SIMPLE-G Application:

Achieving Planetary Boundaries Through Economic Policies: Global Impacts of Local Fertilizer Taxes

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Abstract

Agriculture is a primary contributor to water quality degradation and ecosystem disruption, with particularly high impacts in regions of intensive fertilizer use. While market-based instruments such as taxes on nitrogen fertilizer have been proposed to reduce the application, the broader economic implications of such policies remain uncertain. This paper investigates the local and global economic effects of imposing taxes on nitrogen fertilizer use in regions with high nitrogen leaching. We develop and apply a novel global gridded partial equilibrium model, SIMPLE-G, linked to the LPJmL dynamic vegetation model to evaluate the implications of these location-specific interventions. Our approach accounts for grid-cell level heterogeneity in input substitution, crop production responses, and trade dynamics, enabling a spatially explicit assessment of policy impacts. We introduce a new integration of emulated Gompertz yield functions and nitrogen leaching functions into the economic model, capturing nonlinearities and spatial differences in fertilizer efficiency and pollution. This study provides a simple experiment of a uniform tax. The simulation of a 100% nitrogen fertilizer tax in high-leaching zones demonstrates significant reductions in nitrogen runoff in targeted areas (up to 37% in parts of Eastern Europe) while highlighting important market-mediated spillovers.

1 Introduction

Agriculture is a significant contributor to nitrogen pollution, which, in turn, harms water quality and ecosystems. The leaching of nitrogen from farmland is a major cause of freshwater contamination, triggering eutrophication and loss of biodiversity. To stay within planetary boundaries of biogeochemical flows, economists have suggested using market-based tools --like taxes on fertilizer or agricultural production-- as a way to cut down on nitrogen application and runoff. However, the unanswered question is whether these policies can strike a balance between protecting the environment and supporting agricultural output. The final impact on food security and the environment depends on the crop and fertilizer markets. Due to significant spatial heterogeneity, evaluating the benefits and likely unintended consequences of such policies requires spatially resolved quantitative frameworks.

A number of computational studies have explored the impacts of taxes and subsidies on fertilizer markets in quantitative equilibrium models (e.g., Suprapto, 1988; Elshennawy, 2011; Bartelings et al., 2016). Generally, the magnitude of the impacts of policies depends on the cost share of fertilizer, crop production flexibilities (substitution elasticities), as well as fertilizer demand, supply, and trade elasticities. The empirical studies suggest that the demand elasticities for fertilizer products, including nitrogen, phosphorus, and potassium fertilizer, can range from -0.25 to -0.75 (e.g., Steiner 2014, Minear 2015). These studies also suggest a significant correlation between natural gas and fertilizer prices, suggesting critical intersectoral linkages (Huang et al., 2009; Fischer et al., 2024) and trade sensitivity to natural gas prices as illustrated in Figure 1-a.

Overall, economic studies suggest that a tax on nitrogen fertilizer could reduce its use, implying that it can help reduce environmental damage. However, there is a gap in the research when it comes to understanding the wider economic effects, particularly about market-mediated spillover effects of such taxes on global food production and in non-target locations (Liu et al., 2023). This paper introduces a new gridded economic model coupled with a gridded crop model to evaluate the economic and environmental impacts of a local tax on nitrogen fertilizer application and agricultural production. The policy targets the regions with high nitrogen leaching rates. The goal is to assess how such local policies might affect global agricultural markets, fertilizer trade, and water quality.

2 Methods

We conduct our analysis at 5 arc-min resolution dividing the world into 1.3 million production units. At this resolution, we combine a global gridded economic model with a global crop model to simulate the impacts of a tax on nitrogen fertilizer use in high-leaching regions. We have calibrated gridded margins and implemented partially flexible asymmetric substitution and supply elasticities with alternative functional forms (Figure 1-c). One of the key innovations is the integration of the Gompertz function to show crop output response to fertilizer application. By using grid-cell-specific functions emulated from the crop model, we account for spatial differences shaped by biophysical characteristics. The model has also been thoroughly validated, ensuring it handles nonlinear relationships more accurately. The new model can capture the interactions between agricultural practices, fertilizer use, and environmental pressures at the grid cell level --an important addition for the GTAP community as it seeks to model global trade, policy, and sustainability in increasingly complex contexts.

2.1 Gridded Equilibrium Model

SIMPLE-G (Simplified International Model of agricultural Prices, Land use, and the Environment - Gridded version) is a multi-scale, gridded, partial equilibrium economic model (Haqiqi and Hertel, 2025).

2.1.1 Gridded Production: Partially Flexible Nested CES

The standard SIMPLE-G model represents agricultural production at the grid-cell level using a nested constant elasticity of substitution (CES) function. At the top level, output is produced from a CES aggregation of nitrogen fertilizer and other inputs. The next layer is a CES aggregation of land-water and a composite non-land input. The land-water layer combines land input and water (if irrigated). Within this structure, each input group is combined using grid-specific substitution elasticities, allowing for differentiated input shares and substitution patterns across locations.

In the current study, we replaced the top nest with a flexible Gompertz functional form, which provides asymmetric substitution possibilities. This function is parameterized using the crop model and yield response to nitrogen fertilizer application.

2.1.2 Gridded Land Allocation

Land allocation between irrigated and rainfed production within each grid cell in SIMPLE-G is modeled using a quantity-preserving constant elasticity of transformation (QCET) function. This functional form maintains the total land area constant while allowing for reallocation between irrigated and rainfed uses based on relative returns.

2.1.3 International Trade

International trade in SIMPLE-G is modeled across 17 aggregated regions. On the demand side, imports and domestic products are treated as imperfect substitutes using a CES Armington specification. For the composite crop commodity, regional demand combines imports from the global market and domestically produced goods, with substitution governed by Armington elasticities. On the supply side, total production in each region is allocated between domestic use and exports through a constant elasticity of transformation (CET) function. This captures the trade-off producers face based on relative prices. Within regions, a sub-regional Armington structure further differentiates products by their location of production. This allows the model to account for spatial heterogeneity within countries or regions.

2.1.4 Nitrogen Fertilizer Trade

On the regional demand side, nitrogen fertilizer imports are incorporated using a constant elasticity of substitution (CES) Armington function to capture the imperfect substitutability between imported and domestically produced nitrogen fertilizer. A CET function determines exports allocation. The data on fertilizer trade is obtained from FAO and aggregated to 17 regions.

2.2 Crop Model

The LPJmL model, which stands for Lund-Potsdam-Jena managed Land, is a dynamic global vegetation model developed by the Potsdam Institute for Climate Impact Research (PIK). It estimates nitrogen runoff and the resulting water quality impacts in different regions based on changes in fertilizer use. We estimate how reductions in nitrogen use lead to changes in crop yields and how these changes might affect nitrogen pollution.

2.3 Gompertz Function Implementation

The integration of biophysical dynamics into the economic model represents a key advancement. Specifically, outputs from the LPJmL crop model are used to estimate grid-cell-specific Gompertz functions that capture the nonlinear response of crop yields to nitrogen fertilizer application. The Gompertz function is well-suited for this purpose, as it reflects the diminishing marginal returns of fertilizer input and the saturation effect at high application levels. These yield response functions are estimated for each grid cell based on simulations of varying fertilizer application rates under current climate and management conditions. In parallel, nitrogen leaching functions are derived from the same LPJmL simulations, quantifying the relationship between fertilizer use and nitrogen losses to the aquatic systems. The leaching response also follows a nonlinear trajectory, with steep increases in runoff beyond certain threshold application rates. These functions are emulated at the grid level to reflect local soil, climate, and management conditions. Once estimated, both the Gompertz yield functions and leaching functions are embedded directly into the SIMPLE-G model. Fertilizer application choices now affect both yields and nitrogen losses through the embedded functions. The incorporation of these response functions will enable simulation of policy impacts on food production and environmental quality in a spatially explicit and biophysically consistent manner.

2.4 Experiment Design

We apply a 100% uniform fertilizer tax to grid cells with high nitrogen leaching rates and estimate how this tax affects nitrogen fertilizer use, crop production, and trade. These locations are identified based on LPJmL model runs.

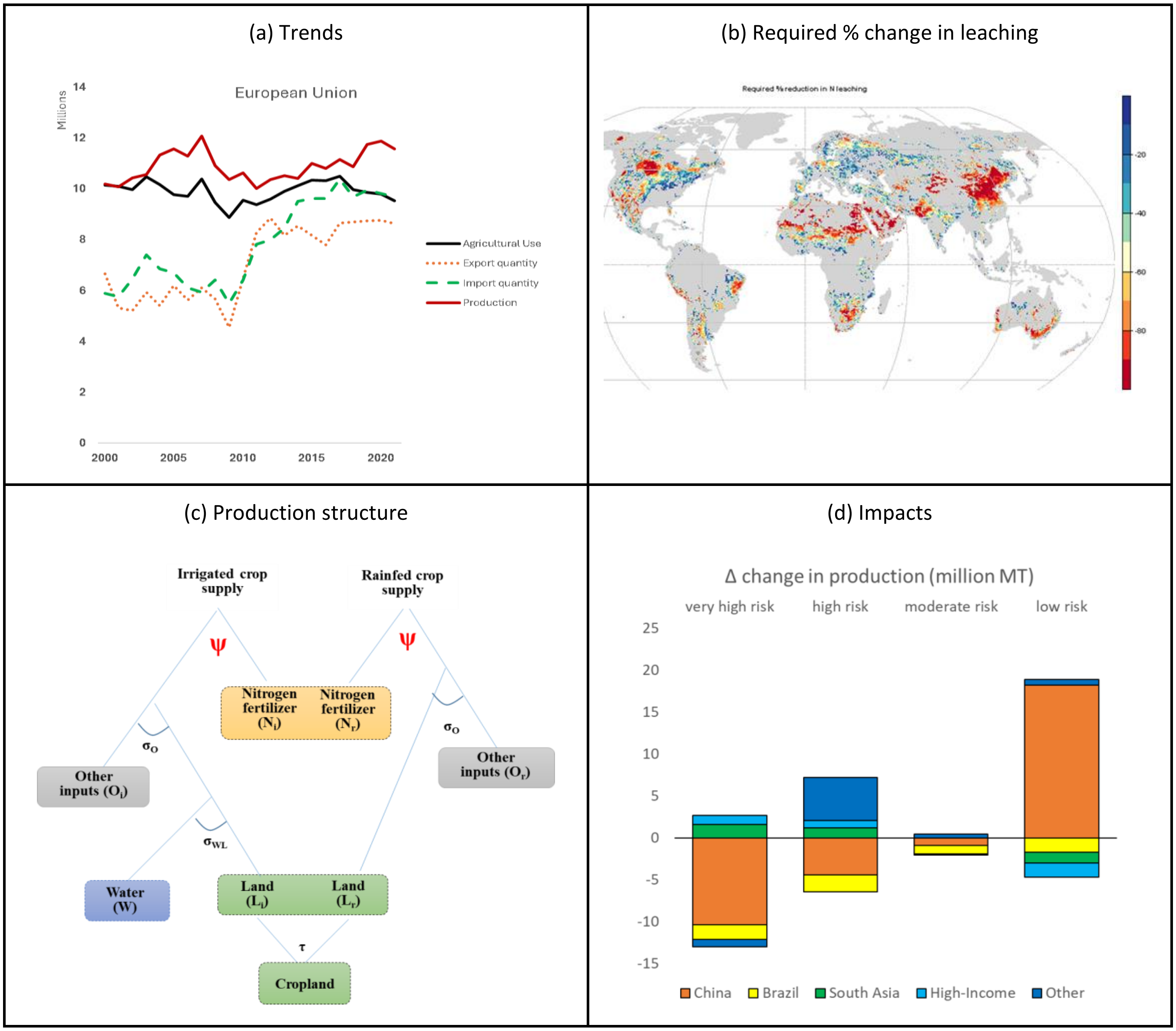

Figure 1. Nitrogen fertilizer: (a) Market trends for EU. (b) Required reduction to achieve sustainable levels. (c) The production structure of the model with flexible substitution elasticity ψ. (d) the impacts of 100% targeted N tax.

2.5 Data

We employ the global gridded economic data on the value of agricultural production, input costs, input supply elasticity, and substitution elasticities as provided in the SIMPLE-G Book (Haqiqi et al., 2025) for the year 2017 at 5 arc-min resolution. The data for emulating the yield response to fertilizer application is from the LPJmL simulations (von Bloh et al., 2018). We simulated the crop yields, assuming 30 different levels of fertilizer to emulate the yield response function. The outputs, data, and codes for this study will be released as open access upon publication.

3 Results

We evaluate the impacts of a 100% tax on nitrogen fertilizer in target locations. We also provided sensitivity analysis with respect to trade and production parameters. The target locations are identified in Figure 1-b. The impact on crop production is illustrated in Figure 1-d. Due to the decline in fertilizer application in high-risk regions, the prices will fall and trigger an increase in fertilizer application in currently low-risk locations. This highlights how price corrections can significantly change the spatial pattern of production. Depending on elasticities, the price may decline from 6.45% to 22.60%. The tax policy has reduced nitrogen leaching in target regions in East Europe by 37.43%, in the US by 8.05, and in China by 3.44. As a result, the import of N fertilizer declined by 8.62% in China but increased by 7.95% in Central Asia accompanied by a 2.62% increase in China's exports of N fertilizer.

4 Conclusion

The results of this study suggest that while local taxes on nitrogen fertilizer can effectively reduce nitrogen leaching in targeted regions, the global economic impacts are much smaller than anticipated. The global reduction in nitrogen fertilizer use is partly offset by an increase in fertilizer use in non-target regions. Future research should explore these alternative policy options to enhance the effectiveness of market-based instruments for clean water governance.

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