertilizer application has diminishing returns in yield. With increasing fertilizer use, expected profit first increases and then declines with increasing marginal cost exceeding stagnating marginal benefits. Nitrogen use efficiency (NUE) declines and leached

N (TNL) increases with increased application rates. According to Figure 6, optimal application rate at the beginning of the game is 53 kg-urea, which creates 1096 kg yield of dry biomass with 884 $ profit, 0.19 nitrogen use efficiency and 2.82 kg total leached N.

III.2. Game Interface and Treatments

Game interface is illustrated in Figure 7. Game instructions for treatment T1 are provided in Appendix A.

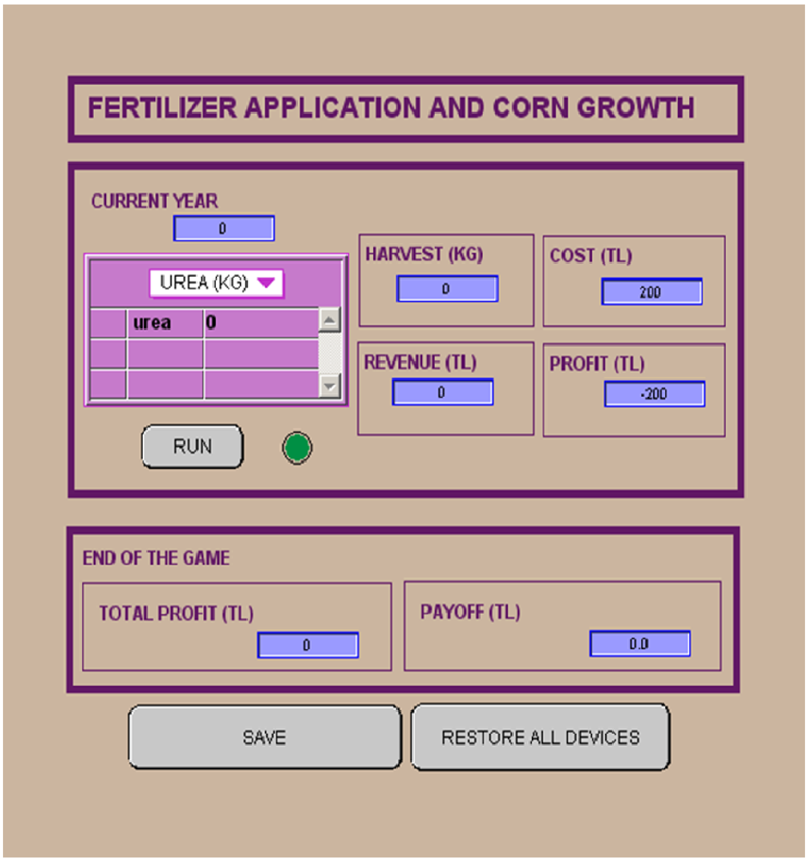


Figure 7. Game interface.

As years unfold, if no fertilizer is applied, soil inorganic nitrogen levels gradually decline and yields and profits are reduced. If fertilizer rate is kept constant or increased, yields are sustained however profits decline with increasing fertilizer costs, NUE is reduced and leached N is increased.

A long term near optimal strategy entails gradual decline in fertilizer rates so as to keep soil inorganic N at desired levels to ensure maximum yield while minimizing environmental and economic losses. A near-optimal benchmark strategy for farm profits is found by trial and error and described in the results section.

III. 3. Experimental design

Pilot experiments are conducted with graduate assistants at the Institute of Environmental Sciences in Bogazici University in May 2014. After necessary amendments on game interface and instructions, experiments are conducted in June 2014, with 61 undergraduate students recruited from different classes on global climate change, evolution and social ecology. Subjects are paid incentives between 10-25 TRL (approximately 5-12.5 $), in correlation to their performance in the experiments.

The experimental variables are the initial residual N concentration (low and high) and the outcome feedback on soil residual N (not present and present). Experiments are conducted in full factorial between-subject design. Number of participants in each treatment is depicted in Table 1.

Table 1. Design of the experiments

		Initial condition	
		underfertilized	overfertilized
Outcome feedback (residual nitrogen)	No	T1 – 16	T3 - 16
	Yes	T2 - 15	T4 - 14

Figure 8. A scene from an experiment session.

RESULTS

The results are summarized in Figure 8. The horizontal axes of the graphs are the years and the vertical axis is the annual urea application rates (kg-urea/ year). Darker lines depict benchmark fertilizer rates that maximize net accumulated profits over the years. The subjects' averages and the 95% confidence interval according to t-statistics are depicted with the lighter colors.

The benchmarks for T1 and T2 and for T3 and T4 are identical because their initial residual nitrogen levels are the same. For T1 and T2, a near-optimum fertilizer management entails gradual reduction in fertilizer rates because, at the first round once nitrogen deficiency is repaired, future rates can be gradually reduced since residual nitrogen supplies the nutrition required by the crop. For T3 and T4, because the soil is rich in N at the first round, the prescribed rate is low. However, because the residual consumed and washed out in the first season can not be supplied by the low initial application rate, by the second year the soil needs to be enriched with high rates and after that the rates can be gradually reduced, as in T1 and T2.

For T1 and T2, benchmark lies within the confidence bounds, indicating that the overuse hypothesis can be rejected. The outcome feedback on annual farm profits is accurate but weak because fertilizer prices are considerably low. It looks, subjects are able to follow this feedback and reduce their rates. What is interesting is, only a few subjects tend to increase at the first round. In T2, feedback on residual N further helps the players to reduce their rates. However, for both of the treatments, the average subject still lies above the benchmark and this will show statistically significant consequences on nitrogen use efficiency (NUE) and total nitrogen leached (TNL).

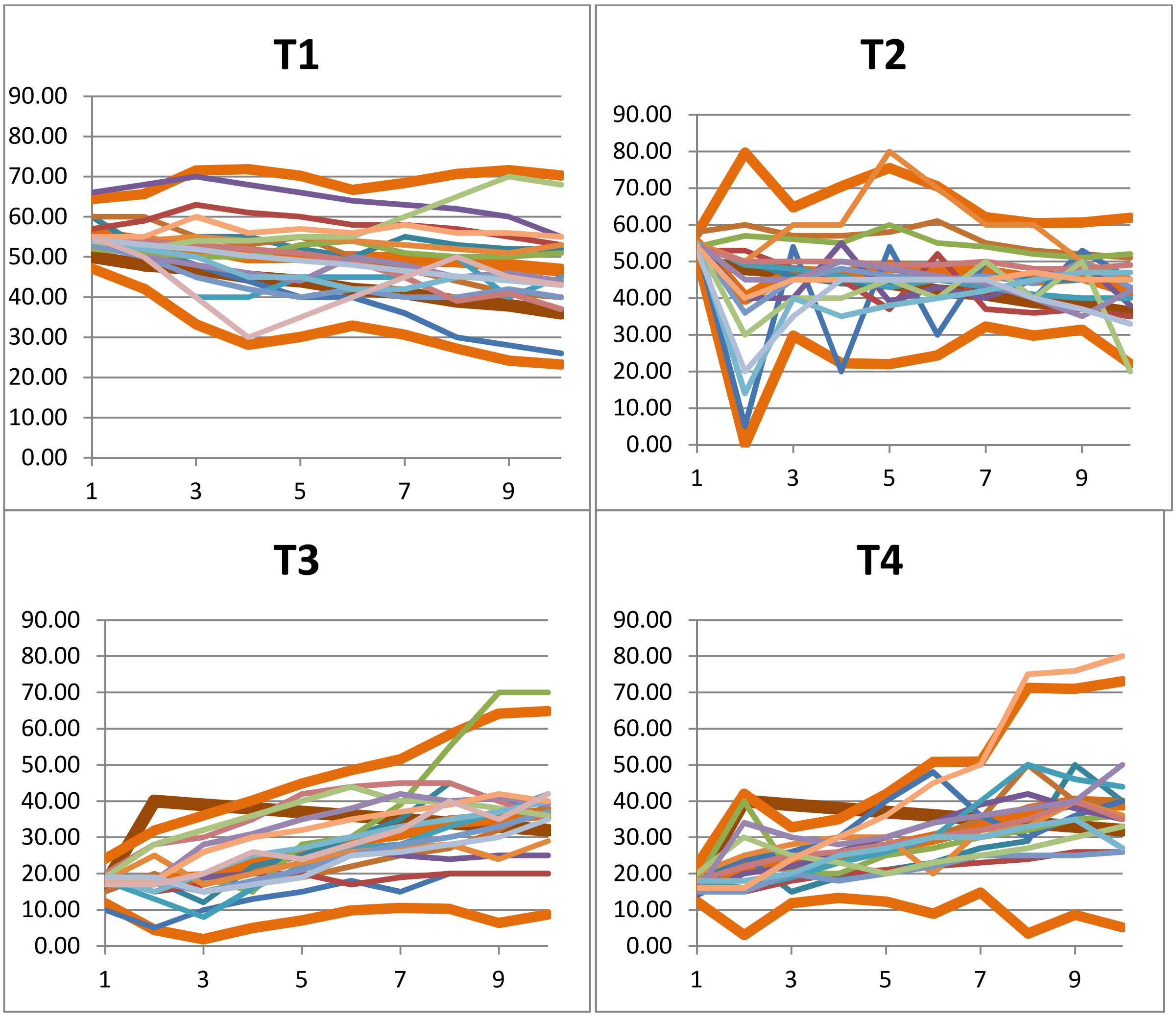


Figure 8. Benchmarks, subjects' average fertilizer rates and the 95% confidence intervals

For T3 and T4, after the first four rounds where the subjects adjust their rates following the annual profit feedback, benchmarks lie within the confidence bounds. As rounds proceed, average rates approach and the overshoot the benchmark. Yet, it seems feedback works after the overshoot and subjects tend to reduce their rates and approach to the benchmark application rate. Here again, feedback is stronger in T4, where the subjects can read the annual residual nitrogen data.

Resulting NUE and TNL are shown in Table 2.

Table 2. Average nitrogen use efficiency (NUE) and average total nitrogen leached (TNL) at the end of the game.

	Benchmark T1-T2	**Benchmark T3-T4**	**T1**	**T2**	**T3**	**T4**
NUE %	0.23	0.23	**0.21**	0.22	0.23	0.23
TNL kg-N	28.98	29.57	**35.11**	31.81	**25.19**	**26.70**

On Table 2, it is observed that, for T1 and T2, subjects' averages for NUE is lower and for TNL is higher than the benchmark values. For T3 and T4, subjects' averages for NUE are equal to the benchmark value while their averages for TNL are lower. Table 3 shows the p values for one sample t-test. For T1 and T2, total amount of nitrogen leached is significantly higher than the benchmark values at $p<0.05$. For T3 and T4, TNL is significantly lower than the benchmark at $p<0.05$. For T1, NUE is significantly lower than the benchmark value at $p<0.05$.

Table 3. P values for one sample t-test

T1-NUE	T1-TNL	T2-NUE	T2-TNL	T3-NUE	T3-TNL	T4-NUE	T4-TNL
0.001	0.000	0.144	0.041	0.360	0.001	0.266	0.023

DISCUSSION

Although outcome feedback on farm profit helps subjects adjust their fertilizer rates, in real life, cause and effect between fertilizer rates and crop yields is confused by various factors, such as seed variants, weather changes, soil management practices and changing soil characteristics. Outcome feedback on residual N further helps subjects improve their decisions. In real life, the cause and effect between residual N and appropriate fertilizer rates can be more reliable and salient. On the other hand, this requires regular soil analysis for residual N however, that may be unavailable or costly to warrant its use by the farmers.

We propose the following activities for further research: First, a strategy game on paper and pencil can be run to see to what extend subjects benefit from outcome feedback on farm yields and profits. Second, the simulation game can be modified to allow farmers to choose or not to choose to purchase residual N analysis on a specific cost, and in return receive recommendation on appropriate N rates. This modified version can be treated with cases on (a) uncertain yields due to factors other than N availability and (b) uncertain N availability because of uncertain change in N mobilization, immobilization and loss processes.

The modified versions of the game can be applied in the field with farmers to improve their understanding of N accumulation processes and its influence on appropriate N rates. If the farmers can be convinced that soil analysis may help them improve their farm incomes (given soil analysis is provided with reasonable cost), they will be more eager to seek regular in-field assistance and soil analysis. This can considerably reduce the N rates, hence the amount of N lost to the atmosphere and oceans resulting in global climate change, water pollution and eutrophication.

APPENDIX A: GAME INSTRUCTIONS T1

You took over one decare farmland from a farmer and decided to raise corn for the next 10 years. Your goal is to maximize your infinite horizon profit (total profit discounted by an annual discount rate of 5%) at the end of 10 simulated years. Your task is very simple: Each year, you will only decide on the amount of urea fertilizer that you will apply on your farmland. Once you decide on the amount, urea will be applied three times at equal amounts: Just before sowing of corn seeds; and one and two months after sowing. Because all sowing and harvest is taken care by the simulator, all you need to do is to enter your annual urea application decision and then to hit the run button to proceed to the next year.

Urea is a relatively mobile organic N compound. Shortly after it is deposited on the farmland, it transforms into mobile, inorganic N forms which the corn plant can assimilate. N is an essential macronutrient for corn. If N assimilation by corn is less than it is required, its growth will be impaired and there will yield losses. Only if the corn can assimilate sufficient amounts of N, the yield will be at satisfactory levels.

There are two sources of mobile N in soil: (1) Inorganic N sourced from fertilizer application, which is urea in your case. (2) Soil organic N mobilizing into inorganic N forms that corn can assimilate. Note that only a part of the urea N that you apply on your farmland is assimilated by corn. The rest is either lost to atmosphere and groundwater in gas and liquid forms, or immobilized into organic, immobile soil N.

As you took over this farmland at the start of the game, agronomists in your region made some analysis of your soil and concluded that the soil is under-fertilized (1 kg-N/decare). They suggested that you should start by around 50-55 kg-urea/year application rate, so as to maximize your annual profit. If you follow their advice, you can expect to harvest around 1100 kg corn, sell all of it for 1 TL/kg, and because you pay 4 TL/kg for urea, you may expect to earn (1100x0.5)-(4x50)=900 TL. Note that your sole income is corn sales and your sole cost is the urea. The agronomists also tell that maximum corn you can harvest at the most favorable soil N conditions is 1150 kg.

You can test this with a trial on the simulator. On the upper frame, you observe the pink input device for your current urea decision. After you enter your decision, hit the run button and observe the resulting harvest, revenue, cost and profit values. Proceed until the ninth year when the green button turns to yellow. Yellow color means, you have one more decision for the tenth year. After the tenth year, yellow button turns red and you should no more make a new decision but hit the save button below to save your results. In the lower frame, now you can observe your total discounted profit and your payoff that you will receive from the experiment leader. Note that the more profits you make throughout the game, your end of the game profit will be more. Your payoff will increase with increasing end of the game profits! (Between 10 and 25 TRL.)

Until the experiment starts, please do not touch the computers. Before the experiment, be sure that you understand the instructions. After reading the instructions, follow the experiment leader's instructions on the slide projector. During the experiment, please fill in your decisions and your observed outcomes to the tables provided on the second sheet. After you finish the game do not leave your seats and wait until the experiment is over. Then you can approach to the experiment leader to receive your payoff.

All the data provided during the experiments are anonymous and will be used in research funded by Bogaziçi University Research Fund Project No: 6376.

Thank you for your participation!

T0 – S1

YEAR	UREA DECISION	HARVEST	PROFIT
0			
1			
2			
3			
4			
5			
6			
7			
8			
9			

TOTAL PROFIT:

PAYOFF:

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