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Halving mineral nitrogen use in European agriculture: insights from multi-scale land-use models

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Abstract

In this paper, we explore the effects of a public policy that reduces by 50% the use of mineral nitrogen in European agriculture. We use two techno-economic models to investigate the impacts on agricultural production, prices, and land use changes at the EU and global levels. Results show that halving synthetic fertilizer use leads to a decrease in agricultural production, a substantial increase in nitrogen use efficiency, and lower use of organic fertilizer. More importantly, we show that the results will critically depend on the potential for supply side adjustment, particularly, regarding the expansion of cropland area.

Keywords: agriculture, land use, nitrogen pollution, trade, environment.

JEL Classification: Q11, Q12, Q15, Q18, Q52, Q53, Q54

Introduction

With the introduction of the Green Deal, the Commission intends to revive the European project, aiming to involve the younger generation in achieving the objective of "[reconciling] our economy with our planet". Since early 2020, a succession of proposed regulations and strategies has led to the development of an ambitious, far-reaching plan that can act as the EU's new growth strategy, cutting greenhouse gas emissions, protecting the environment and delivering jobs. Several components of the Green Deal will impact the EU agricultural sector, including those dealing with climate, circular economy, clean energy, etc. (see Guyomard et al., 2020). Two of European Commission's proposed strategies are particularly aimed at the sector, the Biodiversity strategy for 2030 and the so-called "Farm to fork strategy" (F2FS). The two strategies are consistent, setting similar objectives in terms of reduction of pollution and of risks from fertilizers and phytosanitary and antimicrobials products. A target involves the reduction of nutrient losses (nitrogen and phosphorus) by at least 50% by 2030 which, according to the EC, would lead to a reduction in fertilizer use of at least 20% by 2030 (European Commission, 2020).

Reduction in fertilizer use could be achieved through a combination of advisory services, innovation and taxation. However, it calls for more analysis so as to gauge the consequences on output, trade, food prices and pollution. In this paper we provide simulations of a drastic decrease in the use of synthetic nitrogen fertilizer in the EU (-50%). While our scenario differs from what is planned under the F2FS, our simulations provide some insights on the economic consequences of a reduction in synthetic nitrogen consumption. We use techno-economic models to represent agricultural technology in the arable crop sector and to illustrate what could be achieved with a more detailed representation of the technology – i.e. not relying on a simplistic production function – and that is able to explore areas that differ from a sample of past observations.

European agri-environmental policy context

A significant reduction in an input such as synthetic fertilizer is likely to cause a negative supply shock, leading to a reduction in output. There is clearly a need to assess more precisely the economic consequences. However, the economic models usually used for impact assessments are ill-suited to that purpose. They hardly allow for the changes in technology required to assess crop response and farm systems adaptation. They could in theory be calibrated to include induced innovation and technical change to save inputs in a non-homothetic manner. Substitutions between chemical inputs and land and labor can also be easily calibrated in principle, but the separability assumptions implicit in most functional forms used in models hardly match reality (e.g. substitution elasticities between say, chemical inputs and land are not independent of the level of labor as typically implied with a CES function structure).

In this paper, we do not provide a complete assessment of the Commission's proposal: assessing the impact of the F2FS would require, for example, modelling structural changes in production techniques and consumption patterns. We focus on the reduction of the consumption of synthetic nitrogen, without structural changes in production techniques (agroecology) and demand (reduction of calories intake and animal sourced proteins as included in the F2FS). The reduction in synthetic nitrogen consumption to achieve a 50% reduction in nitrogen losses stated in the F2FS is difficult to estimate. Synthetic nitrogen is only one source of the nutrient, others including manure, biological fixation by leguminous crops and atmospheric deposition. Moreover, the different nitrogen inputs may interact, with possible substitutions linked to farmers' economic and agronomic choices. While the EU Commission estimates this would correspond to a reduction of roughly 20% in nitrogen use, here we simulate the consequences of a 50% reduction in synthetic nitrogen (only).

Synthetic nitrogen in agriculture

Synthetic or mineral[1] nitrogen use in agriculture is a complex issue with important trade-offs between productivity and environmental quality. In 1898, the British Academy of Sciences predicted that the lack of available nitrogen would limit the world population by the 1930s, unless a method could be found to transform atmospheric nitrogen (N) into its reactive forms in order to use it as fertilizer (Hager, 2009). This achievement, mainly through the Haber and Bosch process and modern ammonia synthesis, was one of the major technological advances of the 20th century, allowing agriculture to feed the growing global population (Erisman et al., 2008). However, massive nitrogen use in arable farming is behind a cascade of environmental impacts including soil acidification, inland and coastal water eutrophication, and atmospheric N_2O and NO_x emissions affecting the global climate system and regional air quality. According to Steffen et al. (2015) and Rockström et al. (2009) the imbalance in nitrogen and phosphorus biogeochemical flows is the area where planet boundaries have most been trespassed beyond pos-

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[1] We use these terms interchangeably throughout this paper.

sible resilience, even before biodiversity losses and climate change. The OECD (2018) suggests that the anthropogenic perturbation of nitrogen flows is perhaps causing particularly irreversible damage. In 2018, the UN started funding a "nitrogen equivalent of the International Panel on Climate Change" to address these issues. Agriculture and land use change are behind most of the issues related to nitrogen (Foley et al., 2011). In particular, intensive use of nitrogen fertilizers in agriculture is a major contributor to greenhouse gas (GHG) emissions, air quality degradation, and eutrophication of catchments.

In economic terms, Europe has greatly benefited from the availability of affordable nitrogen fertilizers in agriculture. Nevertheless, the negative environmental consequences of nitrogen losses resulting from fertilizer use are particularly severe in Europe (Erisman et al., 2008). Sutton et al. (2011) evaluated the environmental costs associated with the impact of atmospheric and water pollution on ecosystems and human health in EU Member states at €70–320bn euros per year. Such an amount of magnitude suggests that the social costs of N fertilizers in Europe now offset a large share of the gains. And that social benefits of reducing nitrogen use would exceed private losses.

Related literature

There are few studies in the literature quantifying the effects of nitrogen policies on agriculture. Dalgaard et al. (2014) review the public policies implemented in Danish agriculture since the mid-1980s which had significant effects on surpluses (from 170 kg$N$/ha/year to below 100 kg$N$/ha/year), efficiency (from around 20–30% to 40–45%) and environmental loadings of N (-50% of N-leaching). Laukkanen and Nauges (2014) analyzed the impacts of agri-environmental payments in Finland and showed that they had a small effect on fertilizer use (-1.5%) and nitrogen loading (-11%). Moreover, they estimated the own price elasticity of the demand for fertilizers to be -0.91. Lacroix and Thomas (2011) evaluated fertilizer own price elasticity to be -0.37 in France which is similar to the estimate of -0.28 by Bayramoglu and Chakir (2016) for the French department of the Meuse. At the EU level, Velthof et al. (2014) found that the Nitrates Directive decreased nitrate leaching in the EU-27 by 16% between 2000 and 2008. Van Grinsven et al. (2015) show that a 2030 scenario for the EU-27 reducing consumption and production of animal products by 50% (demitarean diet) reduces N pollution by 10%. These contributions and those reviewed in Bouraoui and Grizzetti (2014) quantify the effects of nitrogen management options on nitrogen loads and losses into the environment. They do not, however, take account of the effects on land use, agricultural production, or agricultural prices.

This paper contributes to this literature by assessing the impacts of a policy aiming to halve synthetic nitrogen fertilizer use in Europe. We use two types of techno-economic model: an agricultural supply-side model of the European Union, AROPAj (Jayet et al., 2018) and a global scale partial equilibrium model, NLU (Souty et al., 2012). These models allow us to analyze and compare the effects of the policy in terms of agricultural production, prices, land use change and greenhouse gas emissions at local and global scales.

The paper is organized as follows. Section Materials and methods describes our methodology. Section Results presents and discusses the simulation results. Section Discussion and conclusion concludes.

Materials and methods

The two models used in this paper – AROPAj and NLU – rely on different modeling strategies (supply-side model vs partial equilibrium model) and use different datasets (see below). Each model has its strengths and weaknesses, AROPAj including a comprehensive description of farm types and crop choices and NLU providing a global perspective with price feedbacks and details on the nitrogen balance. Thus, comparing their results gives us a more comprehensive and robust picture of the consequences of a N-reducing policy.

AROPAj is built on data from the Farm Accountancy Data Network (FADN) and models agricultural supply by (groups of) farmers, representative at the regional level[2]. Each agent in the model maximizes its gross margin, the difference between production revenues and variable costs. The model's mathematical programming structure aims to solve this maximization problem while respecting a number of constraints associated with physical processes and the EU Common Agricultural Policy (Galko and Jayet, 2011).

NLU provides a simple representation of the main agricultural intensification processes for crop and livestock production: the substitution between i) land and fertilizer[3] for the crop sector and ii) grass, food crops, residues and fodder for the livestock sector. It does so by minimizing the total production cost under a supply-use equilibrium in food and bioenergy markets. In

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[2] FADN regions are similar to the EU NUTS2 level.

[3] For a given quantity of agricultural product, farmers have to combine land and inputs. The amounts of these production factors are supposedly decided in a rational way where the objective is to reduce costs. If input prices increase (e.g. via a tax), farmers will have to cultivate a greater area of land in order to attain the same level of production. Thus the reduction in inputs (the intensive margin of agriculture) could lead to an increase in land cultivated (the extensive margin of agriculture).

NLU, the agricultural sector is divided into 12 global regions, inter-connected by international trade. A detailed description can be found in Souty et al. (2012) or in Brunelle et al. (2015). Futhermore, NLU incorporates a nitrogen balance that depicts the main fluxes of nitrogen in the agricultural system. A complete description of the nitrogen balance in NLU is available in Prudhomme et al. (2020).

To describe the change in the technical system induced by the half N policy, we refer in this paper to four key components of the nitrogen balance: (i) a change in the amount of harvested nitrogen through the harvest of plant products which may thus affect crop yields and crop production; (ii) a change in biological nitrogen fixation by leguminous crops; (iii) a change in nitrogen use efficiency associated with improved agricultural practices and (iv) a change in organic fertilizer use. In the remainder of this section, we detail the main features of the AROPAj and NLU models in relation to these components.

Input level choice in the models

Dose-response functions

AROPAj and NLU rely on a similar methodology to simulate crop yields based on functional forms relating those yields to fertilizer levels. There are, however, some important variations in the way technical change in the crop sector is represented in both models: in NLU, technical adjustments are mainly determined by substitutions between land and synthetic fertilizers (nitrogen, phosphorus and potassium), with relatively few constraints on agricultural expansion. In AROPAj, technical change is governed by substitutions between land, nitrogen fertilizers and irrigation. However, compared to NLU, the possibilities of agricultural expansion are fewer, given that local constraints on land use are better taken into account. AROPAj is indeed a European model with a more detailed representation of local constraints (e.g. crop rotation, cultivation costs) than the global model NLU.

In AROPAj, production processes are calibrated at the farm scale at the EU level. By using nitrogen-water dose-response functions derived from a crop model (STICS, see appendix Agronomic models), the input level choice by farmers in AROPAj is endogenous, on the assumption that they maximize their gross margin. The nitrogen-water dose-response functions are estimated for nine major crops: winter and durum wheat, barley, maize, rapeseed, sunflower, soybean, sugar beet, and potatoes. These nine crops account for 78% of the EU crop mix at the baseline. The remaining crops are also modeled but the N input per ha is constant at the level estimated on the basis of FADN data (Jayet et al., 2018).

NLU considers 60 land classes with homogeneous potential crop yields in each of the 12 regions. In each of these land classes, production intensification in the crop sector is modeled with a non-linear response of yield to fertilizer inputs. The asymptote of this function corresponds to the potential crop yield given by the LPJmL vegetation model (Bondeau et al., 2007, appendix Agronomic models). The yield-fertilizer relationship is calibrated on the fertilizer consumption values calculated with FAOSTAT data. Nutrients are represented as complementary inputs without any substitution possibilities between them. Parameters of the yield-fertilizer relationship (minimum yield and slope at the origin) are calibrated so as to minimize the error between modeled and observed crop yields over the period 1961-2006. NLU includes a nitrogen balance based on Zhang et al. (2015) which represents the different sources and outputs of nitrogen in the cropping system (for more details see Prudhomme et al., 2020).

Livestock breeding and organic nitrogen availability

The livestock sector is important here, as it may provide organic nitrogen, in the form of manure, substituting for synthetic nitrogen. AROPAj and NLU both include a detailed representation of this sector, with explicit links to crop production providing animal feed or benefiting from animal manure.

AROPAj models 31 animal categories, namely sheep, goats, pigs, poultry, and 27 categories of cattle. The latter depend on age, sex, origin, final output, and Common Agricultural Policy subsidies. Animal activities are constrained by animal feeding and demography. The resulting manure is either directly applied to pastures by grazing animals or collected and applied to fields with a constraint on maximal quantity of 170 kg$N$/ha.[4]

NLU considers two farming systems for ruminant production based on Bouwman et al. (2005): (i) the pastoral system where animals are fed mainly by grazing on extensive pastures and to some extent by scavenging; and (ii) the intensive system for which animals are fed not only with grass but also with residues and fodder, food crops, animal products and by scavenging. The share of each system in the livestock sector is driven by the relative price of feed and land. Each ruminant farming system is associated with specific coefficients reflecting the manure collected and applied to fields. The amount of manure applied to cropland per unit of ruminant production in the intensive system is 14.4 kgN/Mkcal on annual crops and 4.96 kgN/Mkcal on perennial

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[4] A restriction imposed for nitrate vulnerable zones as defined in the EU Nitrates directive. Since we ignore the exact geographical location of farmers, we extend this restriction to the whole EU territory.

crops, while there is no manure from the pastoral system applied to cropland due to collection constraints.

Crop choice

Two categories of crops are distinguished in NLU: “dynamic” crops, corresponding to most annual crops (cereals, oilseeds, sugar beet and cassava), and “other” crops corresponding mostly to perennial crops (e.g., sugar cane, palm oil and some fodder crops). All categories of crops are aggregated based on their calorific values. Changes in the area under cultivation and yields for “other” crops are determined exogenously while “dynamic” crop yields are endogenously determined taking into account biophysical constraints and the amount of fertilizer used. The type of crops and their contribution to the aggregates are fixed for each crop category and cropping intensity is assumed to be constant. Thus, NLU is not able to endogenously simulate an increase in N-fixing crops.

AROPAj has a much finer crop representation. AROPAj covers 32 crop-producing activities representing most of the EU cropland and pastures. Crops are either sold on the market or used as animal feed. Land allocation between land uses (different crops and pastures) is decided along with some input levels (nitrogen fertilizer and irrigation) in order to maximize profits while respecting a total area constraint and some other constraints associated with crop rotations. The semi-variable costs associated with different crops (e.g. grains, pesticides, labor, machinery operating costs, etc.) are estimated for each economic agent. These costs are, however, considered fixed regardless of the input choices in terms of fertilization and irrigation.

International trade

As mentioned before, AROPAj is an EU supply-side agricultural model. It does not take into account price feedback at the intra-EU or extra-EU level. NLU represents international trade in a simple manner based on relative regional prices. Imports and exports of plant and ruminant products are computed using a pool representation. With this specification, each region’s imports of crops (for food, feed and energy from biomass) and ruminant products are assumed to be equal to a proportion of the domestic demand for the corresponding products. This proportion is calculated on the basis of regional relative prices and on a coefficient calibrated in each of the model’s regions. The level of the trade pool is the sum of all regions’ imports. The distribution of the pool among the exports in each region is calculated using relative regional prices. The

Table 1. Comparison of AROPAj and NLU models

	AROPAj	NLU
Type of model	Agri supply model	Partial equilibrium
Spatial scale	EU	Global
Spatial resolution	1993 groups of farms	12 regions divided in 60 land classes
Crops	32 crops	2 groups (annual and perennial crops)
Crop model	STICS	LPJmL
Livestock	31 animal categories	2 systems (intensive and extensive)
Trade	No trade	Yes (pool representation)
Data (main sources)	FADN, Panagos et al. (2012)	FAO, Ramankutty et al. (2008)

objective of this modeling is to capture basic adjustments to the changes in terms of trade (i.e. the ratio between domestic and international prices). However, some important features such as regional specialization are not well accounted for. Table 1 summarizes the comparison between the two models used in this paper.

Simulation protocol

Two scenarios are simulated by AROPAj and NLU: a baseline scenario in which nitrogen consumption is not constrained and a half-N scenario in which total synthetic nitrogen consumption is reduced by 50% compared to the baseline. The simulations are performed for the year 2012, which is the most recent year with dose-response functions available in AROPAj. The models' results have been converted into harmonized units and displayed in a common spreadsheet template to facilitate comparison (see Supplementary Information).

In both models, the use of synthetic N is reduced by imposing a tax on the fertilizer price at the EU level. The tax level has been determined by testing different values and selecting that which is associated with a 50% reduction in mineral N consumption. For NLU, the tax is applied to the different types of fertilizer (nitrogen, potassium and phosphorus) as NLU does not consider a specific fertilizer price per type of mineral element. In AROPAj, the tax is applied as a multiplier to the price of mineral N with respect to its content in the marketed fertilizers.

At baseline, both models consider similar consumption of synthetic nitrogen fertilizer in 2012 (12.5 TgN in NLU vs 12.4 TgN in AROPAj). In contrast, organic N use is higher in NLU (4.7 TgN vs 1.2 TgN in AROPAj) because of optimistic assumptions about the distribution of organic N among farms (i.e. there is no loss between the amounts of manure produced and spread). Total crop production is also similar with 384 vs 338 million tons of dry matter for NLU and AROPAj respectively.

Results

The results of the simulations conducted with the two models are summarized in table 2. All results are expressed in percentage change from the baseline. Halving synthetic nitrogen use is achieved in Europe by both models through quite similar increases in nitrogen price: +150% in NLU and +208% in AROPAj. This corresponds to own price elasticities of the demand for fertilizers of -0.33 (NLU) and -0.24 (AROPAj) which are consistent with the literature (Lacroix and Thomas (2011) and Bayramoglu and Chakir (2016)).

However, at the global level, the results of the NLU model show an increase in synthetic nitrogen use of +1.7% due to a +9% rise in consumption in the rest of the world (RoW). This result on a global scale is explained by production dynamics between Europe and the rest of the world (see next Section).

Changes in production

A direct effect of the policy is the reduction in harvested nitrogen (i.e., the amount of nitrogen recovered through the harvesting of plant products) resulting from a decrease in agricultural production. This effect is observed in both models, albeit to different extents and as a result of distinct processes. These differences can be explained by the very nature of each model.

In the supply-side model AROPAj, the increase in the price of synthetic N lowers the use of the input and consequently agricultural production. This lowers the per ha gross margin (the difference between revenues and variable costs) and some parcels are set aside as fallow land because it is impossible to cover the costs of putting them into production. This process recalls the post war abandonment of low-fertility land in mountain areas because of the increasing labor cost and the introduction of agricultural intensification policies (MacDonald et al., 2000). The total reduction in production following the introduction of the half N policy amounts to -34%. Oilseeds suffer the greatest impact (-40%) followed by cereals (-32%), tubers (-35%), and leguminous crops (-7.4%[5]). Table 5 in appendix AROPAj results disaggregated details the effects in terms of cropland and nitrogen reductions.

Compared to the AROPAj results, the decrease in production is lower in NLU (-12.4%). This is explained by two main economic processes operating simultaneously in the NLU's partial equilibrium structure. First, farmers substitute land for fertilizer in response to the change in

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[5] In AROPAj, these crops are associated with some amounts of synthetic nitrogen use which can occur in some specific cases (Salvagiotti et al., 2008).

Table 2. Summary results from half-N simulations in percentage change from the Baseline scenario. Tons are expressed in dry matter. TgN = teragrams of nitrogen. KgN = kilograms of nitrogen

	Model	
Impact	AROPAj	NLU
Mineral N price	+208%	+150%
Mineral N use (total in TgN)	-50.6%	-50.1% (EU) +9% (RoW)
Mineral N use per ha (kgN/ha)	-41%*	-51.4%
Organic N use (total in TgN)	-10%	-4%
N use efficiency (NUE)	from +1.3% to +156%** (depending on crop)	+38%
Production (total in tons)	-34%	-12% (EU) +2% (RoW) (constant food demand)
Percentage of leguminous crops in crop mix	+15%*	*NA*
Food import (tons)	*NA*	+15% (EU) -4% (RoW)
Food export (tons)	*NA*	-12% (EU) 6% (RoW)
Food price	*NA*	+26.5% (EU) +11.7% (RoW)
LUC (hectares)	-24% crops +3% pastures +191% fallow	+3% crops -6% pastures
iLUC (hectares)	*NA*	+1% crops -0.7% pastures

* Change in N per ha and crop mix excluding fallow land.

** Calculated on the basis of kg of yield per kg of N (organic and mineral).

relative prices. This drives an expansion of cropland by +3% at the expense of pasture (-6%) and a decrease in crop yields of -18%. This mechanism reflects an increased market share for low-input farming. The expansion of cropland is made possible by a reduction in ruminant production in the EU, which frees pasture areas. Indeed, food prices increase in the EU by +26.5% to maintain the profitability of farming activities within a modeling framework that assumes food demand to be inelastic to price. This, however, undermines the competitiveness of European agriculture on international markets, leading to a loss of market share, both in crop and livestock production. Food demand being held constant between the baseline and half-N scenarios, this leads to higher imports into the EU and to an increase in production of 2.2% in the RoW. The increase in production outside the EU is obtained by increasing the nitrogen use (+9% for mineral N and +1% for organic N) and the cropland area (+1%) at the expense of pastures (-0.7%, deforestation is fixed exogenously in NLU).

Nitrogen use efficiency

In the literature, the link between yield and nitrogen use is approximated by different types of function and there is no genuine consensus on the best functional form to adopt (Makowski et al., 1999). In both AROPAj and NLU, we use a functional form allowing for 1) non-null yield when mineral nitrogen use is null, 2) functional continuity, and 3) asymptotic potential yield (figure 1). Such functional form is convenient for the economic analysis, where farmers decide the amount of N by maximizing the gross margin, comparing revenues and variable costs. This is presented on the figure by the tangents to the dose-response function. Reducing input use through taxation, for instance, moves the production choice along the dose-response function to a point with greater tangent slope and greater marginal product of N or, in agronomic terms, better nitrogen use efficiency (NUE).

Results from the two models show a large increase in NUE. In NLU, the NUE is defined as the ratio between the harvested nitrogen and the sum of harvested nitrogen and N losses. For the representative annual crop in NLU, NUE rises by +38% (from 40.7% to 56.2%, see table 3), corresponding to a 54% reduction in N losses.

For AROPAj, we compare the ratio between yield and total N input. Detailed changes are provided in table 5 in the appendix AROPAj results disaggregated. For crops with dose-response functions, the yield-to-N ratio increases between 9% (sunflower) and 157% (sugar beet). Along with the movement on the dose-response function described previously, the improvement in this

Figure 1. Dose-response functions and optimal input use

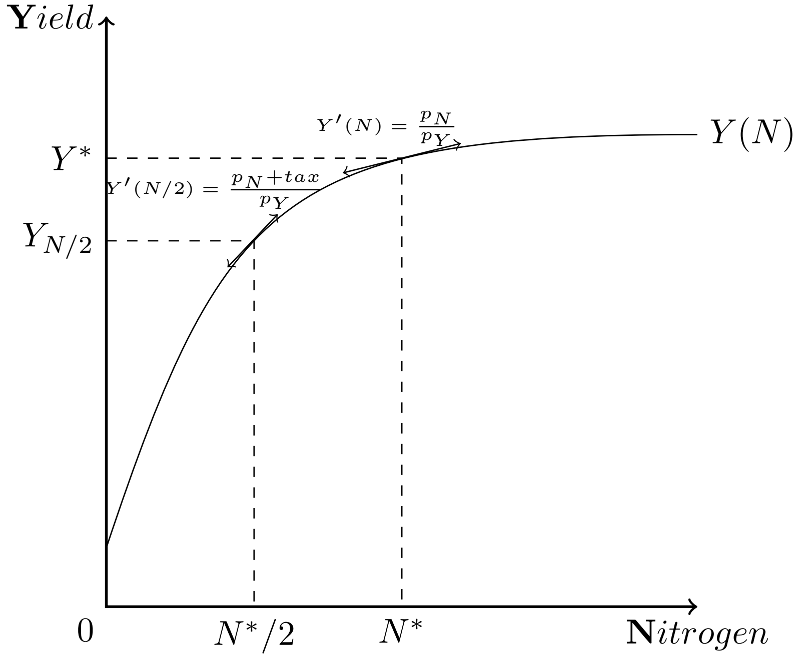


Table 3. Nitrogen outputs in NLU in Teragrams N per year (TgN/yr) and nitrogen use efficiency (NUE)

	Baseline	Half N
N harvested	7.90	6.80
N losses	11.5	5.30
NUE	40.7%	56.2%

ratio can also result from farmers concentrating their activity on more fertile land. Following these results, we can expect a significant reduction in N losses since evidence in the literature shows that N leaching increases exponentially with the amount of N applied to fields (Zhang et al., 2017; Manevski et al., 2016).

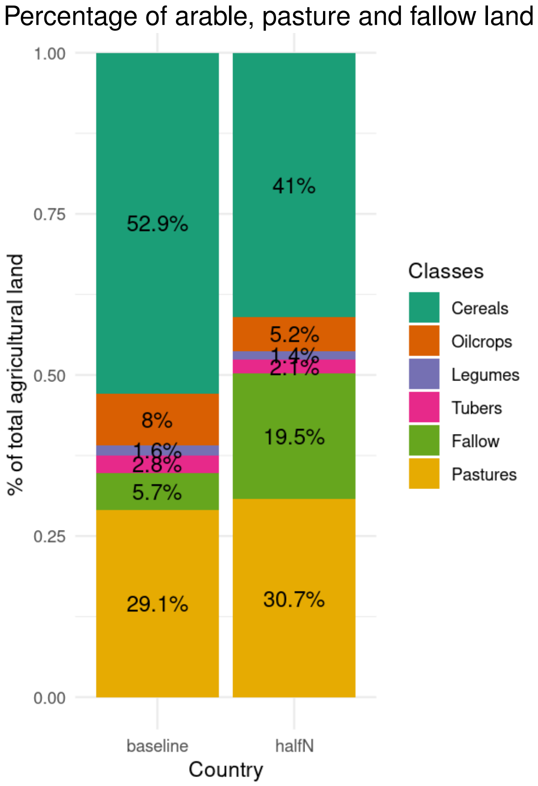
Organic nitrogen

Increasing organic fertilizer application is often considered as an option for compensating the reduction in synthetic nitrogen. However, AROPAj and NLU consistently estimate a decrease in total use of organic fertilizer which results from two different mechanisms. In AROPAj, available organic nitrogen remains stable along with the total number of animals while its use decreases by -10%. As mentioned before, the model constrains the use of organic nitrogen on cropland at 170 kg per ha (EU Nitrates Directive). Since there is less cropland in the half N scenario (-24%), manure spreading is thus limited and some of it is lost as there is no manure exchange possible between farmers in the model. Nevertheless, as land devoted to crops shrinks, there is, on average, more manure per ha (figure 4 in the appendix, bottom row). In this sense, not only does the best land remain in production but the scarce mineral and organic N resources are concentrated on it. In NLU, animal manure availability is reduced by 4% in Europe since livestock numbers decrease and they are bred in a more extensive manner due to the increase in feed price. Extensive animal breeding reduces the availability of manure due to collection constraints. In the RoW, there is an inverse trend with an increase in organic N use of 1% as ruminant production increases, especially in the intensive system.

Crop choice

Crop choice is an important instrument of adaptation for farmers. In NLU there is a single representative mix for annual crops which aggregates crop choices by farmers at the baseline. The model does not allow for that crop mix to change. On the other hand, the crop choice is explicitly modeled in AROPAj. The land allocation between crops, pastures and fallow land is shown in figure 2. As mentioned before, fallow land increases by +192% and pastures expand by +3%, both at the expense of cropland. Looking at the crop mix alone, percentages of cereals and tubers remain stable, while oilcrops shrink by -15%. We can see that the percentage of legumes is increasing, due to the capacity of these crops to fix nitrogen from the atmosphere.

Figure 2. Land allocation between crops in the AROPAj model for the baseline and half-N scenario

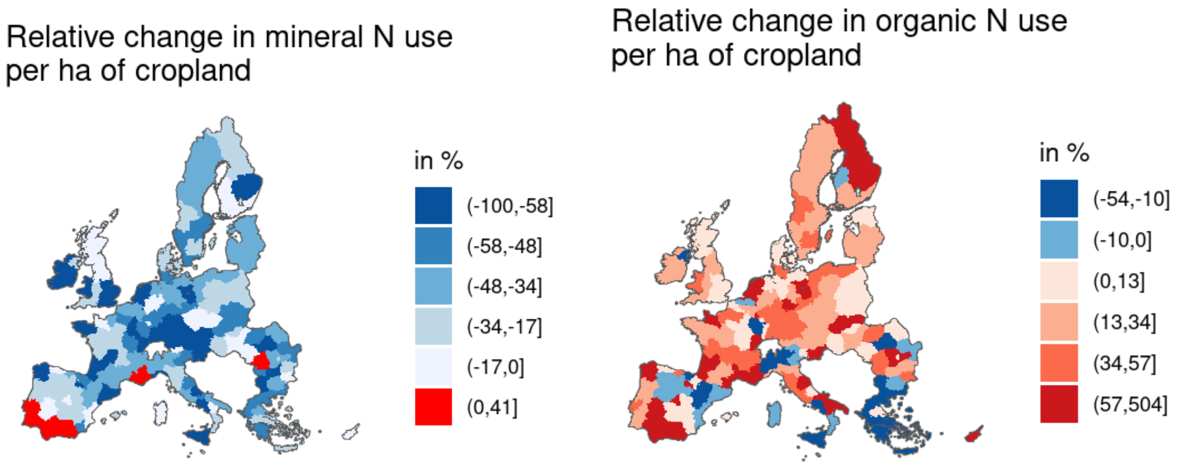


Spatial heterogeneity in policy impacts

Figure 3 displays two maps of changes in mineral and organic N use per ha of cropland (no fallow or pastureland considered) at the FADN region level. It clearly shows the geographical heterogeneity in the AROPAj results. When we compare this figure with the results reported in table 2, we can see that the numbers reported at the EU scale mask the great inter- and intra-countries differences. The heterogeneity in agricultural practices, farmers' skills, and soil and climatic conditions are captured by the model through the process of selection and calibration of the dose-response functions (Humblot et al., 2017).

Figures 4 and 5 in the appendix provide results on N and land use at the national level. The top row plot in figure 4 shows the reduction in mineral N applied to cultivated land (no fallow land or pastures considered) as predicted by AROPAj. There is a significant decrease in the per ha use of mineral fertilizers in countries with high initial levels (more than 200 kgN/ha) such as Ireland (IE), Sweden (SE), and Luxembourg (LU). There are also significant geographical disparities in the results as shown on the map in figure 3. Two interesting cases are noticeable for Spain and Portugal, where the mineral N per ha increases with the half N policy. This is

Figure 3. Change in the per ha application rate for mineral and organic N for cropland (fallow land excluded) resulting from the half-N policy as estimated by AROPAj


Relative change in mineral N use per ha of cropland

Relative change in organic N use per ha of cropland

due to the abandonment of low-productivity land and more intensive use of fertilizers on more fertile land.

Greenhouse gas emissions

Greenhouse gas emissions from agriculture consist mainly of methane emissions from livestock breeding, nitrous oxide emissions associated with fertilizer use and soil processes, and CO_2 emissions due to land use change (pastures to cropland). Table 4 summarizes our results concerning greenhouse gas emissions. In AROPAj, we account for methane and nitrous oxide following the detailed IPCC guidelines (Isbasoiu et al., 2020). Methane emissions for Europe increase in AROPAj and decrease in NLU following the respective changes in livestock numbers estimated by the models. Nitrous oxide emissions undergo a more pronounced change since they are related to fertilizer use. Logically, as European emissions decrease (-23% in AROPAj, -36% in NLU), the rest of the world is emitting more and even outweighing the reduction in the EU. NLU estimates that land-use-related CO_2 emissions increase by +0.24% for the EU and +0.29% for RoW because of the conversion of pastures to cropland. The overall greenhouse gas balance for the world is thus worsened by +0.6%.

Table 4. Relative change in greenhouse gas emissions and livestock

	AROPAj	NLU		
	EU	EU	RoW	World
Livestock	+0.54%	-4%	+1%	+0.2%
Methane (CH_4)	+1.35%	-4.5%	+0.9%	+0.5%
Nitrous oxide (N_2O)	-23.39%	-36%	+6%	+1.4%
CO_2	-	+0.24%	+0.29%	+0.28%
All	-9.59%	-7.8%	+1.6%	+0.6%

Discussion and conclusion

The objective of this paper was to assess the economic impact of a public policy aimed at halving mineral nitrogen use in European agriculture. To do this, we benchmark the results of two techno-economic models: NLU, a global scale partial equilibrium agricultural model and AROPAj, a European agricultural supply-side model. In the context of the existing literature, our study's contribution is to provide a detailed description of the technical changes in relation to N-use from two different perspectives: AROPAj includes a comprehensive description of farm types and crop choices, while NLU integrates the main components of the nitrogen balance and explicitly models land-fertilizer substitution and price feedbacks.

The results presented correspond to a 50% reduction in the use of synthetic fertilizer in the EU ceteris paribus. That is, we ignore adjustments such as a structural change in demand from consumers (meat) and structural change in the production technology (e.g. agroecology). We find that a 50% reduction in synthetic fertilizer in European agriculture leads at the European level to (1) a decrease in agricultural production (2) a substantial increase in nitrogen use efficiency (3) a decrease in use of organic fertilizer (4) a loss of competitiveness of EU agriculture, while at the global level it may lead to (5) greater nitrogen consumption and (6) a possible increase in greenhouse gas emissions. These results, their limitations and policy implications are discussed below.

Discussion of main results

The two models are consistent in finding that a 50% reduction in synthetic fertilizer in Europe adversely affects agricultural profitability and leads to a decrease in agricultural production in

Europe. The magnitude of the reduction, however, differs substantially between the two models due to their different structures: we find a higher reduction with the pure supply-side approach used by AROPAj than in NLU's partial equilibrium approach. The main discrepancy between the two models concerns changes in land use and in particular the distribution of agricultural land between pasture and crops (cropland increases in NLU and decreases in AROPAj). These divergences are consistent with each model's general assumptions. In NLU, there are relatively few constraints on the conversion of pasture into cropland, which facilitates technical adjustments through land-fertilizer substitution and explains the expansion of cropland. In contrast, AROPAj contains a more refined representation of the constraints on land-use for each representative group of farms. In this framework, farmers adjust to the constraint on fertilizer by substituting between fertilizers and irrigation, a mechanism whose effectiveness varies greatly across European regions. In this way, the reduction in nitrogen use has a more direct impact on the profitability of cropland, which is subsequently either converted into pasture or abandoned as fallow land.

Going further into the description of the technical changes, our between-model analysis shows that the fertilizer reduction policy leads to a substantial increase in nitrogen use efficiency (high degree of agreement between AROPAj and NLU), and counter-intuitively, to a lower use of organic fertilizer, but for different reasons in the two models. In AROPAj, the lower use of organic fertilizer is directly linked to the reduction in cropland area, while in NLU it stems from reduced availability due to there being fewer animals in intensive systems.

The general conclusion that can be drawn from our study is that the effect of nitrogen input reduction will critically depend on supply side flexibility. Imposing a constraint on fertilizer use, when possibilities of land expansion are already limited as modeled by AROPAj, is likely to have a substantial negative effect on agricultural profitability and production. On the other hand, if there is greater scope for substitution between land and fertilizer as modeled by NLU, farmers will be able to adapt more easily to the new conditions and the impact on production will be lower. A combination of halving nitrogen and keeping a constant area of permanent pasture as currently set out in the European common agricultural policy would lead to negative effects showing greater similarity to AROPAj results. Labor and capital substitutions (e.g., N leaching can be reduced by more fragmented spreading, but this involves more labor, equipment, and energy) are not represented in AROPAj and NLU, as labor and capital are fixed factors per hectare. These substitutions are additional adjustment paths that could facilitate the transition to low-input farming systems.

Limitations of our approach

For a comprehensive assessment of a synthetic fertilizer reduction policy several other dimensions should also be taken into consideration. A reduction in mineral fertilizer can lead to a decrease in yield per hectare as well as in yield per worker (Huang et al., 2015). Integrating leguminous crops into the rotation and improving the efficiency of fertilizer use may require significant additional labor inputs. Thus, for the N-reducing policy to be effective, supply-side adjustments should also concern substitutions between fertilizer and labor.

Empirical evidence on fertilizer use reveals substantial between-farmer heterogeneity. This is related to many factors associated, for example, with the type of cultivation, the soil and climate context, and farmers' risk aversion. Indeed, decisions about the volumes of fertilizer applied are made upstream of the production cycle, in a situation of incomplete information about the plants' actual growing conditions. The literature generally suggests that fertilizer is a risk-increasing input and risk-averse farmers should thus be applying less rather than more than the recommended rate for risk-neutral farmers (Babcock, 1992; Rajsic et al., 2009; Finger, 2012). The type of model used in this paper is not suitable for correctly assessing farmers' risk aversion. Therefore, we cannot offer any conclusions on this point. Based on the results available in the literature, it is possible that taking risk aversion into account would result in a more favorable evaluation of a fertilizer tax by over-penalizing excessive use (Bontems and Thomas, 2000; Finger, 2012). Heterogeneity in fertilizer use may also result from variability in farmers' skills. This is only partially captured by AROPAj thanks to its structure and calibration to farmer-level data. In this case, a tax on fertilizer could lead to sectoral reorganization by benefiting those farmers who use fertilizer most efficiently (Hertel et al., 1996).

Finally, it should be noted that the assumptions made in the two models have a decisive influence on the results. In both models, yields are simulated using dose-response functions, thus placing us in Liebig's limiting factor paradigm which is inherently unfavorable to organic systems in which the interrelationships and synergies between crops prevail. In this sense, our representation of technical change remains limited. Models more oriented towards a systemic approach to farming would probably be more favorable to a mineral nitrogen reduction policy (Meynard, 2017).

Policy implications

A significant reduction (20%) in nitrogen use is expected under both the F2FS and Biodiversty strategy, albeit smaller than the one simulated here. Reduced nitrogen fertilization in Europe and consequent losses would improve local environmental conditions by reducing nitrogen-induced eutrophication and ammonia-induced air pollution. The welfare gains for European citizens could thus be considerable as reported in Sutton et al. (2011). Furthermore, de Vries and Schulte-Uebbing (2020) argue that for 15-20% of EU agricultural land a reduction in fertilization rates and yields is inevitable in order to attain water and air quality objectives.

Opponents of the Green Deal argue that even the 20% reduction in nitrogen fertilizer planned under the F2FS might result in a deterioration in the EU net trade balance, and, possibly, lower farm incomes and higher food prices for consumers, including those in the poorest categories. Our results suggest a tax on mineral nitrogen fertilizer would be a cost-efficient instrument that can be very powerful in promoting nitrogen-efficient agricultural practices. Nevertheless, it can have negative impacts on food supply at least in the short term, the extent of which will depend on the ability of farmers to adapt to new production conditions. Such a taxation might have indirect effects that could offset, at least partially, local benefits in terms of global nitrogen consumption and associated greenhouse gas emissions.

Our findings show that a global approach is necessary to accompany a reduction in the use of synthetic nitrogen. First, There is a margin for input reduction without altering production, by moving further to the "best practice" production frontier thanks to training and innovation. The wide heterogeneity in fertilizer application in Europe suggests that there is a significant potential for efficiency gains, which could offset the nitrogen reductions in terms of yields. Indeed, a broad estimate is that in a country such as France, it would be possible to reduce pesticides and fertilizer consumption by 10 to 20% simply by reducing inefficiencies using current technologies. Going beyond that level of reduction without reducing output would be possible but would require production systems to be modified. For example, reducing pesticide use by 50% would require farming a large proportion of farmland to be managed using agro-ecological techniques, relying more on biological cycles, crop association and biological control organisms.

Innovation is another, necessary pathway. Seven decades of well-funded research has led to impressive technical progress in industrial crops such as corn and soybeans, while there is still very large potential for innovation in agro-ecological techniques and organic agriculture (Guyomard et al., 2020). Because most agronomic RD has focused on intermediate input intensive production systems, there is probably a considerable potential for yields increasing pathways that rely less on nitrogen without incurring significant losses. In both cases, a nitrogen tax would induce innovation in this area, while providing resources for the necessary advisory services.

Limiting land take for urbanization and infrastructure, which is currently a major driver of the reduction in agricultural land in Europe, could help to limit the need for more N-intensive production (European Environment Agency, 2020).

However, our results show that reducing nitrogen pollution in the EU without pollution displacement effects abroad require deeper changes in the global EU food system. For local environmental benefits not to be offset by more pollution abroad, a reduction in the use of fertilizers in the EU would also require reducing food losses and a change in food consumption patterns, including an increase in the proportion of legumes as a protein source. Such changes could significantly improve the effectiveness of the policy. Prudhomme et al. (2020) show that an increase in legume consumption in Europe from its current level of 2.7 kg/capita/year to 11.4 kg/capita/year in the form of substitution for ruminant products drastically reduces greenhouse gas emissions. This confirms the need for a coherent approach like that of the Green Deal, which associates these reductions in nitrogen pollution with a more economical and vegetarian diet. There is room for maneuver in this area, given the excessive caloric intake of our nutritional standards and the proportion of animal proteins which could be reduced with health benefits (Guyomard et al., 2020). The Green Deal is a global project that also involves major changes in demand, through reduction in waste and loss, better nutrition, including lower calorie intake and consumption of less animal protein and fat, which would absorb a significant proportion of the production shock.

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Appendices

Agronomic models

STICS model

STICS is a generic crop model designed for plot level applications and covering twenty annual and permanent crops. STICS simulates the functioning of a plant cover and soil system. The model accounts for crop-specific daily time-step phenology, photosynthesis and growth of leaves, roots and shoots, fruit or grain formation, water, carbon and nitrogen flows. For a full description see Brisson et al. (2009, 2003). The model is generic in the sense that its core equations are common to all crop types simulated, yet with variable parameters and crop-specific phenology.

The main input data are daily weather variables, agricultural practice calendar including sowing dates, fertilizer types and rates, and irrigation schedules as well as the initial state and characteristics of soils in terms of water and nutrient content. Outputs include crop yields and harvest quality (C/N ratio), nitrogen compound losses such as nitrate leaching and N_2O emissions. Outputs from STICS are used in the agricultural supply-side model AROPAj (see below for details). Simulations were conducted to estimate and calibrate dose-response functions of yields with respect to the input of nitrogen and irrigation water (Humblot et al., 2017). The dose-response functions are fitted to points representing STICS simulations at different levels of nitrogen and water input. Nitrogen applications for the response functions were varied from 0 to 600 kg/ha/year and irrigation water amount from 0% to 100% of plants' water needs. Irrigation is only allowed for some AROPAj agents for whom we know to be currently irrigating.

Because we lack geographical information about farmers, we are testing a set of parameters concerning soils characteristics, crop varieties, and sowing dates. We then choose the "best" dose-response function with respect to economic data provided by the FADN on observed yields, input and output prices. For each economic agent (our representative farmer), we have a set of dose-response functions for the crops they are growing.

Lund-Potsdam-Jena managed Land (LPJmL) model

The Dynamic Global Vegetation Model with managed Land, LPJmL (described in Schaphoff et al., 2018) models natural and agricultural vegetation in terms of growth and productivity through its links with water, carbon and energy flows.

To represent biophysical constraints affecting cultivation, yield in each NLU region is parameterized on potential crop yields and calibrated on actual crop yields. Both values are calculated by the LPJmL vegetation model which simulates biophysical and biogeochemical processes impacting the productivity of the most important crops worldwide using a concept of crop functional types (CFTs) (Bondeau et al., 2007). LPJmL describes crop production with 11 CFTs on a 0.5° × 0.5° grid representing most of the cereals (4 CFT), oil seed crops (4 CFT), pulses, sugar beet and cassava with irrigated and rainfed variants.

Climatic potential yields are computed by LPJmL for each of the 11 CFTs with irrigated and rainfed variants, at each grid point of global land area, by setting management intensity parameters in LPJmL (leaf area index, harvest index and a scaling factor between leaf-level photosynthesis and stand-level photosynthesis) such that crop yield is maximized locally. Climatic potential yields are taken as a mean of five LPJmL simulation years between 1999 and 2003 in order to minimize the climatic bias due to interannual variability.

AROPAj results disaggregated

Table 5. Surface, total nitrogen use, yield percentage change per crop between half-N and Baseline scenarios and Yield/N ratios and percentage change in AROPAj (crops with N dose-response functions are in bold type)

Crop	Surface % change	Nitrogen % change	Production % change	Yield/N ratio Baseline	Half N	% change
Cereals						
rice	-3.95%	-5.01%	-3.77%	54	55	1.30%
other cereals	-0.65%	-4.09%	0.72%	57	59	5.01%
rye	-4.10%	-9.93%	-1.54%	46	50	9.31%
oat	-2.74%	-15.74%	0.77%	51	61	19.60%
common wheat	-36.47%	-61.66%	-54.04%	30	36	19.87%
barley	-5.64%	-36.72%	-18.08%	36	47	29.44%
durum wheat	-75.32%	-86.97%	-80.81%	26	38	47.26%
maize	-32.80%	-62.88%	-44.37%	40	61	49.88%
Oilseeds						
sunflower	-27.84%	-36.89%	-31.44%	30	33	8.64%
rapeseed	-39.18%	-69.65%	-44.30%	15	28	83.51%
Leguminous crops						
protein crops	-12.29%	-23.92%	-3.77%	88	112	26.49%
soybean	-8.91%	-89.70%	-28.27%	22	156	596.68%
Tubers						
potatoes	-11.06%	-40.21%	-11.22%	194	288	48.49%
sugar beet	-39.01%	-83.98%	-58.85%	271	697	156.96%

Figure 4. Tons of mineral and organic N per ha of arable land (excluding fallow land) for the 27 EU member states.

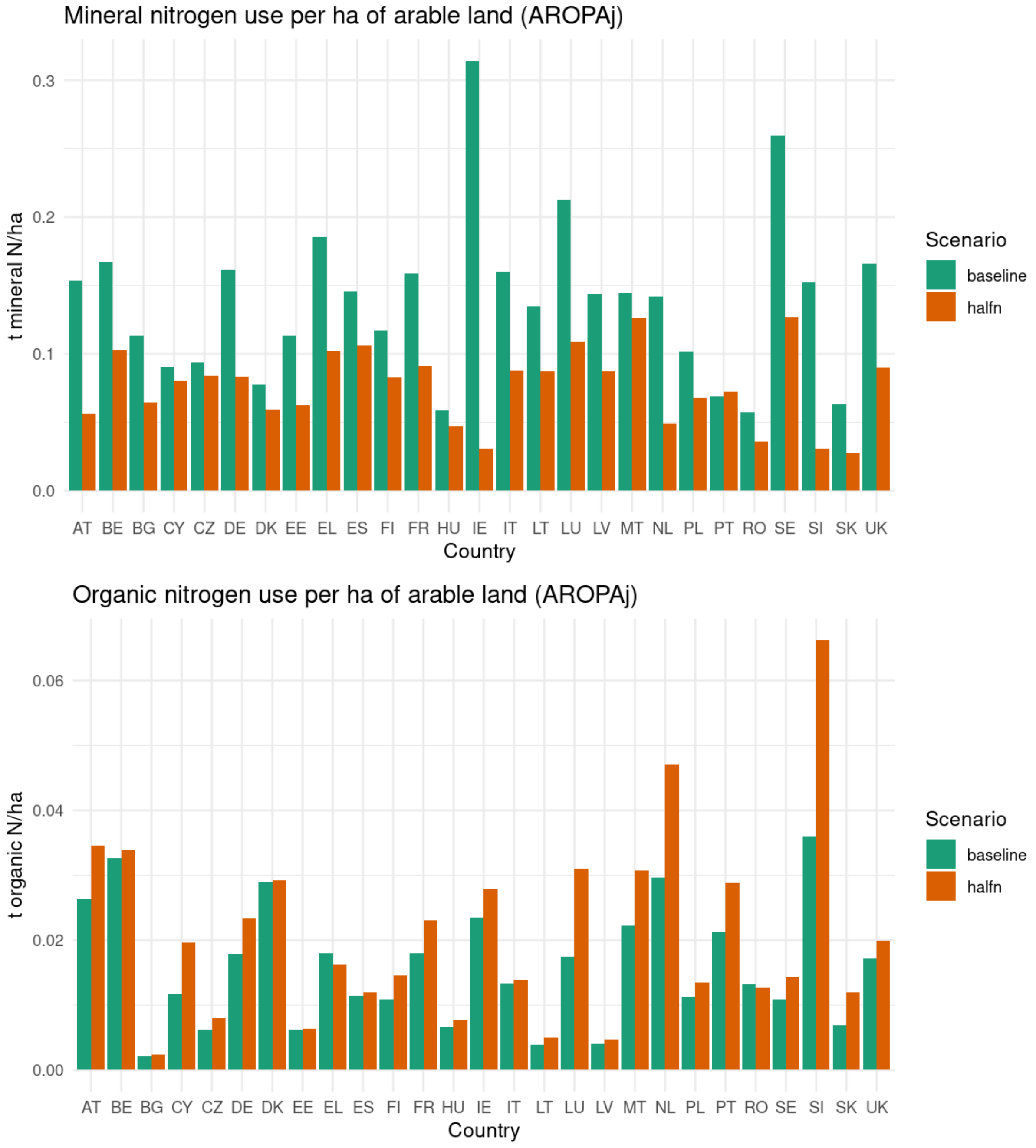


Figure 5. Land allocation between crops by AROPAj model for the baseline and half N policy for the 27 EU countries

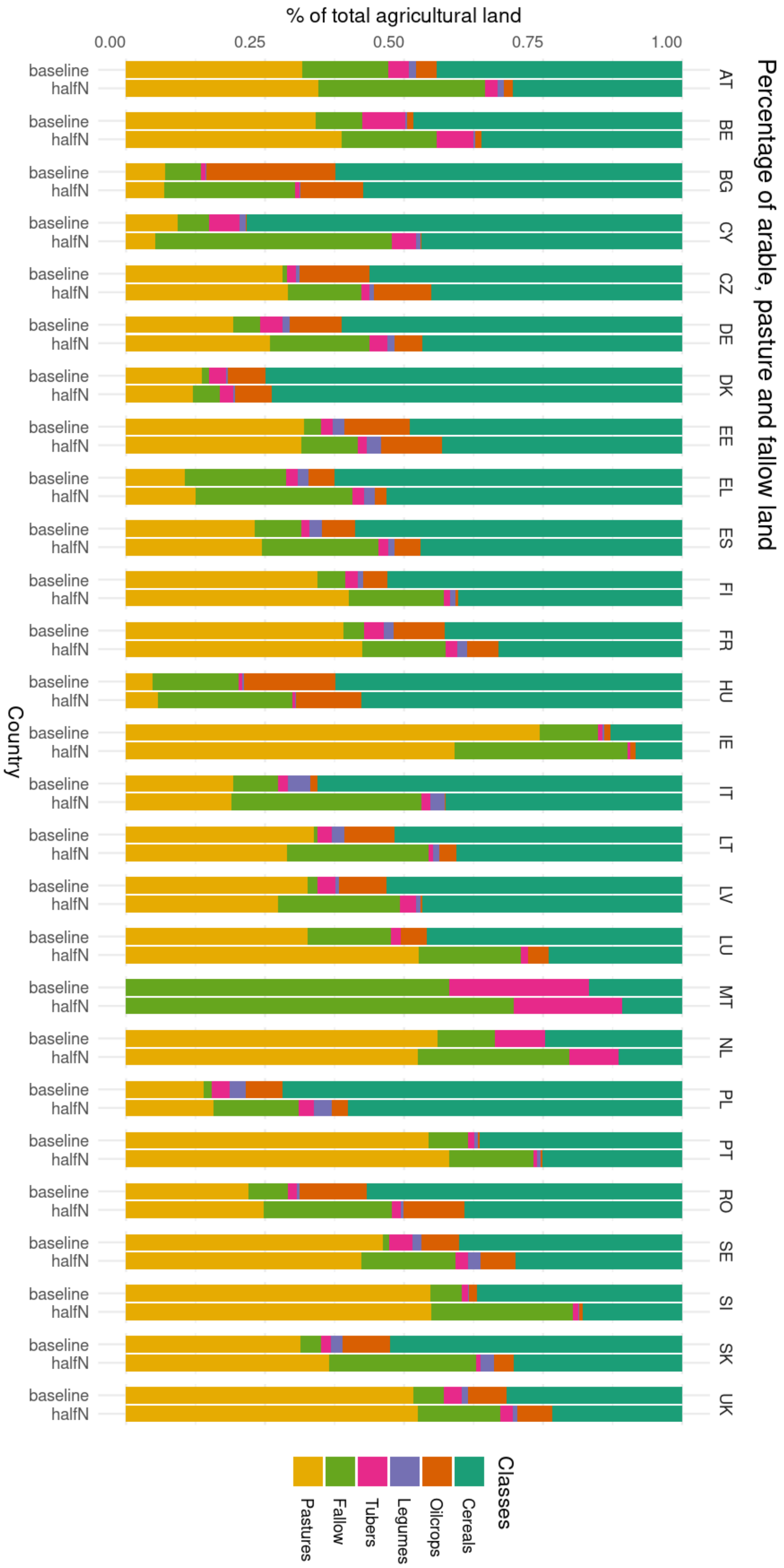
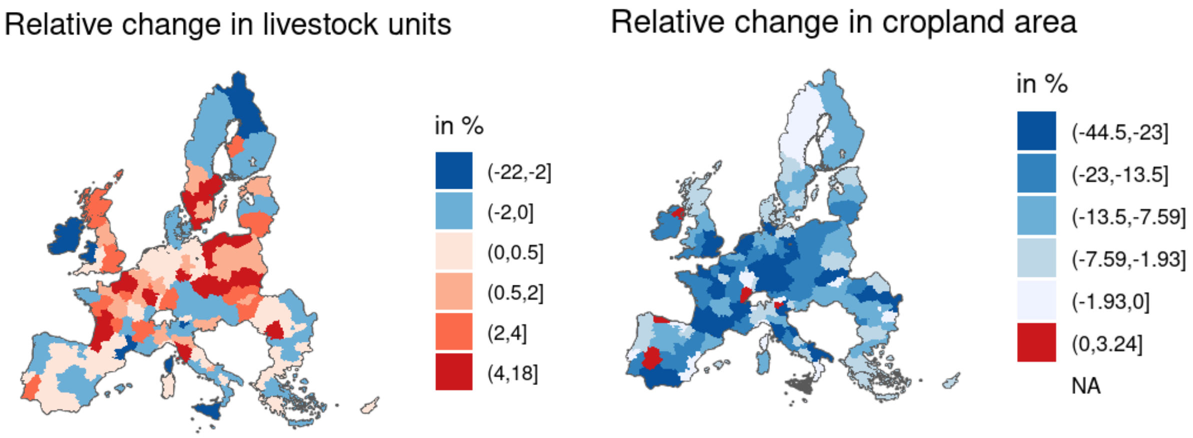


Figure 6. Relative change in the number of livestock units (on the left) and relative change in cropland area in AROPAj (on the right)



Major results from NLU and AROPAj

Table 6. Major results from NLU and AROPAj for the two scenarios

		NLU				AROPAj	
		EU-27		RoW		EU-27	
Variable	Unit	Baseline	Half-N	Baseline	Half-N	Baseline	Half-N
Price|Synthetic Nitrogen|Index	Index (2012 = 1)	1	2.50	1	1	1	3.08
Fertilizer Use|Synthetic Nitrogen	TgN/yr	12.55	6.29	90.86	98.93	12.38	6.12
Fertilizer Use|Organic Nitrogen	TgN/yr	4.68	4.49	31.09	31.44	1.21	1.09
Land Cover|Cropland|Total	million ha	116.41	119.92	1557.44	1574.63	85.49	65.32
Land Cover|Cropland|Cereals	million ha	–	–	–	–	69.29	53.84
Land Cover|Cropland|OilCrops	million ha	–	–	–	–	10.49	6.84
Land Cover|Cropland|LegCrops	million ha	–	–	–	–	2.10	1.85
Land Cover|Cropland|TubCrops	million ha	–	–	–	–	3.62	2.80
Land Cover|Fallow	million ha	–	–	–	–	7.47	25.59
Land Cover|Pasture	million ha	57.55	54.12	2438.57	2421.37	38.08	40.27
Land Cover|Forest	million ha	234.61	234.61	4483.56	4483.56	–	–
Price|Agriculture|Total|Index	Index (2012 = 1)	1.00	1.26	1.00	1.12	–	–
Imports|Food Crops	million t DM/yr	168.21	193.74	391.46	375.49	–	–
Exports|Food Crops	million t DM/yr	101.44	88.86	466.48	493.33	–	–
Agricultural Production|Total	million t DM/yr	383.50	335.86	2686.70	2744.52	337.54	227.86
Agricultural Production|Cereals	million t DM/yr	–	–	–	–	276.78	188.65
Agricultural Production|OilCrops	million t DM/yr	–	–	–	–	27.67	16.47
Agricultural Production|LegCrops	million t DM/yr	–	–	–	–	4.94	4.57
Agricultural Production|TubCrops	million t DM/yr	–	–	–	–	28.16	18.17
Agricultural Production|Livestock	million t DM/yr	52.44	50.40	261.93	264.57	–	–
Agricultural Production|Livestock	million livestock units	–	–	–	–	98.27	98.80
Yield|Total	tDM/ha/yr	2.56	2.10	1.53	1.74	3.95	3.49
Yield|Cereals	tDM/ha/yr	–	–	–	–	3.99	3.50
Yield|OilCrops	tDM/ha/yr	–	–	–	–	2.64	2.41
Yield|LegCrops	tDM/ha/yr	–	–	–	–	2.35	2.47
Yield|TubCrops	tDM/ha/yr	–	–	–	–	7.79	6.50
Emissions|CH4	MtCO2eq/yr	193.80	185.05	3215.30	3242.56	212.36	215.23
Emissions|N2O	MtCO2eq/yr	316.56	202.84	2564.29	2718.67	168.49	129.08
Emissions|CO2	MtCO2/yr	836.40	838.44	2896.40	2904.67	–	–