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Nitrogen and Phosphorus pollution mitigation through down-scaling cattle production in Germany

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Abstract

Reactive nitrogen (N) and phosphorus (P) pollution in Germany is mainly caused by production of cattle meat and milk, which is mostly consumed domestically. This pollution comes at a high external costs not yet addressed by current policies. We explore scenarios where reduced domestic cattle production aims to lower N and P pollution. We also analyze the potential effects of two policy measures, cattle buy-outs and input taxation, on reducing production. The research discusses the need to decrease cattle milk and meat consumption alongside cattle production reduction to ensure that negative environmental effects such as N and P pollution are not merely shifted to other production regions. Further research should examine the policies under consequential computational economic framework toward precise magnitude of effects.

Keywords: Nutrient pollution mitigation, Policy measures, Buyout, Taxation, Grassland utilization, Nutrient cycles
JEL: Q52, Q53, Q18, H23

1. Introduction

Reactive Nitrogen (N) and Phosphorus (P) pollute air, water, and ecosystems. They adversely affect human health, the environment, and climate, spanning from local to global effects (Oenema, 2006; Sakadevan and Nguyen, 2017; Rockström et al., 2009). Demand for animal-sourced commodities in developed and transitioning economies is the main driver of this pollution (Uwizeye et al., 2020; Liu et al., 2017). In Germany, a global hotspot for N and P pollution, national indicators for domestic N losses show some improvement in air quality, mainly due to reduced ammonia emissions since 2015 (Figure 1a). However, the condition of water bodies and terrestrial ecosystems remains critically affected by excess of reactive N and P, with most emission reduction targets yet to be attained (Figure 1b-f). Domestic production of cattle meat and milk, mainly consumed within Germany, is the primary source of pollution from both nutrients.

Global frameworks, such as the Global Partnership on Nutrient Management (GPNM) and the UNEP Working Group on Nitrogen, typically result in voluntary territorial-based political responses. These non-binding frameworks often lead to inaction or weak and unfocused pollution-control policies that fail to consider consumption-side policies for effective mitigation, perpetuating these issues. In the German context, supranational and national legal frameworks, developed to aid in achieving N and P reduction targets, are predominantly governed by detailed production-side command-and-control provisions. These policies often suffer from enforcement deficits, rebound effects, and shifting effects (Garske and Ekardt, 2021; Gazzani, 2017). Backed by the Common Agricultural Policy (CAP), numerous agri-environmental subsidies have also been ineffective in addressing hotspots of both nutrient imbalances (Früh-Müller et al., 2019; Uthes et al., 2010). So far, neither CAP policies nor command-and-control provisions have considered intervening cattle production as the main N and P immediate polluter.

While we anticipate comprehensive policies targeting the main driver of pollution, animal-sourced food consumption, we focus on targeting cattle production as the primary immediate reactive N and P domestic polluter. Here we explore,

i) How would down-scaling domestic cattle production in Germany contribute to N and P pollution reductions in Germany?

ii) What do cattle buy-out schemes and taxation of nutrient-intensive inputs offer as means to address N and P pollution in Germany? New in implementation but not in discussion, these policies seem set to determine the N and P outcomes of the ongoing decade in the EU context.

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Our study provides insights into whether we can expect different outcomes or similar results as the past with upstream production-side policies but now directed at the primary immediate polluter.

We utilize quantitative attributional analysis to answer the first question, by extending previous estimates of German cattle N and P nutrient budgeting and external pollution costs. For the second question, we review the literature concerning both policy instruments. We discuss the need to decrease cattle milk and meat consumption alongside reductions in cattle production to ensure that negative environmental effects such as N and P pollution are not merely shifted to other production regions, also known as leakage effects. Here, ‘technical’ refers to how biophysical production reductions translate into domestic consumption decreases rather than being an outcome of a specific policy. The remainder of this work is structured as follows: in Section 2, we present the methods used, followed by the results in Section 3. Finally, in Section 4, we discuss the main findings, limitations, broader implications, and conclusion.

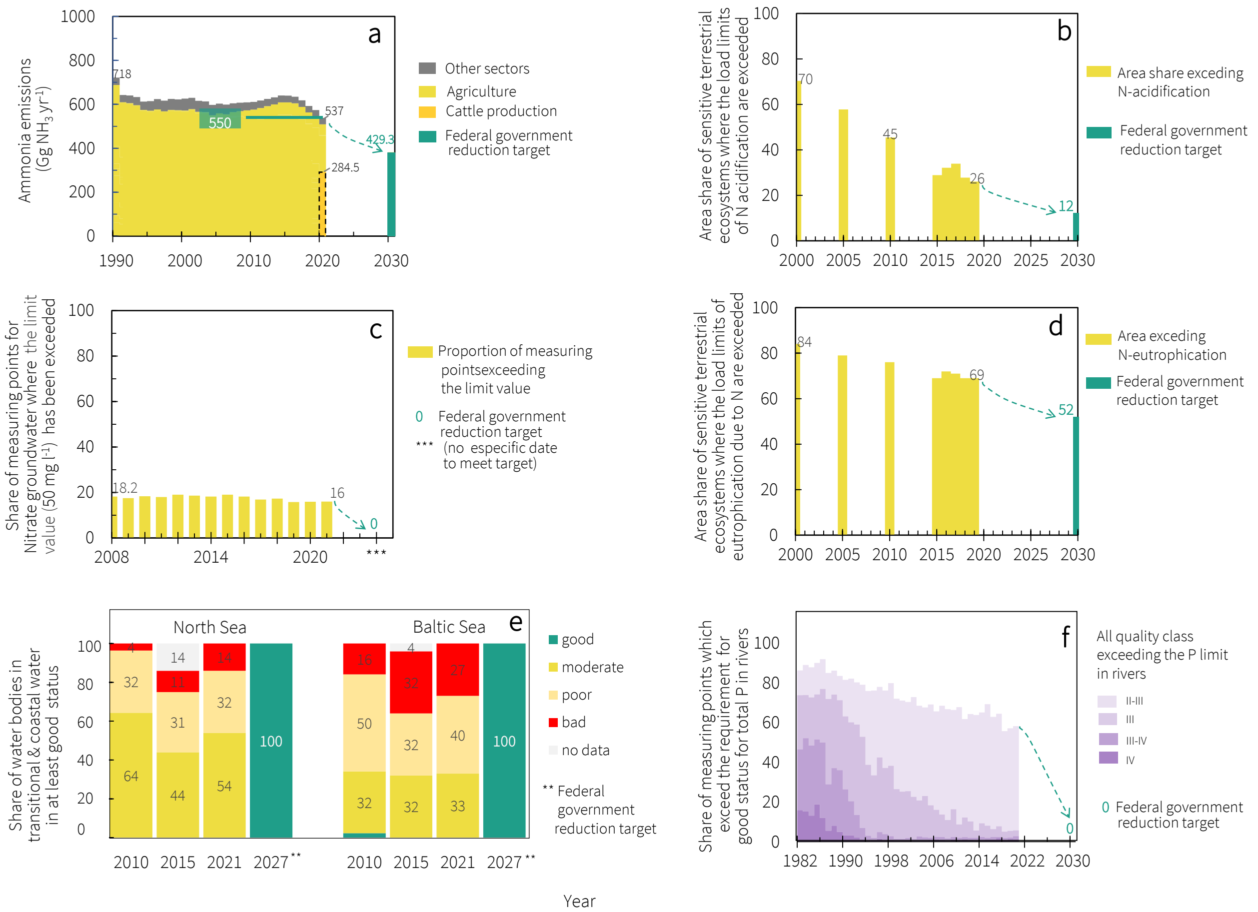

Figure 1: **Status of key Nitrogen (N) and Phosphorus (P) pollution indicators for Germany**. **a.** Ammonia emissions: total national and agriculture (1990-2020), cattle primary level of production-related (2020) with discrimination of emission origin, and national reduction target (2010-2020 and 2030); **b.** Area share of sensitive terrestrial ecosystems where the load limits of acidification are exceeded, several years between 2000 and 2019, reduction target, 2030. **c.** Share of measuring points for Nitrate groundwater where the limit value (50 mg l^{-1}) has been exceeded, modeled development, 2008-2020, reduction target with no date specified. **d.** Area share of sensitive terrestrial ecosystems where the load limits of eutrophication are exceeded, modeled development, several years between 2000 and 2019, reduction target, 2030. **e.** Share of transitional and coastal water bodies in at least good status; 2010, 2015, 2021, and reduction target to 2027. Annual data refers to the year of reporting to the EU. When reporting for the year 2010, information was gathered up until 2008. The data for the 2015 reporting year covered the time frame 2009-2014 and for 2021, 2014-2019. **f.** Share of measuring points that exceed the requirement for good status for total P in rivers, 1982-2021 and reduction target 2030. Color intensity shift from II-III to IV shows worsening status. **Data sources**: **a**, national, agriculture related, and reduction target, Vos et al. (2022); cattle-related, calculated in a previous own independent study. **b**, **d**, Schaap et al. (2023). **c**, **e**, **f**, Umweltbundesamt (2022).

2. Methods

2.1. Scenarios of downs-scaled domestic cattle production to reduce related N and P related nutrient surpluses

In a separate study, we have estimated Germany’s N and P cattle primary production-related surpluses and potential reactive compounds fate for 2020. We refer to these estimates in the following as ‘reference 2020’.

In this paper, such an estimation based on nutrient budgeting serves as our basis for exploring five scenarios for reducing the domestic surpluses of both nutrients. These scenarios, abbreviated onward as Sn, factor in reductions in cattle production inputs and stocking rates on the reference 2020 nutrient budget, specifically: S1, limiting domestic cattle production to the permanent domestic grassland potential, S2, decreasing current feed use, and S3, decreasing current fertilizer rates in feed procurement for domestic cattle. The following two options involve cattle proportionally reducing its N surpluses, aligning with two distinct levels of ambition. Under S4, the aim is moderate, requiring cattle to reduce surpluses commensurate with their share in national agricultural pollution and in line with national N surplus reduction targets. For S5, the ambition is higher, following expert recommendations to halve N surplus, with cattle contributions adjusted accordingly. The scenarios are described below, along with a summary in Table 1 on how the criteria mentioned above are combined. The scenarios express only technical, non-market mediated agricultural reductions for Germany as a whole. We modify the nutrient budgeting of the reference 2020, as highlighted in the scenario description, to obtain alternative production figures, land use, feed demand, main nutrient flows, nutrient use efficiency, and surplus fate for each alternative scenario. In addition, the estimated production reductions are expressed in terms of the reduction needed in domestic cattle milk and meat consumption while keeping other domestic food consumption unchanged (and its N and P pollution generated). This serves as an indicator of the changes that a policy in consumption would have to induce to avoid simply geographically relocating effects.

Table 1: Scenarios (Sn) to reduce N and P Surpluses originating from a down-scaled German cattle production.

Sn	Production limited to grassland	Reducing N fertilizer	Reducing feed use: Lower ambition in N surplus reduction	Reducing feed use: Higher ambition: halving N surplus
S1. grass	x			
S2. cap-fert			x	
S3. grass-cap-fert	x	x		
S4. cap-feed-low			x	
S5. cap-fert-feed-high		x		x

S1. grass: reduction of domestic cattle production to the available permanent grassland potential with unchanged N fertilization rates. Implementation of exclusively grassland-based feeding systems in mixed dairy farming has the potential to reduce N input in agriculture by decreasing the use of concentrates in the feeding ratio (Mack and Huber, 2017). This scenario assumes domestic cattle to be fed according to the current permanent grassland potential and not on imported or domestic feed from arable land (Garnett, 2009). The demand for grassland by ruminants is maintained at the same proportion as in the reference year 2020. The assumption seems rigid but allows excess manure to be transferred to other agricultural lands to support cropping to maintain the EU legal maximum manure application limit of 170 kg N ha^{-1} yr^{-1}. Recognizing legumes' key role in supporting the EU-protein transition, increasing N fixation, and improving forage yield, quality, and seasonal distribution (Lüscher et al., 2014), grasslands are enriched with legume mixtures. The output of marketed products, such as milk and cattle live animals derivatives, are adjusted to reflect output quantity differences between grass-fed and concentrate diets. N and P in manure production are recalculated to reflect the shift to a grass-feed diet (Šebek et al., 2014; van Krimpen et al., 2014). Pasture grazing remains the same as in the reference year, but pasture exercising is increasingly implemented from spring to autumn. Total fertilizer demand per land unit remains as in the reference year 2020, and seedling material is readjusted to reflect grassland resowing needs.

S2. cap-fert: reduction of N fertilization rates in domestic cattle feed production based on the social optimum and P fertilization bound to P bio-available legacies in topsoil. This scenario operates under similar assumptions as the reference year 2020, except that N and P fertilization regimes are reduced as follows. Total domestic N fertilizer demand is reduced to promote a socially optimal N rate as proposed by von Blottnitz et al. (2006), rather than pursuing the typical agronomic optimum rate of N fertilization. To find a proxy for the socially optimal N rate, we refer to studies by van Grinsven et al. (2015) and Henke et al. (2007), which suggest social optimum N fertilization levels for winter wheat and rape seed representative for Northwest Europe and German conditions, respectively. Based on van Grinsven et al. (2015), we assume that a 27% reduction in N fertilization (falling within the original range proposed by the authors of 25-30%) will result in a 15% decrease in plant yield (situated within the original range of 10-20%) compared with the reference year 2020. The assumption of manure re-circulation in our balance formulation yields a 15% reduction in N manure and 38% in inorganic N fertilizer. P fertilization is entirely covered via cattle manure and the bio-available legacies of P in topsoil (0–20 cm). In contrast, P inorganic fertilizer is disregarded, and its utilization is only reconsidered when bio-available topsoil legacies are substantially reduced. P legacy bio-utilization increases from the reference year 2020 utilization, i.e., 8.14 kg P ha^{-1} to 8.85 kg P ha^{-1}, discounting legacies from the average 83 kg P ha^{-1} estimated to be labile in German agricultural topsoil according to Panagos et al. (2022). While this strategy could minimize import dependency on mined P, such a P fertilization approach would necessitate country-wide manure procurement strategies. Additionally, it requires a comprehensive understanding of the spatial arrangement of pre-existing P legacies, their bioavailability for plant uptake, and site-specific conditions, such as soil texture and organic matter content (Buczko et al., 2019).

S3. grass-cap-fert: reduction of domestic cattle production to the available permanent grassland with N fertilization bound to a social optimum. This option combines the premises of extensification and low-input farming by adopting the assumptions of S2 regarding N and P fertilization reduction rates and S1 regarding feed use based on the grassland potential. We recreate the effects of climate change on crop yields by adding the hurdle of grassland yield reductions as in a warmer-than-average condition year, i.e., we take 2018 Germany's grassland yields as reference (BMEL, 2021). The assumption of lower yields adjusts cattle numbers further so that stocking rates for grassland support an average of 0.5 livestock units (LSU) ha^{-1}. This scenario assumes pasture access from spring to autumn and hay/silage grass in the wintertime.

S4. cap-feed-low: reduction of absolute domestic cattle numbers bounded to domestic agriculture N surplus reduction target. In this scenario, domestic cattle numbers are decreased to meet the moderate 2030 goal of reducing Germany's agricultural N surplus from 80 to 70 kg N ha^{-1} utilized agricultural area (UAA) yr^{-1}. We assume that the reduction in cattle numbers will be strategically distributed nationwide. A reduction in cattle absolute numbers implies a reduction in cattle feed-related domestic arable land and imported feed use, while permanent grassland utilization remains the same as in the reference year 2020. Imported feed and green fodder (mostly silo maize) are reduced more than proportionally, whereas the remainder of the domestic arable land feed components are reduced proportionally until the target is reached.

S5. cap-fert-feed-high: reducing absolute domestic cattle numbers and N fertilization toward achieving a more ambitious N surplus reduction target. This scenario combines the assumptions in S2 with an absolute reduction in cattle numbers to ensure cattle, proportionally to its N surplus, contributes to halving the reference 2020 domestic N agricultural losses. This ambitious target, which exceeds current national goals for N surplus reduction, was previously employed by Leip et al. (2022). They identified such a reduction as required to avoid exceeding critical limits of N losses into air and water in the EU, provided that, in practice, spatial allocation is appropriately considered.

3. Results

3.1. Cattle production scenarios to reduce related N and P surpluses

Table 2 summarizes the domestic cattle production scenarios designed to reduce related N and P domestic surpluses. These scenarios involve reducing the use of fertilizers, land, feed, and, ultimately, reduced cattle numbers. Here, we assume that other domestic N and P emission sources remain unchanged, and domestic cattle milk and meat consumption are reduced in line with related production reductions. The proposed domestic down-scaled cattle production pictures cattle related domestic N and P surpluses reductions between 15% and 48% and between 14% and 94%. Such a domestic reduction in reactive components' pollution would require a contraction of the domestic cattle herd between 15% and 75%. Additionally, it would necessitate a shrinkage in domestic inorganic N and P fertilizer consumption for cattle feed procurement between 16% and 54%, and between 29% and a cessation of imports, correspondingly. Major nutrient use efficiencies are achieved unequivocally via scenarios that consider fertilizer reduction (S2 and S5). While these measures would considerably reduce societal external costs (i.e., damage avoidance) compared with the reference, they would not be enough to internalize the total human health, climate, and ecosystem costs identified. Reductions of external costs range from 13% to 53% in the case of N and 27% to 65% in the case of P.

Note that S5, the most ambitious scenario for N surplus reduction, which evidently yields lower reactive N compound into air, water, and soil, and lower external costs does not necessarily deliver the best results for reactive P reductions. S3 presents the most considerable reduction in P surplus, which is anticipated due to the potential for utilizing labile P, yet elusive to achieve in practice without comprehensive nationwide P stocks monitoring.

While S5 suggests almost halving (reducing by 44% and 43%) domestic cattle meat and milk consumption, S3 proposes even more prominent cuts in consumption. Essentially, S3 implies that to achieve the goal of sourcing all cattle-related domestic demand from pasture-based sources while simultaneously targeting a two-thirds reduction in current sector-related P surplus, German consumers would need to reduce their intake of cattle meat to under one-quarter of their current consumption and limit their consumption of cattle dairy to less than one-fifth, other sources of livestock consumption unchanged.

3.2. Pursuing N and P pollution reductions via two production-side policies

3.2.1. Livestock buy-out schemes

The livestock buy-out scheme is a state-subsidized scheme the Dutch government has introduced as part of a new policy package to reduce N pollution from domestic livestock production. This scheme offers

Table 2: Technical down-scaled cattle production scenarios (Sn) in Germany designed to reduce related N and P surpluses compared to 2020 reference. Increased hue of red colors for options indicates increasing production or mean of production or consumption, while increased hue of yellow and purple colors indicate increasing social costs associated with N and P, respectively. **Data sources:** Physical figures for reference 2020 sourced from the same authors' separate research, and remaining data from the present study.

Main category	Indicator	**2020** ref	**S1.** grass	**S2.** cap-fert	**S3.** grass-cap-fert	**S4.** cap-feed-low	**S5.** cap-fert-feed-high
Production figures	Cattle animal numbers (million head)	11.3	5.2 (-54%)	9.6 (-15%)	2.8 (-75%)	8.1 (-28%)	6.4 (-43%)
	LSU (million)	8.1	3.7 (-54%)	6.9 (-15%)	2.0 (-75%)	5.8 (-28%)	4.6 (-43%)
	Dairy cows (million head)	3.9	1.9 (-51%)	3.3 (-15%)	1.0 (-74%)	2.8 (-28%)	2.2 (-44%)
	Cattle meat output (million tons CW)	1.09	0.45 (59%)	0.93 (-15%)	0.24 (-78%)	0.78 (-28%)	0.62 (-43%)
	Milk output (million tons)	33.6	11.2 (-67%)	28.6 (15%)	5.8 (83%)	24.2 (28%)	19.2 (-43%)
	Cattle output (Billion Euro yr^{-1})	13.8	4.9 (-64%)	11.8 (-14%)	2.5 (-82%)	10.0 (-27%)	7.9 (-43%)
Land use	Domestic UAA allocated to feed cultivation (million ha)	6.9	4.2 (-39%)	6.9 (0%)	4.2 (-39%)	5.5 (-20%)	5.5 (-20%)
	thereof arable land (million ha)	2.7	0.0	2.7	0.0	1.3	1.3
	Stocking rate (LSU Domestic UAA allocated for feed cultivation^{-1})	1.2	0.9 (-25%)	1.0 (-17%)	0.5 (-58%)	1.1 (-8%)	0.8 (-33%)
Feed demand	Imported rich protein feed (million tons)	1.6	0.0 (-100%)	1.4 (-12%)	0.0 (-100%)	1.0 (-37%)	0.7 (-56%)
Domestic consumption	Cattle meat (kg cattle meat $capita^{-1}$ yr^{-1})	10	4 (-60%)	8.3 (-17%)	2.2 (-78%)	7.1 (-29%)	5.6 (-44%)
	Cow milk & dairy products (kg cow milk $capita^{-1}$ yr^{-1})	333	111 (-67%)	283 (-15%)	57 (-83%)	240 (-28%)	190 (-43%)
Nitrogen							
Main flows	Total N surplus (Gg N)	**753**	**573** (-24%)	**486** (-35%)	**494** (-34%)	**641** (-15%)	**387** (-48%)
	N Surplus in area basis (kg Total Germany UAA 2020 $^{-1}$)	45	35 (-22%)	29 (-36%)	30 (-33%)	39 (-13%)	23 (-49%)
	N in cattle manure (Gg N)	724	341 (-52%)	615 (-15%)	179 (-75%)	521 (-28%)	413 (-43%)
	N inorganic Fertilizer (Gg N)	775	478 (-38%)	479 (-38%)	419 (-46%)	652 (-16%)	355 (-54%)
	Virgin N (Gg N)	988	638 (-35%)	686 (-31%)	579 (-41%)	811 (-18%)	512 (-48%)
	Recycled to total N (ratio)	0.65	0.59 (-9%)	0.69 (6%)	0.43 (-34%)	0.62 (-5%)	0.67 (3%)
N Use efficiency (NUE)	NUE_food (ratio)	0.076	0.031 (59%)	0.089 (17%)	0.017 (78%)	0.060 (21%)	0.082 (8%)
Surplus fate	Air emission (NH_3, N_2O, NO_x) (Gg N)	217	171 (-21%)	130 (-40%)	144 (-34%)	188 (-13%)	106 (-51%)
	Denitrification (N2)_a (Gg N)	376	292 (-22%)	246 (-35%)	257 (-32%)	321 (-15%)	198 (-47%)
	Leaching and run-off_a (Gg N)	160	110 (-31%)	109 (-32%)	92 (-42%)	132 (-18%)	83 (-48%)
External costs (Billion Euro yr^{-1})	Human health	4.8	4.1 (-15%)	2.9 (-40%)	3.1 (-35%)	4.1 (-15%)	2.3 (-52%)
	Climate	0.3	0.2 (-33%)	0.2 (-33%)	0.2 (-33%)	0.3 (0%)	0.2 (-33%)
	Ecosystems	2.2	1.6 (-27%)	1.4 (-36%)	1.3 (-41%)	1.8 (-18%)	1.1 (-50%)
	Cattle production	-4.1	-3.1 (-24%)	-2.6 (-37%)	-2.7 (-34%)	-3.5 (-15%)	-2.1 (-49%)
	Total N related external cost	3.2	2.8 (-13%)	1.9 (-41%)	2.0 (-38%)	2.8 (-13%)	1.5 (-53%)
Phosphorus							
Main flows	Total P surplus including slaughterhouse waste (Gg P)	**145**	**77** (-47%)	**124** (-14%)	**55** (-62%)	**109** (-25%)	**8** (-94%)
	P Surplus in area basis (kg P Total Germany UAA in 2020 $^{-1}$)	8.8	4.6 (-48%)	7.5 (-15%)	3.3 (-62%)	6.6 (-25%)	5.3 (-40%)
	P inorganic fertilizer (Gg P)	17	10 (-41%)	0 (-100%)	0 (-100%)	12 (-29%)	0 (-100%)
	P cattle manure (Gg P)	107	56 (-48%)	91 (-15%)	39 (-64%)	77 (-28%)	61 (-43%)
	P Soil stock depletion/utilization (Gg P)	62	34 (-45%)	61 (-2%)	34 (-45%)	45 (-27%)	45 (-27%)
	Virgin P from other sources (Gg P)	115	50 (-57%)	84 (-27%)	22 (-81%)	82 (-29%)	57 (-50%)
	Domestically recycled to total P (ratio)	0.76	0.79 (4%)	0.79 (4%)	0.85 (12%)	0.77 (1%)	0.80 (5%)
P Use efficiency (PUE)	PUE_food (ratio)	0.062	0.043 (59%)	0.071 (15%)	0.054 (12%)	0.062 (0%)	0.071 (15%)
Surplus fate	Accumulation in soil (Gg P)a	121	64 (-47%)	104 (-14%)	45 (-63%)	91 (-25%)	73 (-40%)
	Leaching and run-off_c (Gg P)a	24	13 (-46%)	21 (-12%)	10 (-58%)	18 (-25%)	14 (-42%)
External costs (Million Euro yr^{-1})	Ecosystems: eutrophication and leaching to drinking water	146	78 (-47%)	125 (-14%)	55 (-62%)	110 (-25%)	88 (-40%)
	Ecosystems: loss of biodiversity	15	8 (-47%)	11 (-27%)	5 (-67%)	11 (-27%)	7 (-53%)
	Human health: Cd potential to cause several health damage	142	76 (-46%)	105 (-26%)	45 (-68%)	103 (-27%)	70 (-51%)
	Total P related external cost	304	162 (-47%)	241 (-21%)	105 (-65%)	223 (-27%)	166 (-45%)

financial support for decommissioning dairy, pig, and poultry herds to help reduce their size. (Government of the Netherlands, 2020). At the moment, Germany focuses on animal welfare and nutrient management rather than buy-outs to tackle N pollution (Boezeman et al., 2023). The first potential concern with a buy-out scheme implementation in Germany is its voluntary basis, in which farms willing to participate in the program may not correspond to the geographical hotspot areas of N and P pollution. Adopting a mandatory approach for the buy-out scheme with national livestock permits with strategic issuance targeting minimizing current nutrient pollution hotspots could solve this. However, this proposition will encounter considerable resistance from most stakeholders. The second concern with implementing a buy-out scheme in Germany lies in the insufficient reasons supporting its jurisdictional effectiveness. In the case of the Netherlands, the implementation of the scheme is mainly justified as a considerable portion of the nutrient pollution externalities generated by intensive livestock production are not driven by local demand. However, Germany's conditions are different. With a self-sufficiency rate for cattle meat at 98.2% and milk at 111.9% (Rasche et al., 2023), any substantial reduction in dairy cattle could impact meat production, as much of the beef supply is linked to the dairy industry. Reducing dairy cattle to achieve 100% self-sufficiency in milk production could inadvertently increase N and P pollution elsewhere as cattle production might shift to other countries, thus offloading Germany's environmental responsibilities and avoiding accountability for the reactive compounds generated by its own consumption. Targeting German pig production could prove to be more jurisdictionally effective for localized nutrient pollution reduction since its national pork self-sufficiency stands at 132%. However van Grinsven et al. (2018) estimated that relocating intensive pig production within Germany would result in total external cost increases and intensive pig production relocation within the EU27, specifically to Romania, could reduce EU27 N pollution external costs by 10%. In contrast, we argue that relocating Germany's livestock to other EU state members would only move and possibly amplify existing issues to another site in the same yard by increasing environmental inequality across Europe. Central and South-Eastern Europe experience higher exposure to particulate matter than the West (Ganzleben and

Kazmierczak, 2020), an environmental problem that can exacerbate with increased ammonia emissions from increased livestock farming intensity. Therefore, a more comprehensive approach is needed than a within-EU-intensive livestock relocation to maintain consistency with policies targeting sustainable and inclusive EU growth.

3.2.2. ***Taxing the use of nutrient intensive inputs or generation of nutrient surplus***

Taxing inputs such as inorganic fertilizer and commercial animal feed, or taxing farm reactive component surplus, has been a topic in EU agricultural economic literature for decades. These measures aim to reduce domestic N and P pollution, specifically to protect water. Some studies concluded that given the inelastic demand for mineral N and P fertilizer, a fertilizer tax would need to be set at a very high rate to induce such fertilizer use reduction (WBAE and WBW, 2016). Some results of ex-ante simulations of N taxation within economic frameworks in the German context are summarized in Table 3. The potential market-mediated effects of N taxation in Germany as a whole or in part of it, include decreased crop yields, reduced farmer profits, and lower agricultural sector income. Mixed effects are observed on livestock production, with mixed jurisdictional effectiveness in N reduction in areas of intensive livestock production. Neufeldt and Schäfer (2008) stated the primary mechanism of mitigation is expected to be through the reduction of mineral N use, with little effect on livestock and organic N. Interestingly, taxation of N fertilizers was found to be more effective at reducing N-species emissions than livestock extensification. For both intensive and forage-based farms, selling livestock would not be financially beneficial due to high meat and dairy prices. Consequently, farmers may opt for lower N intensity in feed crop production, leading to decreased emissions and improved agricultural practices. Overall, the evidence suggests N surplus reductions, but considerable economic challenges associated with such fertilizer taxation. These studies do not estimate leakages to non-taxed areas, but in some studies, such leakages are also a concern. Germany, thus, did not implement it. In contrast, various European countries taxed N and P pollution despite expected negative effects (Table 4).

Table 3: Ex-ante simulations of N within economic frameworks in the German context.

Author	Study area	Ex-ante simulation	Market mediated effects
Hartmann and Schmitz (1994)	West-Germany	Halving mineral N fertilizer use	28-40% decrease in farmers' profits, and 4-8% reduction in animal production.
Neufeldt and Schäfer (2008)	Baden-Württemberg	Tripling synthetic N fertilizer price	10% income decrease and 15% reduction in N_2O-species emissions.
Wendland et al. (2005) Gömann et al. (2005)	Ems & Rhine catchments	200% tax increase on mineral fertilizer	Reduces N use by 10-25 kg/ha/yr, N surplus by 27-34%, and N-input into waters by 25%.
Henseler et al. (2020)	Whole Germany	N tax level varying from 20% to 80% increase in N fertilizer	3-15% drop in cereal and cash crops production, 3-10% agricultural income loss, and 2-7% N balance drop.

As of today, the measures have been lifted in most of these countries mainly due to their accession to the EU and the need to comply with more harmonized environmental directives. Evidence is mixed regarding the post-implementation effectiveness of these taxes. Some studies indicate that they have led to a reduction in fertilizer use, with minor or no effect on agricultural production output and income, and overall positive environmental outcomes. Others argue that the tax levels have been too modest to induce considerable changes in usage or positive environmental effects so that the outcomes may have been influenced by a combination of policies, including CAP support and global economic factors, rather than solely by the tax.

Regardless of the non-conclusive post-effectiveness evaluation, it is clear that the limited results of the policy were partly due to its geographical scope and addressee. The European Economic Area (EEA) should have been the implementation scope, as the interconnected trade within the AEE posed a risk of 'leakage', where farms could bypass national taxes by sourcing inputs from other AEE nations. Additionally, implementing taxes at the import level is considerably more feasible than at the farm level, given that a limited number of addresses can make the measure operational and maintain it under reasonable administrative costs. A partial solution for internalizing these N and P pollution issues is the recently implemented EU Carbon Border Adjustment Mechanism (CBAM). Despite covering the geographical scope and addressee mentioned above, the measure has been motivated only by climate mitigation rather than the full environmental externalities embedded in nutrient trading. Even with its objective of climate mitigation, the current EU CBAM covers fertilizers but not agri-food, leaving loopholes such as animal feed trading. During the transitional phase of the EU CBAM, importers are not compulsorily taxed. However, with full CBAM implementation from 2026, fertilizer costs are expected to increase. For instance, ammonia fertilizer production costs are expected to double from 30 to 60 Euros ton^{-1} (McDonald, 2023), and will be passed onto producers, potentially causing policy backslash. Starting in December 2023 and ongoing into January 2024, Germany has seen protests against the government's plan to cut the diesel fuel tax rebate, a climate-damaging subsidy (Clean Energy Wire, 2024), suggesting potential resistance to future reforms.

Table 4: Overview of production-side tax implemented by some European nations on N and P fertilizer use, P commercial animal feed use, and N and P farm-surplus. **Data sources**: Table adapted from OECD (2017) with additional data added regarding instrument implemented, effects and constraints sourced from WBAE and WBW (2016); Andersen et al. (2022); Döring and Smith (2013); Gazzani (2017); Prestvik et al. (2013); Rougoor et al. (2001); OECD (2020). **Note:** Used 3-letter ISO country abbreviations.

Instrument	Country	Application period	Main objective	Instrument design	Revenue use	Possible effects (mostly correlation not proven causation)	Political and practical constraints
P- inorganic fertilizer input tax	FIN	1976-1995	Reduce P fertilizer use	Revised multiple times	Financing export subsidies	–	Repealed due to concerns about effects on farmers' competitiveness and administrative difficulties in implementing the tax
N- inorganic fertilizer input tax	NOR	1988-2000	Fund other policy measures to the benefit of agriculture	Ad-valorem for N-based fertilizers, Tax gradually increased from 1% to 20% in 1991	Finance environmentally friendly cultivating practices and information measures	–	–
N, P and K- inorganic fertilizer price regulation	SWE	1984-2010	Reduce chemicals leakage into soil	Approximately 20% of the fertilizer price	Finance export subsidies and R&D measures for agriculture	Positive reductions but no direct causation. Fertilizer use reduced by 15-20% (1991-1992), 10% in 1997. Agricultural production remained stable, due to improved fertilizer efficiency. Farmers' incomes unchanged, high input costs balanced by subsidies. Administrative costs around 0.8% of revenue.	–
N and P-inorganic fertilizer input tax	AUT	1986-1994	Soil and water conservation and create incentives for alternative cropping	Initially at a rate of 3.5 ATS (0.25 Euro) kg N^{-1} and 2 ATS (0.15 Euro) kg $P_2O_5{}^{-1}$. gradually increased over the years	Finance export refunds for cereals and other agriculture policy measures	Fertilizer use decreased by 3% annually, during the tax period. Fertilizer prices increased as of 10%; Administration costs were low, about 0.75% of the tax revenues.	Abolished upon Austria joining the EU
N fertilizer input tax	DNK	1998-2016	Reduce nitrate pollution	DKK 5 per kg N input, with broad exemptions for agriculture, levied on the sale of N fertilizers, applies to both chemical fertilizers and organic fertilizers.	Channeled back to farmers via reductions in land use tax. Annual N-based tax revenue: DKK 20 million (3 million Euro).	From 1990 to 2011 the use of imported N fertilizers reduced 42%. Mid-1980s-2010 farm NUE doubled (from 20% to 40%), N load in coastal waters dropped by a third. NH_3 emissions from agriculture and NH_3 deposition reduced by 30% and 20-25%, respectively, N_2O emissions (though not targeted) decreased by 35%. Groundwater and drinking water nitrate concentrations not clear effects, rather increased slightly. Mixed evidence.	Due of its exemptions, users were generally unaware of the tax
P-commercial feed input tax	DNK	2005-2019	Reduce P saturation in soils, leaching to surface waters	Tax on commercial imported and domestically produced animal feed phosphate used to feed livestock. Pet food and own livestock feed produce exempted. DKK 4 (Euro 0.53) kg P^{-1}. Levied on the point of sale Administered with the value-added tax.	–	Limited effect than anticipated: ex-ante assessment, tax to yield a reduction of 33% to 37% from baseline. Actual reductions, between 2005 and 2015, 15% , while livestock numbers were about the same. Increasing the international price of mineral P had probably reduced the consumption of P independently of the tax. The tax increased feed costs by 25%, while phytase could be added at a cost of only DKK 2 per kg. On farm P surplus reduced from 33 Gg P in 2001 to about 16 Gg P in 2014. Provided relief to surface waters, but lakes continue eutrophied due to P soil deposits; Greater efficiency in the use of animal feed for non-ruminants.	No revenue loss neutral for farmers
N and P surplus tax	NLD	1998-2005	Increase fertilizer use efficiency	levy on kg surplus N and P_2O_5 'above a levy free allowance' per ha of a regulated threshold; levied across all farm types as part of the MINAS program (Mineral Accounting System). Tightening up of the system over the period, with the levy-free surpluses declining, and the rates of levy increasing steeply, especially in the case of P. Initially, applied only to livestock farms having more than 2.5 LSU ha^{-1} and some pigs and poultry farms. The levy applied to all farm holdings since 2002.	Feeds into general government budget, not earmarked.	Nitrate concentrations in sandy regions improved declining from about 135 mg/l before MINAS to about 95 mg/l in the last 4 years. Nitrate concentrations on farms in clay and peat regions show no clear trend. P concentrations in surface water have not decreased at all The ecological status of ditches and brooks remains poor. Although the agricultural sector managed to reduce P surplus by 30% since 1997, soils are still accumulating P, and P leaching did not decrease, pointing to the difficulty to observe results in medium term due to large P legacies.	Specific price elasticity were unavailable. The price elasticities of demand applied relate to demand for fertilizer per se, and not to surplus nutrients. MINAS abandoned to comply with EU Nitrates Directive.
Surplus manure tax	BEL	1991-2020	Prevent the excessive production and use of manure and fertilizer	Basic manure tax: 0.01 Euro kg N^{-1} and P Import of manure tax 2.48 Euro per t imported Overproduction of manure tax 0.99 Euro kg N^{-1} and P production above the amount allowed Tax for farmers who have not met requirements 0.99 Euro kg N^{-1} and P not processed or exported regarding mandatory manure processing or export	- -	- -	- In the Walloon and Brussels region no manure levy exists.

4. Discussion and conclusion

Germany continues to exceed the established ceilings for most N and P pollution indicators. Under its current policies, it is likely to miss any future targets for pollution reduction, with dire consequences. In this study, we built upon our previous work on nutrient budgeting and damage cost valuation for N and P cattle production. This enabled us to explore the technical plausibility and external costs of down-scaling cattle production in Germany as a means to mitigate reactive N and P pollution. We have formulated such production scenarios in alignment with domestic reduction targets and supranational academic recommendations for sustainability. They picture considerable local domestic improvements regarding N and P surpluses and lower external pollution costs. Fertilization reduction strategies seem more promising than reducing domestic cattle numbers. In addition, the most effective scenario for N surplus reduction does not necessarily yield the best outcomes for reactive P. This emphasizes the importance of Germany's technological advances in P recovery and differentiated reactive compound mitigation strategies. Although specific studies for Germany are lacking, our results are similar to those evaluating reactive N and/or P pollution reduction via livestock number shrinkages in Nordic countries (e.g., Röös et al. (2016); Karlsson and Röös (2019)). Some limitations in our biophysical scenarios are: First, the assumption that farmers depend entirely on P soil stocks and P in manure as a P source in one of the scenarios might not be practical due to the uneven geographical distribution of these stocks. Without a specific soil analysis, it could be risky to yield stability, a critical asset for farmers. Second, the scenarios should have considered resource circularity beyond manure, which is crucial for optimizing biomass utilization in agricultural production.

However, the scenarios only provide an attributional perspective on the problem. To achieve the underlying reductions in fertilizer and domestic herd size would require ambitious policy measures. Consequently, this would not only affect the livestock and agriculture sectors but also have economy-wide effects and face political opposition.

We focused on the production side in this paper. We have qualitatively examined two supply-side upstream policy measures, buy-out and taxation, that could induce such N and P pollution reductions. Evidence suggests that taxing, rather than reducing animal numbers via a buy-out, might be more effective in inducing such nutrient surplus reductions within national boundaries. However, such effectiveness could be limited due to the simplified goal of the taxation approach, leakages that were often ignored or incompletely in previous consequential estimations, and the stakeholders' response to the measure. In the recently implemented EU CBAM, the magnitude of N and P reactive pollution reductions achieved may be minimal, as the policies only attempt to address the internalization of climate effects but not the broader environmental issues related to transboundary nutrient cycle imbalances. The behavioral producer responses to the measure, ranging from absorbing the input cost increases to outright opposition, might also dilute or impede the anticipated tax effects. We argue that solely relying on upstream, production-side instruments for internalization, even if they extend beyond climate change to other nutrient-related externalities, could simply shift negative nutrient pollution effects to other regions, potentially deteriorating global nutrient cycles. This highlights the necessity of broader strategies beyond just improving nutrient flows within national or EU boundaries.

Thus, we suggest policymakers should aim at a mix that addresses the cattle supply chain from both ends. Currently, German policies do not touch upon inducing reductions in consumption behaviors that contribute to intensive N and P pollution. In our simplified attribution analysis, we translate the reduction in the production of the herd into a decrease in the average German consumer's consumption of milk and meat while assuming other nutrient-intensive food demands remain unchanged. However, relying on just one source of intensive reactive pollution for reductions is too simplistic, and all livestock supply chains would have to be considered. Simultaneously, policies for N and P cycle balancing should promote less nutrient surplus-intensive production and consumption and more local food consumption. A promising starting point is taxation of demand, which, unlike production, is mainly unregulated today and can drive desired changes in production patterns.

Our research is based on attributional quantifications and previous ex-ante modeling exercises, which did not explore the depth of the danger of leakages. A consequential modeling framework should be used in future studies to understand the quantitative market-mediated effects fully. So far, such models have failed to capture these dynamics adequately since nutrient budgeting in developing countries is poorly documented. We hope that this gap will be addressed soon.

Author contributions

KA Conceptualized and drafted the study. **SvCT** Conceptualized the study, reviewed all sections, contributed to them, and acquired the funding.

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Declaration of competing interest

The authors have no conflicts of interest to declare that are relevant to the content of this chapter.

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