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A decade of missed opportunities: how Europe went off-track to reduce nitrogen pollution over the last decade

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Abstract

The European Union's Green Deal aims to reduce nutrient losses to air and water by 50% by 2030, requiring a substantial reduction in nitrogen (N) surplus from agricultural land. Using Europe-wide datasets of N budget, we show that cropland N surplus declined during 1990–2010 but reversed in 2011–2020 due largely to increasing synthetic fertilizer use and relatively lower crop N uptake. Our assessment highlights the need for improved nitrogen-use efficiency and regionally tailored strategies, while considering climate change impacts on N uptake, to reduce N pollution and meet EU environmental targets.

1 Main

The intensification of nitrogen (N) use on croplands over the last decades, driven by increasing demand for food and animal protein, has led to a significant increase in soil N surplus, being the difference between total soil N inputs and N output by crop harvest. This increase in N surplus is associated with increased losses of ammonia (NH_3), nitrous oxide (N_2O) and nitrogen oxides (NO_x) to air and nitrate (NO_3) to ground water and surface water, negatively affecting air, and water quality and enhancing climate change, and thereby affecting ecosystems and human health [1, 2]. Such impacts underscore the urgency of aligning with the Sustainable Development Goals[3, 4]. In response, the European Union (EU) has enacted several legislative measures since the 1990s, notably the Nitrates Directive (91/676/EEC), the Water Framework Directive and the National Emissions Ceilings Directive, achieving a marked reduction in excess N or N surplus.

Furthermore, the European Commission launched in 2019 the EU Green Deal[5] aiming to reduce N losses to air and water by 50% and net greenhouse gas emissions, including N_2O, by at least 55% by 2030. A recent analysis shows large variation across EU countries but confirms that a 50% reduction in N losses is appropriate at the aggregated EU level[6]. To achieve such reductions while avoiding crop yield decline require a substantial increase in N use efficiency (NUE) by agricultural management practices including enhanced recycling[7] and further a reduction in food waste and dietary changes[8].

N surplus is a key indicator for comprehensive assessment and management of N-related issues, and a planetary boundary has been set for it based on acceptable N losses to air and water[9]. It serves as an indicator to support policy making due to its close association with adverse impacts of N. Here, we tracked the changes in N surplus in EU member states over the past three decades (1991-2020) considering that N policies came in place from around 1990 onwards (see Methods for details on N surplus estimation). Results show that despite progress in reducing N surpluses through the 1990s and 2000s, this positive trajectory began to slow and eventually reversed during the following decade. The period from 2011 to 2020 stands out as a decade of missed opportunities, in which previous gains in NUE were not sustained, and synthetic fertilizer use again increased. We next examine the trends in N surplus and their implications.

We tracked changes in N surplus in the EU (and the respective countries) between 1991 and 2020 using eight estimates derived from alternative methods for fertilizer application and manure allocation[10] (see Methods for details on N surplus estimation). We focused on croplands due to their significant nutrient fluxes and environmental impacts[11], while acknowledging the methodological challenges posed in estimating the N surplus in grasslands. Our analysis reveals a shift in the trend of N surplus of the EU27 in the recent decade (2011-2020), indicating an increase of +6.3 $kg\ ha^{-1}\ yr^{-1}\ decade^{-1}$ after previous downward trends of -12.6 $kg\ ha^{-1}\ yr^{-1}\ decade^{-1}$ (2001-2010) and -4.3 $kg\ ha^{-1}\ yr^{-1}\ decade^{-1}$ (1991-2000), as shown in Figure 1a. The consistency across the eight different N surplus estimates used in our analysis, all reflecting similar patterns for each decade, underscores the robustness to uncertainty of these observed trends (see supplementary Figure S1-S2).

Additionally, the values in tonnes (Figure S3-S4), which are independent of cropland area development, confirm the trends observed. We note that the statistical robustness of decade-specific trend estimates is constrained by the limited number of annual observations ($n = 10$); nevertheless, they allow us to infer the direction of change in N surplus and the relative contributions of its underlying components, which is the core of our analysis.

The upward trend in N surplus ($+6.3\ kg\ ha^{-1}\ yr^{-1}\ decade^{-1}$) in the recent decade in the EU27 is due to a simultaneous increase in N input from synthetic fertilizer ($+5.5\ kg\ ha^{-1}\ yr^{-1}\ decade^{-1}$) and animal manure ($+1.4\ kg\ ha^{-1}\ yr^{-1}\ decade^{-1}$) and a slower increase in N crop uptake/outputs ($+2.8\ kg\ ha^{-1}\ yr^{-1}\ decade^{-1}$ compared to $+9.4\ kg\ ha^{-1}\ yr^{-1}\ decade^{-1}$ in the previous decade) (Figure 1a). This imbalance between input and output highlights the deterioration in N surplus that characterized the 2010s and sets the stage for the challenges Europe now faces in achieving its 2030 reduction targets. A lesser increase in N output compared to the previous decade can be attributed to the relatively dry and hot climatic conditions, leading to lower soil-water availability for plant growth, across EU croplands in the recent decade (2011-2020, as shown in supplementary Figure S5)[12]. Such conditions including extreme events such as droughts and heatwaves are known to reduce crop uptake and N output[13]. As EU-level aggregation masks regional differences, we highlight notable regional differences in the evolution of the N surplus within the EU (see Figure 1b). Only one-fourth of the EU-countries (6 out of 26, Malta is not reported here) showed a downward trend in N surplus between 2011-2020. This stands in stark contrast to the preceding decades, when the majority of EU countries were still reducing their N surpluses. The reversal during this recent decade thus represents a collective setback, where policy momentum failed to sustain the environmental gains in earlier periods, where at-least two-third (2001-2010) and three-fourth (1991-2000) of EU countries experienced reductions.

We analyzed the contribution of different components, i.e. inputs of N fertilizer, N animal manure and other N inputs (biological fixation and atmospheric deposition), and N outputs to the trends in N surplus (see Figure 2 for the recent decade (2011-2020), supplementary Figure S6 for all three decades, and Method for details). The N surplus trends in the EU27 over the first two decades were mainly due to changes in N outputs, contributing 32% in the decade of 1991-2000 and even 63% during 2001-2010 (top level bars for EU27 in Figure 2a,b). In contrast, the recent decade (2011-2020) witnessed a shift with no contribution from N outputs at EU27 level while synthetic fertilizers contributed nearly 60% in explaining N surplus trends. This shift – from output-oriented improvements to input-oriented increases – marks the turning point of the 2010s, when the intensification of fertilizer use once again became the dominant force shaping Europe's N balance.

There is, however, substantial variation across countries since 2010s (Figure 2b). To facilitate comparison across countries, Figure 2c summarizes whether trends in N surplus are mainly associated with changes in N inputs or in N outputs, and whether N surplus is increasing or decreasing. We observe a pronounced increase in N inputs from synthetic fertilizer in the majority of the EU countries (85%), leading to an overall increase in EU27. Changes in the N inputs dominate the N surplus trend in

certain countries, e.g. Germany (DE) and Sweden (SE), where synthetic fertilizers account for the largest share with 69% and 59% respectively (see Figure 2b,c). In Lithuania (LT), N inputs through animal manure play a crucial role, accounting for 46% of total inputs. Countries such as Spain (EL) and Estonia (EE) receive a notable share of N inputs from other sources, being 46% (43% from biological fixation and 3% from atmospheric deposition) and 41% (39% from biological fixation and 2% from atmospheric deposition), respectively. On the contrary, the output of N (crop uptake) dominates the trend in countries such as Ireland (IE) with 72%, Hungary (HR) with 62%, and France (FR) with 56%. In some countries, such as Romania (RO) and Slovenia (SI), both the N input and the N output contribute almost equally to the N surplus trend (Figure 2b,c).

Relatively larger contribution of N inputs in N surplus trends may also be related to recent developments in the EU Renewable Energy Directive (2009/28/EC)[14], which mandates a 20% share of renewable energy by 2020, with a sub-target of 10% biofuels in the transport sector[15], which needs to be increased to 14% by 2030[16]. This directive coincided with an increase in the demand for biofuel feedstocks such as rapeseed and soybeans, which account for a substantial share of liquid biofuels in the EU (77%)[17]. Additionally, the expansion of soybean cultivation has likely contributed to higher N inputs through biological N fixation (BNF), further influencing the overall dynamics of N inputs in cropland systems. Notably the imports of N fertilizers has simultaneously increased in the recent years[18]. Taken together, these interacting pressures (i.e. demand for fertilizers, expansion of biofuel production and climate fluctuations) have meant that the decade 2011–2020 can be defined as a turning point at which the balance between productivity and environmental protection has once again been lost.

Overall, the findings outlined herein illustrate the complex interplay of factors influencing the development of N surplus in European countries. While recent environmental policies and technological advances have helped to reduce N surplus in some regions, increased biofuel production driven by the EU Renewable Energy Directive has contributed to reversing these trends in other regions. These complex influences underline the importance of considering different control mechanisms to effectively manage N surplus.

The diverse European landscape with different socioeconomic factors requires a regionalized approach to management strategies, identifying areas where specific N input sources, specifically fertilizer or manure, are predominant and where possibilities exist to increase the NUE of both N sources[8]. In regions like Germany and France, strategies to limit synthetic fertilizer use may be crucial[19], while in areas of high livestock density, such as the Netherlands, the focus should be on managing the impact of animal manure[20]. In addition, improving soil health through measures to prevent or remedy compaction, improve water availability, increase nutrient buffering and control soil acidity is crucial. These measures can help ensure that all factors potentially limiting crop yields are adjusted, thereby increasing overall agricultural productivity and reducing the risk of N pollution. Furthermore, the expected policy measures to reduce pesticide use could also increase the risk of lower yields[21], which, without an integrated approach to fertilizer management can lead to inefficient

use of N fertilizers and thus further N surpluses. Therefore, a comprehensive strategy that includes improving soil health and integrated pest management is crucial to address these interlinked challenges. The integration of innovative technologies in fertilizer application and precision agriculture offers a promising path toward improving the NUE[22]. Such technological advances are essential to promote both environmental and economic sustainability in European agriculture, effectively aligning with EU environmental goals.

The recent rise in nitrogen (N) surplus in the EU highlights the urgent need to address its environmental and economic implications. This increase, occurring after two decades of steady improvement, demonstrates how fragile progress can be and how easily Europe can drift away from its environmental trajectory. Approaches reducing N surpluses and related N losses, by increasing the NUE, include land use change in response to dietary change, enhanced recycling of organic N by manure, sludge and compost and sustainable management practices [3, 4]. Sustainable management practices are essential to balance agricultural productivity with environmental protection. Tailored management strategies for enhancing NUE are crucial for improving yield and reducing N losses. This is even more pressing when considering the increasing frequency of extreme weather events like droughts and heavy rainfall, adaptive N management strategies are necessary to secure crop yields and minimize N losses. Strategies such as split fertilization, which allows for adjustments based on seasonal weather conditions, and the use of catch crops to capture excess N and improve its availability for subsequent crops, can enhance resilience in N management. These approaches, supported by improved weather forecasting and decision-making tools, will be critical in navigating the challenges posed by unpredictable climatic conditions. Effective N management is also a key component in mitigating climate change given the direct impact on N_2O emissions[11]. By reducing greenhouse gas emissions associated with excessive use of N, the agricultural sector can make a significant contribution to the climate goals of the EU and thus strengthen its commitment to environmental and economic sustainability[5, 23, 24].

While improved NUE can mitigate environmental impacts such as greenhouse gas emissions and water pollution, economic impacts are also significant. Changes in N management affect input costs, crop yields, and market prices, particularly in regions where N applications exceed optimal levels [25]. In addition, combining manure and fertilizer in strategic nutrient planning is key. Thus, there is a pressing need to develop strategies that strike a balance between environmental benefits and economic viability[23]. This is even more pressing considering the broader structural and geopolitical factors which shape Europe's N trajectory. The observed reversal before the 2020s indicates that structural and policy related inefficiencies had already begun to erode earlier gains, independent of later disruptions. Moreover, recent geopolitical events, such as the Russia-Ukraine war, have substantially disrupted global fertilizer markets [26]. While these shocks further complicate Europe's N outlook, they largely amplified vulnerabilities that had emerged during the previous decade. These disruptions, including price increases and trade restrictions, could affect future N surplus trends if the analysis were extended beyond 2020 (i.e., into 2023 and beyond). Hence,

understanding the patterns established during the 2011–2020 period is critical for diagnosing how Europe entered the 2020s already off-track in achieving its environmental targets. The ongoing conflict's impact on fertilizer production and trade may further influence N management practices and environmental outcomes in Europe.

Engaging stakeholders, especially farmers and agricultural advisors, through targeted educational initiatives is essential for the adoption of sustainable N management practices [7, 8, 24]. This engagement should be coupled with ongoing research and development efforts, focusing on innovative fertilizer technologies, efficient crop varieties, soil health, integrated pest management and advanced farming techniques that balance environmental concerns with agricultural productivity. Therefore, the EU's agricultural policies and practices must evolve in tandem with its climate goals, ensuring that efforts to manage N surplus are aligned with broader initiatives to combat climate change. This approach requires a multifaceted strategy that encompasses policy reform, technological innovation, stakeholder engagement and continuous assessment, all geared towards a sustainable and climate-resilient agricultural system in the EU. The coming years will reveal whether Europe can correct the trajectory set during the 2011–2020 decade of missed opportunities and realign its agricultural system with the Green Deal's environmental ambitions.

Methods

Nitrogen surplus data

This study used a long-term gridded dataset containing individual components of nitrogen (N) surplus and land use[10], both at the EU27 level and for individual countries. This dataset provides 16 estimates of N surplus for agricultural and non-agricultural soils across Europe at a spatial resolution of 5 arc-minutes for the period 1850-2019. Our analysis primarily targets croplands, as these generate significant nutrient fluxes and associated environmental impacts[11]. We specifically examine N surplus from the last three decades (1991-2020) using eight estimates for cropland provided by Batool et al. (2022)[10]. N surplus ($Surp$) is defined as the difference between N inputs (In) and N outputs (Out). It was estimated though a N soil surface budget taking into account volatilization losses in manure storage system[27–29] as given in equation (1). N inputs consist of synthetic fertilizers (In_{Fert}), manure (In_{Man}), atmospheric deposition (In_{Dep}) and biological fixation (In_{BNF}), as given in equation (2). N outputs refer to N removal via harvested crops (Out_{crops}) (all variables are in $kg\ ha^{-1}\ yr^{-1}$).

$$Surp(i,y) = In(i,y) - Out(i,y) \tag{1}$$

$$In(i,y) = In_{\mathrm{Fert}}(i,y) + In_{\mathrm{Man}}(i,y) + In_{\mathrm{Dep}}(i,y) + In_{\mathrm{BNF}}(i,y) \tag{2}$$

$$Out(i,y) = Out_{\mathrm{crops}}(i,y) \tag{3}$$

where i is grid cell; y is year. Below we provide a brief description of different components of N surplus utilized here:

Data on synthetic fertiliser application were obtained from FAOSTAT[30] and country-level crop and grassland application rates from the International Fertilizer Association (IFA)[31]. These rates were combined with cropland and grassland areas from FAOSTAT[32] and spatially distributed using gridded land-use data[33]. Two approaches were used to allocate fertiliser applications to cropland and pasture: (1) adjustment of IFA application rates to FAOSTAT totals and (2) refinement using spatial distribution data from Einarsson et al. (2021)[34].

For N inputs from animal manure, two datasets (FAOSTAT[35] and Einarsson et al. (2021)[34]) were used to account for uncertainties in manure application at the country level. Ratios of manure applied to soils and manure left on pasture were calculated relative to total manure production. These ratios were applied to gridded manure production data from Zhang et al. (2017)[36] to derive spatial manure application rates. Two allocation approaches were applied within each grid cell: uniform application and proportional allocation based on cropland area.

Atmospheric N deposition data were obtained from the Meteorological Synthesizing Centre - West (MSC-W) of the European Monitoring and Evaluation Programme (EMEP)[37]. It provides Europe-wide gridded estimates of wet and dry oxidized and reduced N deposition using a chemical transport model[37]. Deposition on cropland was estimated by multiplying total N deposition by the cropland fraction in each grid cell.

Trend assessment

Linear regression analysis was used to quantify trends in N surplus components across European countries. For each component, slope coefficients were estimated against time to determine whether trends increased, decreased or remained stable. Statistical significance was assessed using p-values with a threshold of $p < 0.05$

Factorial contribution analysis

The contribution percentage of the trend (CPT) for a variable X is quantified as:

$$CPT_X = \frac{|TN_X|}{|TN_{\text{sur}}|} \times 100 \tag{4}$$

where TN_X is the trend of the individual N surplus components (i.e. synthetic fertilizer, animal manure, biological N fixation, N deposition, and N outputs), and TN_{sur} is the trend in N surplus.

To normalize the contribution percentages so that their total sums up to 100%, the normalized contribution percentage is calculated as:

$$\text{Normalized } CPT_X = \frac{CPT_X}{\sum_i CPT_i} \times 100 \tag{5}$$

where $\sum_i CPT_i$ is the sum of the contribution percentages of all components considered.

Data Availability

Nitrogen surplus dataset is available at https://zenodo.org/records/6581441 and elaborated in [10].

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Author contributions

RK conceptualized the study. MB conducted the analysis and drafted the manuscript with inputs from RK. All authors contributed to framing and revising the manuscript.

Competing Interests

The authors declare that they have no competing interests.

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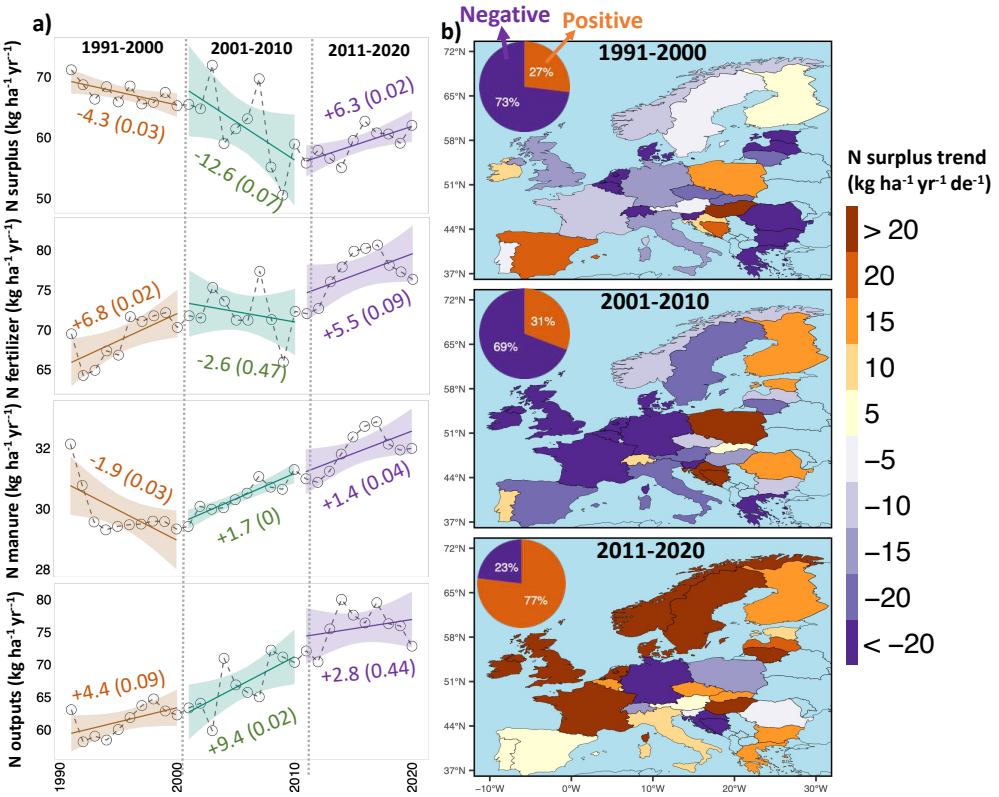


Fig. 1 Nitrogen surplus trends in the EU27 (1991-2020). Panel **a** provides a time series analysis of nitrogen (N) surplus, alongside inputs by synthetic N fertilizers and N animal manure, and the N outputs by crop harvest at the EU27 level, given as $kg\ ha^{-1}$ of cropland area yr^{-1}. The circles represent the annual data and show the fluctuations in N management. Linear regressions for each decade (de), expressed in $kg\ ha^{-1}\ yr^{-1}\ decade^{-1}$, indicate increasing (positive values) or decreasing (negative values) trends in N fluxes. Numbers in brackets are the p-values of the decade-specific trends. Panel **b** maps country-level N surplus trends in the EU, revealing diverse N management evolutions across member states. The pie chart in panel **b** shows the percentage of countries with positive (orange) and negative (purple) trends in N surplus.

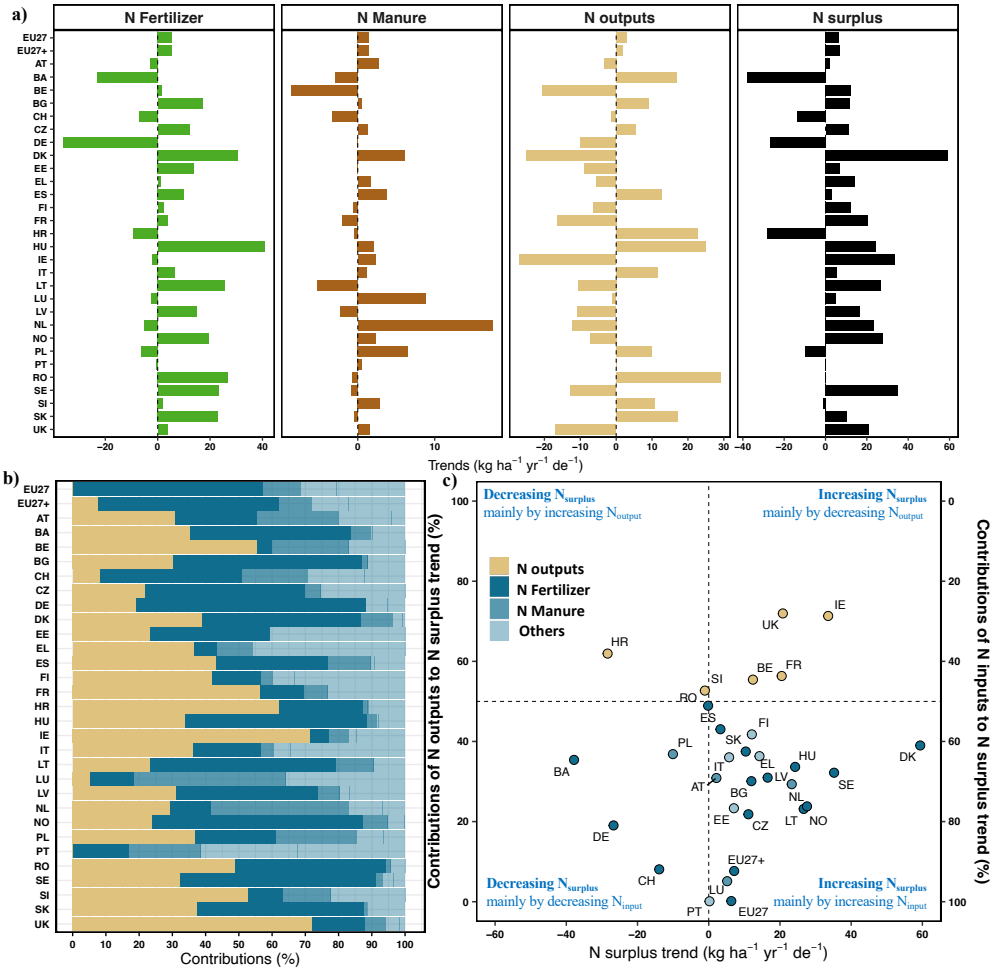


Fig. 2 Contributions to nitrogen surplus trends for the decade 2011-2020 at country level and aggregated at for EU27 and EU27+ (EU27 plus Norway, Switzerland and the United Kingdom). Panel **a** shows the trends in synthetic N fertilizer, N animal manure, N outputs by crop harvest and N surplus ($kg\ ha^{-1}\ yr^{-1}\ decade^{-1}$). Panel **b** presents the contributions (%) of N fertilizer, N animal manure, others N inputs (biological fixation and atmospheric deposition), and N outputs to N surplus trends at the country level in the recent decade (2011-2020). Panel **c** relates the overall N surplus trend (x-axis) to the relative contributions of N outputs and N inputs to the surplus trend (%), highlighting whether changes in N surplus are mainly driven by N inputs or N outputs.

Supplementary Files

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