Science of the Total Environment 786 (2021) 147427

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Reconciling food production and environmental boundaries for nitrogen in the European Union

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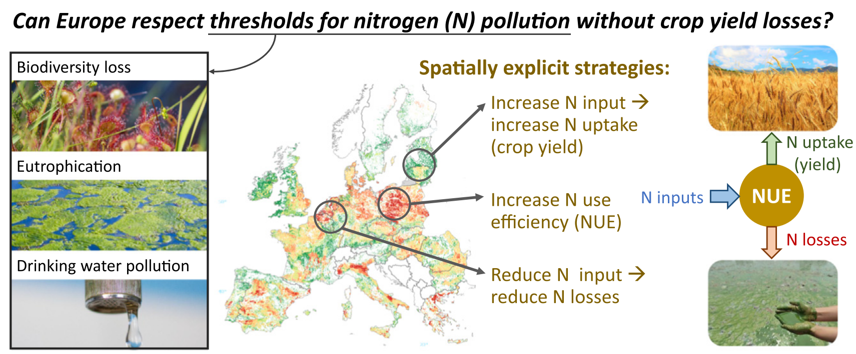
HIGHLIGHTS

- Thresholds for N losses to air and water are exceeded on 85% of EU agricultural land.
- We model spatially explicit options for respecting N thresholds without yield reduction.
- Options for increasing N inputs to close yield gaps within N thresholds are limited.
- At improved N management, 80% of current crop production can be obtained within thresholds.
- In hotspot regions, extensification is required to meet environmental targets.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 29 December 2020
Received in revised form 22 April 2021
Accepted 25 April 2021
Available online 29 April 2021

Editor: Jay Gan

Keywords:
Nitrogen use efficiency
Yield gaps
Critical limits
NH_3 emission fractions
Eutrophication
Spatial variation

ABSTRACT

Meeting European policy targets for reducing nitrogen (N) pollution while maintaining crop production is a large challenge. Strategies to tackle this dual challenge should assess where reducing N losses is most needed while accounting for variation in agricultural systems and ecosystems' vulnerability to N loading. We used a spatially explicit N balance model (INTEGRATOR) to assess whether crop production targets and thresholds for N impacts on biodiversity and water quality in the EU can be reconciled by (i) redistributing N inputs from excess regions to regions where environmental thresholds are not exceeded and (ii) improving N management to reduce ammonia (NH_3) emissions from manure and enhance field-level N use efficiency (NUE). At current NUE, reducing N inputs to comply with three environmental thresholds (critical N deposition on terrestrial ecosystems and critical N concentrations in surface water and groundwater) would reduce European crop production by 50%. The widespread exceedance of thresholds does not provide much room for redistribution: increasing inputs to close yield gaps on land where N thresholds are not exceeded can only increase crop production by 3%. To achieve surface water quality targets without crop production losses, average NUE needs to increase from 0.64 to 0.78, whereas achieving groundwater targets only requires a modest increase from 0.64 to 0.67. In hotspot areas, however, crop production and N thresholds can only be reconciled at NUEs of >0.90, which is not feasible. Reducing manure NH_3 emission fractions to 0.10 by adopting best-management practices reconciles current crop production and thresholds for agricultural NH_3 emission (in view of critical deposition) on only half of the agricultural area. In some regions, technologically feasible improvements in N management are thus insufficient to both maintain current crop production and respect environmental boundaries. Overall, the evaluated measures could reconcile ~80% of current EU crop production with N thresholds.

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https://doi.org/10.1016/j.scitotenv.2021.147427

1. Introduction

Europe is one of the most food secure regions worldwide (FAOSTAT), yet the intensive agricultural systems that support European food production also harm ecosystems and biodiversity (EEA, 2020). A quarter of Europe's land area is dedicated to arable crops (compared to a global average of 11%, FAOSTAT), and livestock densities are among the highest in the world (Gilbert et al., 2018). Both crop and grassland production are supported by high inputs of nitrogen (N), an essential nutrient for plant production. Only about 60–65% of N applied to Europe's soils, however, is taken up by crops (De Vries et al., 2011; EUROSTAT, 2020; Leip et al., 2011a, 2011b). Much of the excess N is lost to the environment, which adversely affects soil, air and water quality. This has resulted in widespread impacts on ecosystems (Dise et al., 2011; Stevens et al., 2020) and human health (Pozzer et al., 2017; Sutton et al., 2011), causing substantial societal costs (Van Grinsven et al., 2013). Reducing N losses is pivotal for meeting several European targets related to water quality and biodiversity (EEA, 2019).

While reducing N losses is urgently needed to protect ecosystems, such reductions should not lead to large reductions in crop and livestock production. Despite already ranking among the world's highest-producing regions, Europe's agricultural production will probably need to increase in the future for several reasons. The first reason is geopolitical: Since 1990, Europe has shifted from food self-sufficiency to import dependency (Sadowski and Baer-Nawrocka, 2016). Many European countries currently produce less than 70% of their domestic demand (FAO, 2012; Puma et al., 2015; Sadowski and Baer-Nawrocka, 2016). Europe is also a net importer of plant proteins, mainly for animal feed (Lassaletta et al., 2014b). This import dependency makes Europe vulnerable in case of scarcity on global crop markets (Puma et al., 2015). The second reason is global food security: while Europe's food demand is only projected to increase by a few percent until 2050 (Bruinsma, 2012), a rapidly increasing global population and shifts towards higher animal protein shares in diets as well as rising demands for bioenergy feedstocks (de Wit et al., 2011) are expected to increase global crop demand by 60% (FAO, 2017) to 100% (Tilman et al., 2011) between 2010 and 2050. Current crop yield growth rates are likely insufficient to meet this demand (Ray et al., 2013, 2012), especially in Sub-Saharan Africa (van Ittersum et al., 2016) and some regions in Asia and South America (Fader et al., 2013). If growing demands cannot be met by domestic production and pressures on global food markets increase, it is likely that trade with Europe will play a role in meeting demands (Pradhan et al., 2014). The third reason is to avoid spill-over effects: at constant global demand, a reduction in European food production would shift production to other regions with potentially less strict environmental regulations, thus effectively relocating environmental damage (Fuchs et al., 2020).

Increasing agricultural output can be achieved in two ways: by increasing agricultural area (land expansion), or by enhancing productivity to close yield gaps on existing agricultural lands (land intensification) (Tilman et al., 2011). Land expansion often increases greenhouse gas emissions and negatively affects biodiversity and ecosystem services (Foley et al., 2011; Lambin et al., 2013), and suitable land for agricultural expansion is increasingly scarce (Lambin and Meyfroidt, 2011). Closing yield gaps, on the other hand, usually requires increasing inputs, such as water, N and other nutrients. Increasing N inputs, however, may counteract efforts to reduce N pollution as mandated by several European Directives, such as the Water Framework Directive (EC, 2000) or the Nitrates Directive (EC, 1991). It is also in contradiction with the ambition of the European Green Deal to reduce agricultural nutrient losses by 50% in 2030 (European Commission, 2020). The challenge is therefore to maintain or even increase European agricultural production while remaining within safe thresholds for N pollution.

Two major options exist to remain within ‘safe boundaries’ for N losses without reducing (or even while increasing) crop yields. First, by spatially redistributing crop and animal production and associated N inputs and losses. This entails intensifying production (i.e., increasing N inputs) in regions where thresholds for N pollution are not yet exceeded, thus compensating for yield losses in areas where N inputs need to be reduced to respect those thresholds (Gerten et al., 2020; Mueller et al., 2012). Second, by improving N use efficiency (NUE) in both crop and animal production systems to reduce N losses and thus environmental impact while maintaining productivity levels. Crop production NUE can be increased by better matching N inputs with crop demand through improved fertilizer technologies and practices (Chen et al., 2014; Ju et al., 2009; Zhang et al., 2015), or by using improved crop varieties or crop rotations (Cormier et al., 2016; Davidson et al., 2015; Hirel et al., 2011). Nitrogen use efficiency in livestock production systems can be increased through improved manure management and recycling, herd management, nutrition, or technological adaptations to housing systems (Oenema et al., 2007; Uwizeye et al., 2020). From a biophysical perspective, each strategy's potential depends on the local characteristics of both agricultural systems (determining the relationship between N inputs and N losses) and the ecosystems receiving N losses (determining how much N inputs an ecosystem can tolerate). Socio-economic factors that determine whether and at what costs these strategies can be implemented are not considered here.

Given the large heterogeneity in agricultural production systems across Europe, developing strategies to balance environmental and production targets requires spatially explicit information on (i) ‘safe’ N losses to minimize environmental risks of N, (ii) the potential to enhance crop production by increasing N inputs on existing agricultural land and (iii) the NUE at which both environmental and crop production objectives can be met. De Vries et al. (2021) performed a first spatially explicit assessment of ‘safe’ N input levels (called ‘critical’ N inputs hereafter) in the European Union (EU) in view of thresholds for: (i) atmospheric N deposition onto terrestrial ecosystems to limit biodiversity loss; (ii) N concentration in surface water to limit eutrophication and (iii) nitrate (NO_3^-) concentration in groundwater to meet drinking water standards in view of human health impacts. Results showed that on 85% of EU agricultural area, current N losses exceed at least one of the three thresholds (Table 1). More importantly, De Vries et al. (2021) showed substantial spatial variation in the exceedance of N pollution thresholds due to large variations in agricultural N inputs, in the biogeochemical and hydrological processes that determine N losses, as well as ecosystems' vulnerability to these losses. In order to maximise nitrogen's benefits for EU food production while limiting its adverse impacts, this variation needs to be considered when developing N management strategies.

The aim of this paper is to explore to what extent thresholds for N losses to air and water can be respected while maintaining (or even increasing) crop and grassland production in the EU. We build on the work by De Vries et al. (2021) and use a high-resolution N balance model to calculate shares of crop and grassland production that can be obtained within safe boundaries for N losses (i) under 'baseline' conditions, (ii) by increasing N inputs to close yield gaps in regions where thresholds allow, and (iii) by improving N management (increase NUE and/or reduce NH_3 emission fractions). In regions where improving N management is insufficient to fully reconcile current crop production and N loss thresholds, environmental targets can only be met at lower yields. The approach assumes that current properties of the agricultural system are maintained, such as the agricultural area (no land expansion) and the mix of crop and livestock production, while not considering possibilities to reduce demand for agricultural produce through, e.g., avoiding food waste and reducing consumption of livestock products (Grizzetti et al., 2013; Westhoek et al., 2014). Results indicate the technical potential of various strategies to reconcile crop production with N thresholds, while not accounting for existing socio-economic, cultural or institutional barriers that may impede implementation of these strategies.

Table 1
Thresholds for environmental impacts of nitrogen (N) and associated agricultural N losses, and share of agricultural area where thresholds are exceeded in the current (year 2010) situation. For details on the methodology, see De Vries et al. (2021).

Thresholds for environmental impacts	Thresholds for N losses from agriculture	Share of area where threshold is exceeded
Deposition: thresholds for N deposition to terrestrial ecosystems in view of biodiversity impacts *(ecosystem-dependent critical loads)*	Critical NH_3 emissions	66%
Surface water: threshold for N concentration in runoff to surface water in view of eutrophication impacts (*2.5 mg N* l^{-1})	Critical N runoff to surface water	74%
Groundwater: threshold for nitrate concentration in groundwater in view of health effects (*50 mg* NO_3^- l^{-1})	Critical N leaching to groundwater	18%
All thresholds respected simultaneously	*Minimum of the above losses*	85%

2. Methods

2.1. Thresholds for nitrogen losses and inputs and their exceedances

Thresholds for N losses and N inputs were derived with INTEGRATOR, a spatially explicit, process-based model that calculates N balances for agricultural land in the EU at a high spatial resolution for the year 2010. INTEGRATOR calculates manure excretion in housing systems and pastures, and N inputs to agricultural soils from different sources, i.e. manure, synthetic fertilizer, biosolids, biological fixation, atmospheric deposition, and net mineralization (only on peat soils). Resulting emissions of ammonia (NH_3), nitrous oxide (N_2O) and nitrogen oxide (NO_x) to the atmosphere, as well as N leaching and N runoff to groundwater and surface water are calculated empirically as a function of N input quantity and source, N management, land use, climate, soil type and slope. Crop N uptake is estimated based on national yield statistics for ~35 crops represented in INTEGRATOR from FAOSTAT (downscaled to zones of similar climate), and N contents and harvest indices from the literature. Grassland yields are estimated based on Smit et al. (2008). Calculations are performed for approximately 40,000 Nitrogen Calculation Units (NCUs), which in turn are sub-divisions of 1244 NUTS3 regions (administrative areas in the EU of 160–440 km^2). For a detailed description of the INTEGRATOR model, see De Vries et al. (2021).

'Critical N inputs', defined as N inputs that cause N losses at exactly the environmental threshold, were derived in three steps (Fig. 1a). First, environmental thresholds to avoid N impacts were defined for (i) N deposition to terrestrial ecosystems to avoid terrestrial biodiversity loss (based on critical loads for nature areas), (ii) N concentration in runoff to surface water to avoid eutrophication, and (iii) NO_3^- concentration in leachate to groundwater to avoid health risks (based on the EU drinking water norm) (step 1 in Fig. 1a; see also Fig. 1b & Table 1). Second, critical N losses (NH_3 emissions, N runoff and N leaching) were back-calculated from environmental thresholds (step 2 in Fig. 1a) while also accounting for N losses from other sectors (e.g., NO_x emissions from traffic and industry) and for dilution of agricultural N losses (e.g., dilution of agricultural runoff by runoff from natural areas). Third, critical N inputs were back-calculated from critical N losses, based on current N loss fractions and N uptake fractions (step 3 in Fig. 1a). A full description of the approach and used thresholds is given in De Vries et al. (2021).

Critical N inputs were compared with current (2010) N inputs to determine reductions needed to respect environmental thresholds. Where thresholds are exceeded, reducing N inputs to critical levels leads to lower crop production (step 4 in Fig. 1a), unless N management factors are improved (Fig. 1b). A higher NUE leads to a lower soil surplus and thus N runoff and/or leaching per unit of N input, while a lower NH_3 emission fraction (EF) leads to lower NH_3 emissions per unit of N input (and thus indirectly also to a higher NUE; Fig. 1b). Consequently, it is possible to derive changes in management factors needed to meet crop production targets while simultaneously respecting thresholds for N losses (step 5 in Fig. 1a, see also Section 2.3.2).

2.2. Required nitrogen inputs to obtain target yields

2.2.1. Yield potentials and target yields

To determine target yields in regions where N inputs can safely increase without exceeding environmental thresholds, we estimated spatially explicit, crop-specific yield potentials for all crops included in INTEGRATOR. A crop's 'yield potential' is defined as the maximum possible yield for a given climate and soil under optimal management, and the 'yield gap' as the difference between yield potential and actual yield (van Ittersum et al., 2013). The Global Yield Gap Atlas (GYGA, www.yieldgap.org) provides data on actual yields and yield potentials (both under water-limited and irrigated conditions) for a variety of staple crops and countries. GYGA yield potentials are estimated by a bottom-up approach using crop growth models calibrated for specific weather stations, and upscaled to the country-level using zones of similar climate (Grassini et al., 2015; van Bussel et al., 2015). This approach produces more accurate estimates than top-down approaches that rely on global datasets of weather, soil and crop management (van Ittersum et al., 2013).

For the EU, GYGA currently reports water-limited yield potentials (Yw), yield gaps and actual yields (Ya) only for wheat, barley and maize in most countries (Schils et al., 2018; Table S1). Data for other crops are not available (neither from GYGA nor from other sources) and yield potentials for these crops were thus estimated by assuming that relative yield gaps follow the same pattern as yield gaps for rainfed wheat (see Supplementary Text S1). Rainfed wheat was used in the scaling approach as it is the most important arable crop in Europe; accounting for about a quarter of the total cropland area. Yield potentials for all crops were estimated by multiplying actual yields from INTEGRATOR by the ratio Yw/Ya for rainfed wheat from GYGA. Resulting yield potentials were then corrected to account for the fact that yield gaps for other crops may differ from yield gaps for wheat by multiplying with the ratio of the 'maximum yield ratios' for the respective crop and wheat (see Eq. S1). The 'maximum yield ratio' expresses the relation between the average crop yield in a given country and the highest country-level crop yield in the EU. Country-level yield potentials for barley and maize estimated with this procedure were compared to GYGA data, which generally gave good results (Fig. S1c,d). Scaling with the maximum yield ratio improved the fit compared to scaling with Yw/Ya for rainfed wheat only (Fig. S1a,b**)**. As data on yield potentials for other crops in Europe are not available, we could not validate estimated yield potentials for these crops.

The 'target yield' was set to 80% of the estimated water-limited yield potential. Eighty percent of the biophysical potential is generally considered the economic optimum for farmers under most conditions (Lobell et al., 2009; van Ittersum et al., 2013). For grassland, target yields were only estimated for intensively managed grassland (defined as grasslands with dry matter production >4500 kg ha^{-1} yr^{-1}), as we assumed that extensive grasslands are not managed by farmers to maximise yields.

2.2.2. Required nitrogen inputs to obtain target yields

Nitrogen inputs required to obtain target yields were calculated by multiplying actual (year 2010) N inputs by the ratio of target yield and actual yield (i.e., assuming that NUE is constant). On the one hand, the

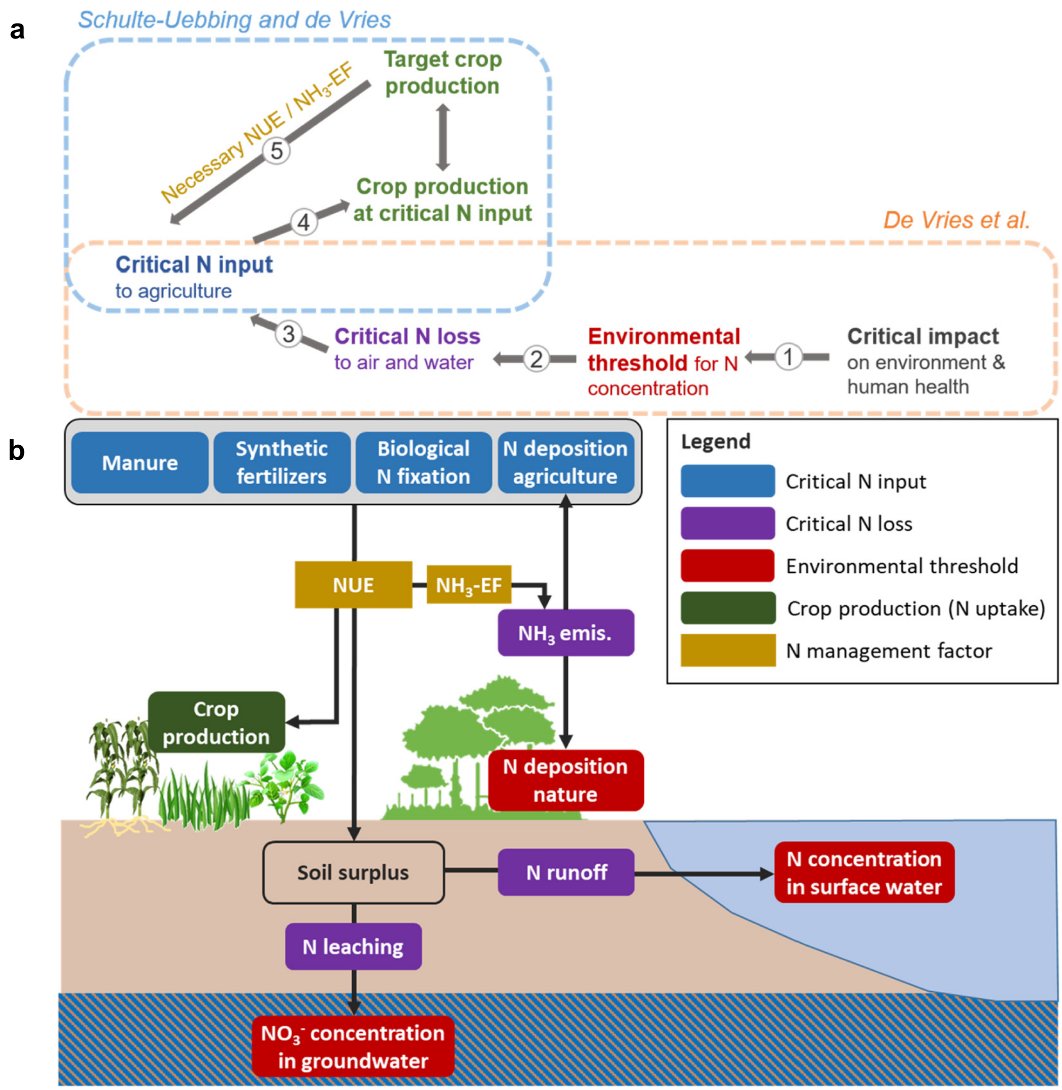

Fig. 1. (**a**) Steps for back-calculating critical nitrogen (N) inputs from environmental thresholds for N and related critical N losses, as well as the necessary nitrogen use efficiency (NUE) or NH_3 emission fraction (EF) to reconcile environmental thresholds with crop production targets. Dashed boxes indicate which steps are described in this paper (blue) and in De Vries et al. (orange). (**b**) Simplified representation of relationships between critical N inputs, critical N losses, environmental thresholds (see also Table 1), crop production (crop N uptake) and N management factors.

assumption of constant NUE may lead to an overestimation of required N inputs, as additional input in the form of synthetic fertilizer generally has a higher NUE than the current mix of N sources (which includes less-available N from manure). On the other hand, according to the law of diminishing returns, the yield response to N inputs (and thus NUE) declines with increasing N input (Bodirsky and Müller, 2014; de Wit, 1992). The net effect of both mechanisms depends on local circumstances, such as the presence of other yield-limiting factors; for this study we assumed that on average both effects compensate each other. This approach is supported by studies showing that diminishing yield responses to inputs mainly occur when yields approach 80% of their biophysical potential (van Ittersum et al., 2013; Van Ittersum and Rabbinge, 1997).

2.3. Opportunities to achieve crop production goals while respecting environmental thresholds for nitrogen

We explored possibilities for reconciling crop production goals with environmental thresholds for N by redistributing N inputs from areas with excess N to areas where thresholds are not exceeded (Section 2.3.1), by improving N management (Section 2.3.2), and by combining redistribution and N management improvements.

2.3.1. Opportunities for redistributing nitrogen inputs

Possibilities for maximising crop production while respecting environmental thresholds for N by redistributing N inputs were assessed as follows: First, in areas where environmental thresholds are exceeded ($Nin_{crit} \le Nin_{act}$), N inputs were reduced to the critical input level (Eq. 1, first row). Second, in areas where thresholds are not exceeded ($Nin_{crit} > Nin_{act}$), N inputs were increased up to the critical input level (Eq. 1, second row), but no further than the level required to obtain target yield at current NUE (in order to avoid unrealistically high N inputs in areas where environmental constraints are not limiting, Eq. 1, third row).

$$Nin_{redist} = \begin{cases} Nin_{crit} \text{ if } Nin_{crit} \le Nin_{act} \\ Nin_{crit} \text{ if } Nin_{act} < Nin_{crit} \le N_{tar} \\ Nin_{tar} \text{ if } Nin_{act} < Nin_{tar} < N_{crit} \end{cases} \quad (1)$$

Where:

Nin_{redist} = N inputs after redistribution to maximise crop production while respecting environmental thresholds (kg N ha^{-1} yr^{-1})
Nin_{crit} = Critical N inputs, i.e. maximum allowable input while respecting environmental thresholds for deposition, surface water and groundwater at current NUE (kg N ha^{-1} yr^{-1})

Nin_{act} = Actual (year 2010) N inputs (kg N ha^{-1} yr^{-1})
Nin_{tar} = N inputs required to obtain target yield at current NUE (kg N ha^{-1} yr^{-1})

Possibilities for redistribution were assessed for each threshold individually, and for all thresholds combined. Crop yield losses or gains from redistributing N inputs were calculated assuming a constant NUE.

2.3.2. Opportunities for improved nitrogen management

Possibilities for reconciling environmental thresholds for N with crop production goals by improved N management were assessed by deriving N management factors at which current or target crop yields can be obtained without exceeding thresholds for N losses (Fig. 1a, step 5). For the thresholds for surface water and groundwater, we focussed on NUE, while for the deposition threshold we manipulated the NH_3 emission fraction (EF). The NH_3 EF is in fact one of the factors determining overall NUE (a lower NH_3 EF implies a higher NUE, see Fig. 1b). However, as the overall NUE is also driven by other losses, the NH_3 EF is a more meaningful indicator in the context of reducing NH_3 emissions to respect deposition thresholds.

Nitrogen use efficiency is defined here as the ratio of crop N removal (by harvest or grazing) to total N input (sum of inputs from synthetic fertilizer, gross manure excretion, biosolids, biological N fixation, deposition and mineralization). The NH_3 EF is defined as the ratio of total NH_3 emissions to total N input for a defined N source. As 80% of European NH_3 emissions stem from manure, we derived necessary reductions in manure NH_3 EF while assuming a constant fertilizer NH_3 EF. The manure NH_3 EF was calculated by dividing total NH_3 emissions from housing systems, manure deposited by grazing animals and manure application by total N manure inputs to soils. This approach implicitly assumes that excretion in housing systems occurs in the same region where the manure is applied. While INTEGRATOR does consider manure export if application of all manure excreted within a region exceeds maximum application rates (250 kg N ha^{-1} yr^{-1} for the Netherlands and Denmark and 170 kg N ha^{-1} yr^{-1} for all other countries), this only occurs in 5% of the agricultural area, and thus this simplification does not substantially affect results.

For areas where critical NH_3 emissions are exceeded, we calculated the 'necessary' NH_3 EF for manure, i.e., the EF at which current or target yields can be obtained at critical NH_3 emissions (see Supplementary Text S2 for details on calculations). Low-emission manure application and adaptations to manure storage and housing systems can reduce NH_3 emissions by 20–80% (Oenema et al., 2009; Velthof et al., 2009). We assumed a 'feasible' minimum NH_3 EF of 0.15, based on a 40% reduction from the current average value of ~0.25, and a 'possible' minimum NH_3 EF of 0.10, based on a 80% reduction in NH_3 emissions from housing and manure application, and animal grazing during most of the year (grazing emissions vary mostly between 0.06 and 0.10, see De Vries et al., 2021).

For areas where critical N runoff to surface water or critical N leaching to groundwater are exceeded, we calculated the 'necessary' NUE, i.e., the NUE at which current or target yields can be obtained at critical N runoff or N leaching rates (see Supplementary Text S3 for details on calculations). At increased NUE, a given yield can be obtained at a lower N input, while the critical N input increases because a smaller fraction of N is lost to the environment. We assumed a 'feasible' maximum NUE of 0.75, which can be achieved by adopting well-proven mostly low-cost measures such as balanced N fertilization and precision farming, such as N application in the right amount, at the right time and right place (Bodirsky et al., 2014; Zhang et al., 2015). As some N losses to air and water are unavoidable, the 'possible' maximum NUE was set to 0.90 (EU Nitrogen Expert Panel, 2015).

3. Results

3.1. Required nitrogen inputs to obtain target yields

Averaged over all crops grown in the EU, derived target yields exceed actual (year 2010) yields by 26% (Table S2). The estimated gap between actual and target yield varies substantially between crop groups, with target yields exceeding actual yields by 16% for roots & tubers and by 34% for cereals (Table S2). The largest gaps are found in Baltic countries, Romania, Bulgaria and Portugal (Fig. 2b and Table S3).

For cereal crops, closing the gap between actual and target yields everywhere in the EU at current NUE would require a 36% increase in N inputs (from an average input rate of 131 to 179 kg N ha^{-1} yr^{-1}; Table S3). Considering all crops, closing yield gaps requires a 27% increase in N inputs (from 145 to 185 kg N yr^{-1}, data not shown).

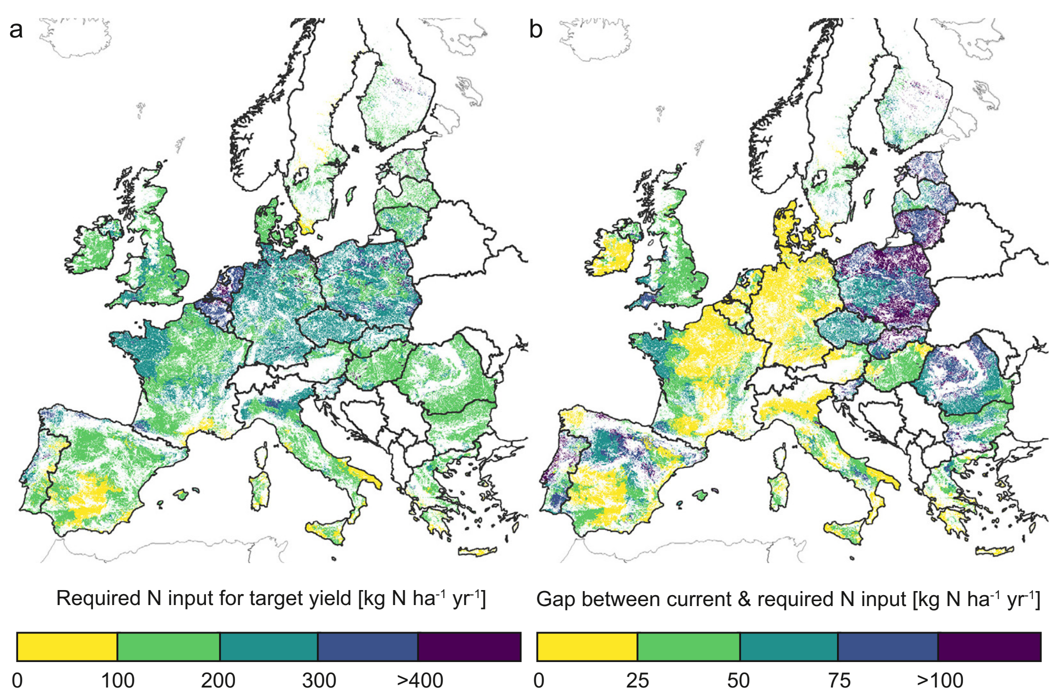

Fig. 2. (**a**) Regional variation in required nitrogen (N) input to obtain target yields (i.e., 80% of estimated water-limited crop yield potential, see Tables S2 & S3) for arable crops (all agricultural crops excluding grassland and fodder crops); (**b**) regional variation in the gap between actual (year 2010) N inputs and required N inputs ('N input gap'). White = no arable crops.

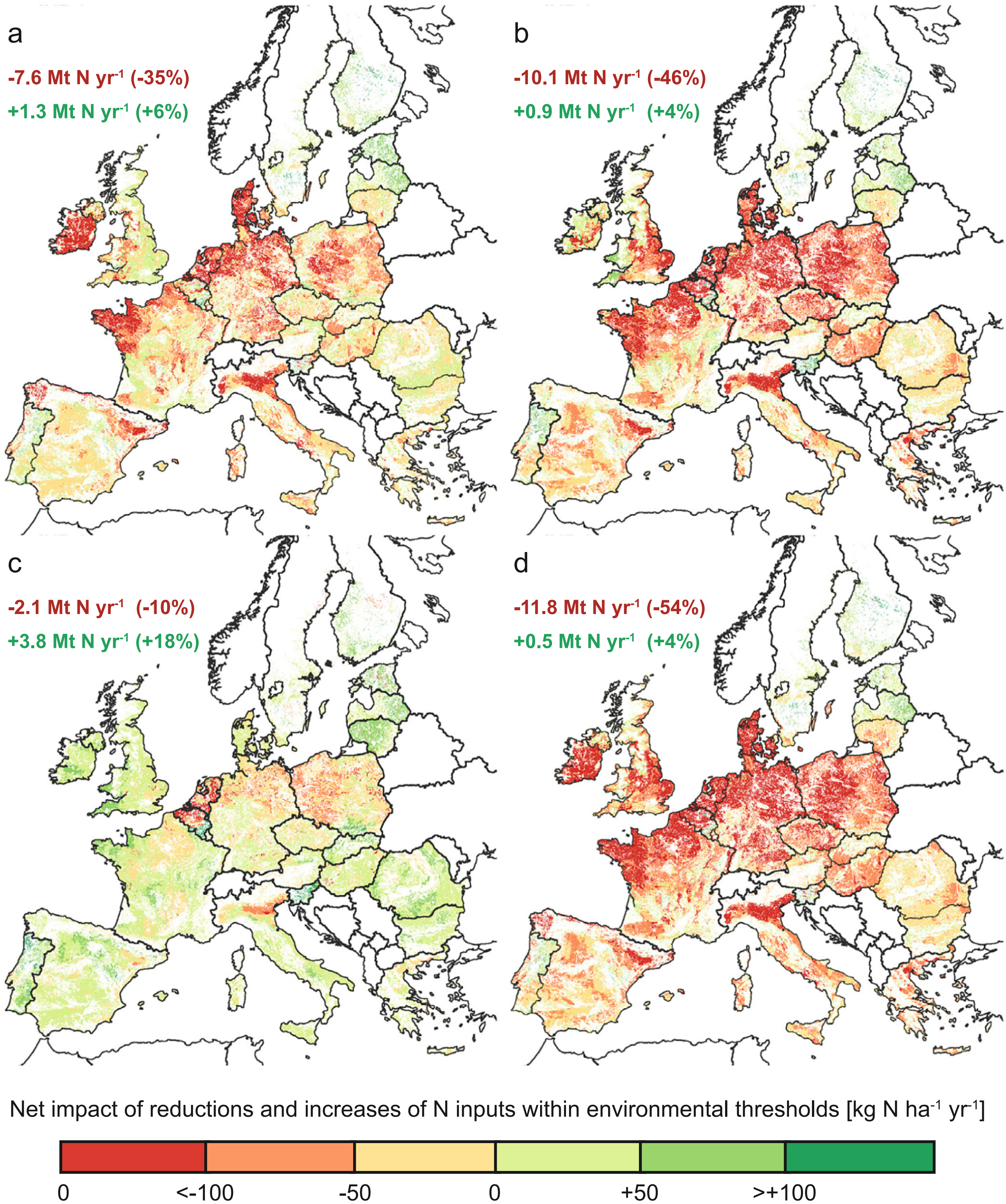

Fig. 3. Restrictions and opportunities for redistributing nitrogen (N) inputs on current agricultural land while respecting thresholds for (**a**) NH_3 emissions, (**b**) N runoff to surface water, (**c**) N leaching to groundwater and (**d**) all thresholds simultaneously. Red areas show required N input reductions to respect thresholds; green areas show allowable N input increases within thresholds. Numbers above maps show total required reductions (red) and allowable increases (green), percentages show change relative to current total N input (21.8 Mt. N yr^{-1} in 2010). Impacts of redistributing N inputs on crop production are shown in Table S6. White = no agricultural land.

Total required N input increases to achieve target yields for the three most important cereals (wheat, barley and rice) is 2.3 Mt. N yr^{-1}, which is close to the N uptake gap of 3.0 Mt. N yr^{-1} for these crops estimated by Schils et al. (2018). For most countries, N inputs need to increase by roughly the same ratio as the ratio of target yield to actual yield, though small differences occur due to regional variations in NUE (Table S3). For Portugal, for example, increasing cereal yields by 72% on average requires N inputs to increase by 89%, showing that the largest yield increases are projected in areas with below-average NUE (Table S3). The largest N input gaps occur in Poland, Romania, Baltic states, Northern Spain and Portugal (Fig. 2b and Table S3). Required N inputs to obtain target yields are highest in the Netherlands and Belgium (Fig. 2a & Table S3), but as input rates in these countries are already very high, the N input gap is small (Fig. 2b).

3.2. Reconciling environmental thresholds for nitrogen and crop production goals

3.2.1. Opportunities for spatially redistributing nitrogen inputs

At 2010 inputs, one or more N loss thresholds are exceeded on 85% of agricultural land, with stronger exceedances on arable land than on grassland (except for the NH_3 emission threshold in view of critical N deposition on natural areas, see Table S4). Increasing N inputs to levels required to obtain target yields would increase the area with exceedances to 89% (Table S4). Respecting N thresholds under current management requires reducing total annual N inputs by 7.6 Mt. N (35%) for the deposition threshold, 10.1 Mt. N (46%) for the surface water threshold, 2.1 Mt. N (10%) for the groundwater threshold, and 11.8 Mt. N (54%) to respect all thresholds simultaneously (Fig. 3 & Table S5). At constant NUE, these N input reductions would reduce annual crop production by 7–50%, depending on the threshold considered (Table S6). Crop production losses vary between crop groups: reducing N inputs to respect thresholds for N runoff to surface water, for example, leads to production losses of 74% for roots and tubers and only 19% for grass and fodder (Table S6b). For all criteria, relative reductions in N inputs to respect thresholds (Table S5) are slightly higher than associated relative reductions in crop yields (Table S6), indicating that crops and regions where the strongest reductions are required have a below-average NUE.

For most thresholds, increasing N inputs in areas where thresholds allow can only compensate a small share of the required N input reductions in excess areas . Only for the groundwater threshold, allowable increases (3.8 Mt. N yr^{-1}) exceed required reductions (2.1 Mt. N yr^{-1}), leading to a small net increase in N inputs of 8% (Fig. 3c & Table S5c). The net impact of redistributing N inputs also varies per crop group: while average N inputs increase for cereals and grass & forage, they decrease for roots & tubers, oil crops and other crops (Table S5c). For the deposition threshold the net impact of redistribution on N inputs is −29%, and for the surface water threshold −42% (Fig. 3a,b & Table S5a,b). If all thresholds need to be respected, the options are even more limited: N inputs can safely increase by only 0.5 Mt. N yr^{-1} (2%), hardly compensating for the needed reductions of 11.8 Mt. N yr^{-1} (54%) (Fig. 3d & Table S5d). At current NUE, crop production that can be obtained while remaining within environmental thresholds is thus only 172 Mt. yr^{-1} (−56%) for grains, 123 Mt. yr^{-1} (−75%) for roots & tubers, and 283 Mt. yr^{-1} (−37%) for grass and fodder crops (Table S6d).

The spatial pattern in reductions needed to respect thresholds varies between the three thresholds (Fig. 3), though all thresholds require strong reductions (>100 kg N ha^{-1} yr^{-1}) in hotspot regions with high inputs such as Germany, Benelux, the UK, Ireland, and Brittany in France. For Ireland, large reductions are required to respect critical NH_3 emission thresholds (Fig. 3a), but N inputs can increase while still respecting thresholds for N runoff and N leaching (Fig. 3b,c), whereas the opposite is true for large parts of the UK. The highest potential for increasing N inputs within thresholds is found in Estonia, Latvia and Portugal (Fig. 3d).

3.2.2. Opportunities for improved nitrogen management

On about a third of agricultural land, NH_3 emission thresholds are respected at current N inputs (Table 2**, a-i**), while an additional 13% of agricultural land can remain within thresholds without yield losses by reducing the NH_3 EF for manure, assuming a minimum of 0.15 ('beast feasible', Table 2, a-ii). Assuming a possible reduction of manure NH_3 EF to 0.10 ('best possible'), threshold exceedance can be reversed without yield losses on 26% of the agricultural area (Table 2, a-ii). To respect thresholds, the average NH_3 EF for manure needs to decrease from 0.27 to 0.20 (assuming a minimum EF of 0.15) or from 0.26 to 0.16 (assuming a minimum EF of 0.10; Table 2, a-ii). Conversely, this implies that in 41–54% of the agricultural area, reducing NH_3 EF is not sufficient to respect NH_3 emission thresholds without yield losses (Table 2, a-iii & Fig. S2a). These areas are mainly situated in the Netherlands, Northern Germany, Poland, Italy, Ireland, Brittany in France, and Spain (Fig. 4a). Low necessary NH_3 EFs occur both in regions with vulnerable ecosystems (low critical N loads) and/or in regions with high current N inputs, yields and livestock numbers. The strongest absolute reductions in NH_3 EF (reductions by >0.30) are needed in parts of Eastern Germany, Poland, Italy and Spain (Fig. 4d). In Ireland, despite low absolute needed reductions (~ 0.05, Fig. 4d) the necessary EF is mostly below the 'best possible' minimum of 0.10 (Fig. 4a), as current EFs are only around 0.15 (due to high prevalence of grazing systems with relatively low NH_3 EFs).

Table 2
Share of agricultural area and current / necessary N management factors for (i) land where environmental threshold is not exceeded, (ii) land where threshold is exceeded but current crop production can be obtained within thresholds by (**a**) reducing NH_3 EF to minimum = 0.15 (best feasible) or 0.1 (best possible) or by (**b,c**) increasing NUE to a maximum of 0.75 (best feasible) or 0.90 (best possible); (iii) land where current crop production and thresholds cannot be reconciled . Current and necessary NH_3 EF / NUE for each of the three categories, and (iv) the average across all land.

	(i) Threshold not exceeded	(ii) Threshold exceeded, reconciliation possible at improved management[a]		(iii) Threshold exceeded, reconciliation not possible by improved management		(iv) Overall
(a) Deposition		$EF_{min} = 0.15$	$EF_{min} = 0.10$	$EF_{min} = 0.15$	$EF_{min} = 0.10$	
Share of area	33%	13%	26%	54%	41%	100%
Current NH_3 EF	0.22	0.27	0.26	0.25	0.25	0.24
Necessary NH_3 EF	–	0.20	0.16	0.06	0.04	0.13
(b) Surface Water		$NUE_{max} = 0.75$	$NUE_{max} = 0.90$	$NUE_{max} = 0.75$	$NUE_{max} = 0.90$	
Share of area	26%	25%	59%	49%	15%	100%
Current NUE	0.74	0.50	0.58	0.65	0.68	0.64
Necessary NUE	–	0.64	0.75	0.87	0.95	0.78
(c) Groundwater		$NUE_{max} = 0.75$	$NUE_{max} = 0.90$	$NUE_{max} = 0.75$	$NUE_{max} = 0.90$	
Share of area	82%	18%	18%	1%	0%	100%
Current NUE	0.69	0.49	0.49	0.49	*n.a.*	0.65
Necessary NUE	–	0.57	0.58	0.78	*n.a.*	0.67

[a] For the deposition threshold, reconciliation is possible if the manure NH_3 emission fraction at which current crop production can be obtained without exceeding critical NH_3 emissions is higher than 0.15 (for 'best feasible' N management) or 0.10 (for 'best possible' management). For the surface water and groundwater thresholds, reconciliation is possible if the NUE at which current crop production can be obtained without exceeding critical N runoff or leaching is lower than 0.75 (for 'best feasible' N management) or 0.90 (for 'best possible' management).

On a quarter of agricultural land, thresholds for N runoff to surface water are currently not exceeded (Table 2, b-i), while on an additional 25% thresholds can be respected without yield losses if NUE is increased to the 'best feasible' maximum of 0.75, and on an additional and 59% if NUE is increased to the 'best possible' maximum of 0.90 (Table 2, b-ii). On land where thresholds can be respected without yield losses by increasing NUE, average NUE needs to increase from 0.50 to 0.64 (for a maximum NUE of 0.75) or from 0.58 to 0.75 (for a maximum NUE of 0.90; Table 2, b-ii). On 49% of the agricultural area, increasing NUE to 0.75 is not sufficient to respect thresholds for N runoff while maintaining current crop production, while this is only 15% at a maximum NUE of 0.90 (Table 2, a-iii & Fig. S2b). Areas where increasing NUE to 0.90 is not sufficient to reconcile environmental goals and current production levels are mainly situated in Eastern Germany, Eastern UK and Northern France (Fig. 4b). Those areas generally either have a low precipitation surplus (low runoff volume), a high share of land used for agriculture (leading to limited dilution of agricultural runoff by runoff from natural land) and/or high current N uptake (leading to high absolute losses even at a high NUE). The highest absolute NUE increases necessary to respect thresholds for N runoff without crop production losses occur in the Netherlands, Belgium, Greece, and Poland (Fig. 4e and Fig. 5a).

For groundwater, small increases in average NUE (from 0.65 to 0.67) are sufficient to respect thresholds for N leaching without yield losses on virtually all agricultural land (Table 2, c-ii, Fig. 4c & S2c). Where increasing NUE is necessary to respect leaching thresholds, these necessary increases are mostly <0.10, except for small areas in the Netherlands, Belgium, South/Central France and Northern Italy (Fig. 4f).

Average country-level NUEs necessary to reconcile current yields with N thresholds vary from 0.61 for Estonia to 0.86 for Sweden for the surface water threshold (Fig. 5a), and from 0.17 for Bulgaria to

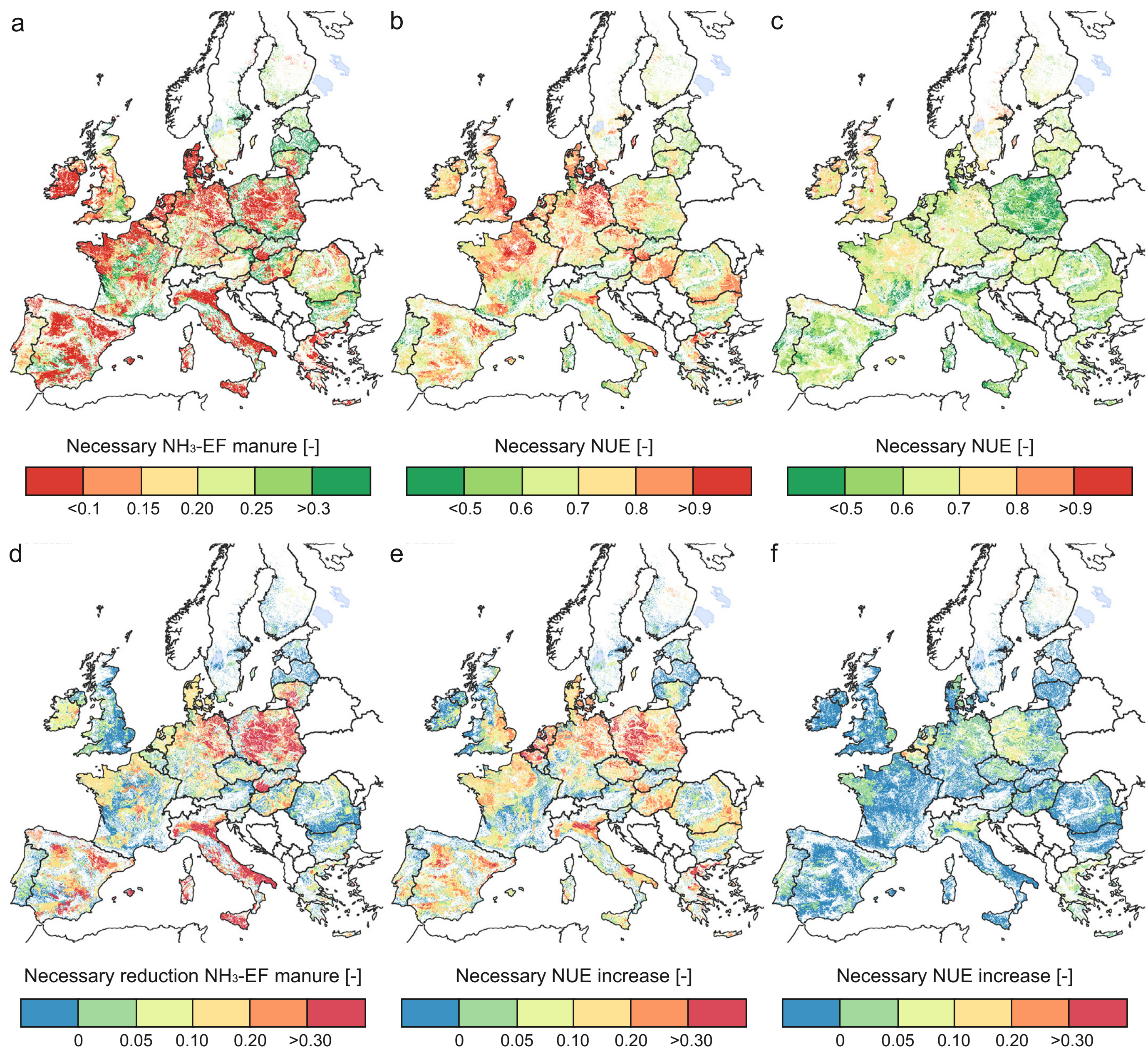

Fig. 4. Regional variation in necessary improvements in N management factors to obtain current yields while respecting environmental thresholds. (**a**) Necessary NH_3 EF for manure to obtain current yields while respecting thresholds for NH_3 emissions, (**b**) necessary NUE to obtain current yields while respecting thresholds for N runoff to surface water, (**c**) necessary NUE to obtain current yields while respecting thresholds for N leaching to groundwater, (**d–f**) necessary changes in NH_3 EF / NUE relative to current (year 2010) values. Corresponding results for target yields are shown in Fig. S3.

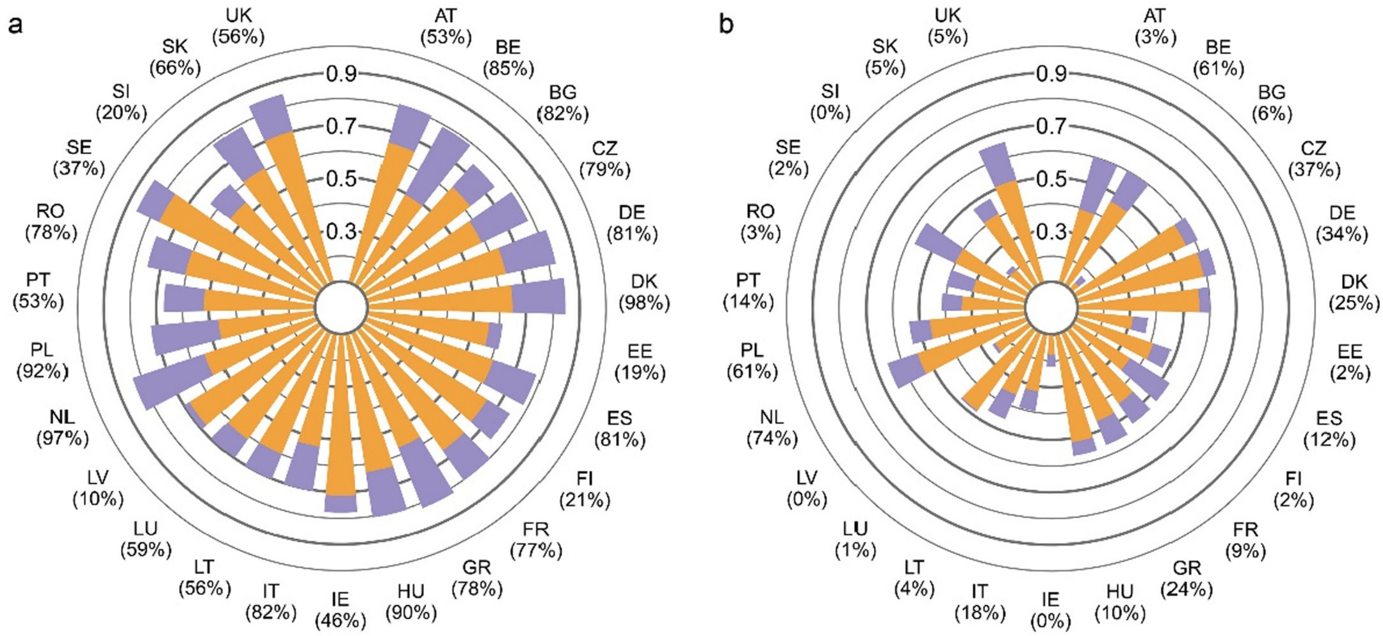

Fig. 5. Actual (year 2010) nitrogen use efficiency (NUE) of crop production in areas where thresholds are exceeded (orange), and necessary NUE to respect thresholds without yield losses (purple) for 25 EU countries. (**a**) N runoff to surface water and (**b**) N leaching to groundwater. Percentages in brackets show share of agricultural area where threshold is exceeded (and for which current and necessary NUEs are thus shown).

0.66 for the UK for the groundwater threshold (Fig. 5b). For all countries, average NUEs necessary to comply with the surface water threshold are higher than for the groundwater threshold. Several countries where N leaching thresholds are exceeded on only a small fraction of agricultural area have very low current average NUEs in these areas (<0.30, Fig. 5).

3.2.3. Combining redistribution and improved nitrogen management

Fig. 6 shows to what extent improved N management, alone or in combination with spatially redistributing N inputs, can reconcile crop production with environmental thresholds. At current NH_3 emission fractions, 68% of current crop production can be obtained within safe limits for NH_3 emissions (Fig. 6b & Table S6a). Gradually reducing the manure NH_3 EF only slightly increases this share to 75% at the 'feasible' minimum of 0.15 and 80% at the 'possible' minimum of 0.10 (Fig. 6b). If both NH_3 EF is reduced and N inputs are increased in regions where critical NH_3 emission rates are not exceeded, this share increases to ~95% (Fig. 6b, dashed line).

At current NUE, only 58% of current crop production can be obtained within safe limits for N runoff to surface water, but almost 100% can be obtained if NUE is increased to 0.8 in combination with increasing N inputs and yields where this is possible within thresholds (Fig. 6c). For groundwater, N inputs and crop production are not strongly constrained by complying with thresholds for N leaching, and thus NUE improvements have limited impact on the share of current crop yield that can safely be obtained (Fig. 6d). At a NUE of 0.75, N inputs can even be increased to the level required to obtain target yields without exceeding N leaching thresholds almost everywhere in Europe (Fig. 6d & Fig. S4d).

The potential of different strategies to reconcile environmental objectives with crop production varies between countries (Fig. S4). Most countries can obtain between 33 and 67% of current crop production while respecting thresholds for N runoff to surface water at current NUE (Fig. S4a-i), while this percentage is between 67 and 100% for most countries if NUE is increased to 0.75 (Fig. S4b-i). All countries can obtain current yields while respecting thresholds for N leaching to groundwater at a NUE of 0.75 (see Fig. S4b-ii).

4. Discussion

4.1. Plausibility of the results

In this section, we discuss the plausibility of several assumptions underlying the calculations. For an additional discussion of uncertainties related to N budgets in INTEGRATOR and the assumptions used in the calculation of critical N inputs, see De Vries et al. (2021).

4.1.1. Plausibility of calculated nitrogen use efficiencies

Country-level NUE estimates from INTEGRATOR were compared to estimates from Lassaletta et al. (2014a), for arable crops only) and EUROSTAT (2020) (Table S7). For most countries, values agree reasonably well (deviations between −8 to +18% for Lassaletta et al. (2014a) and between −18 and + 25% for EUROSTAT). For Bulgaria, Spain, the Netherlands and Sweden, NUE estimates from Lassaletta are 32–47% lower than our estimates, mainly because Lassaletta uses higher N input rates for these countries. A possible explanation is that they over-estimate manure application to cropland, as they only use one value for the fraction of manure applied to croplands for the whole EU, while INTEGRATOR uses country-specific values varying from 5 to 100% (see De Vries et al., 2021). EUROSTAT NUE estimates are substantially (20–30%) lower for Finland, Greece, Luxembourg and UK, mainly because estimated N uptake is lower, and 48% higher for Romania due to both a lower estimated input and a higher estimated uptake (Table S7).

Nitrogen use efficiencies needed to respect environmental thresholds for runoff to surface water without yield losses are in good agreement with the 'desired range' for NUE defined by the EU Nitrogen Expert Panel (2015), while the derived N output at target yields provides support for the postulated minimum productivity target by the Expert Panel (Fig. 7). For the current (year 2010) situation, four out of 25 countries had average NUEs below the minimum target of 0.50, while N removal by cereals was below the suggested minimum productivity target of 80 kg N ha^{-1} yr^{-1} in more than half of all countries (Fig. 7a). Estimated necessary NUEs to reconcile

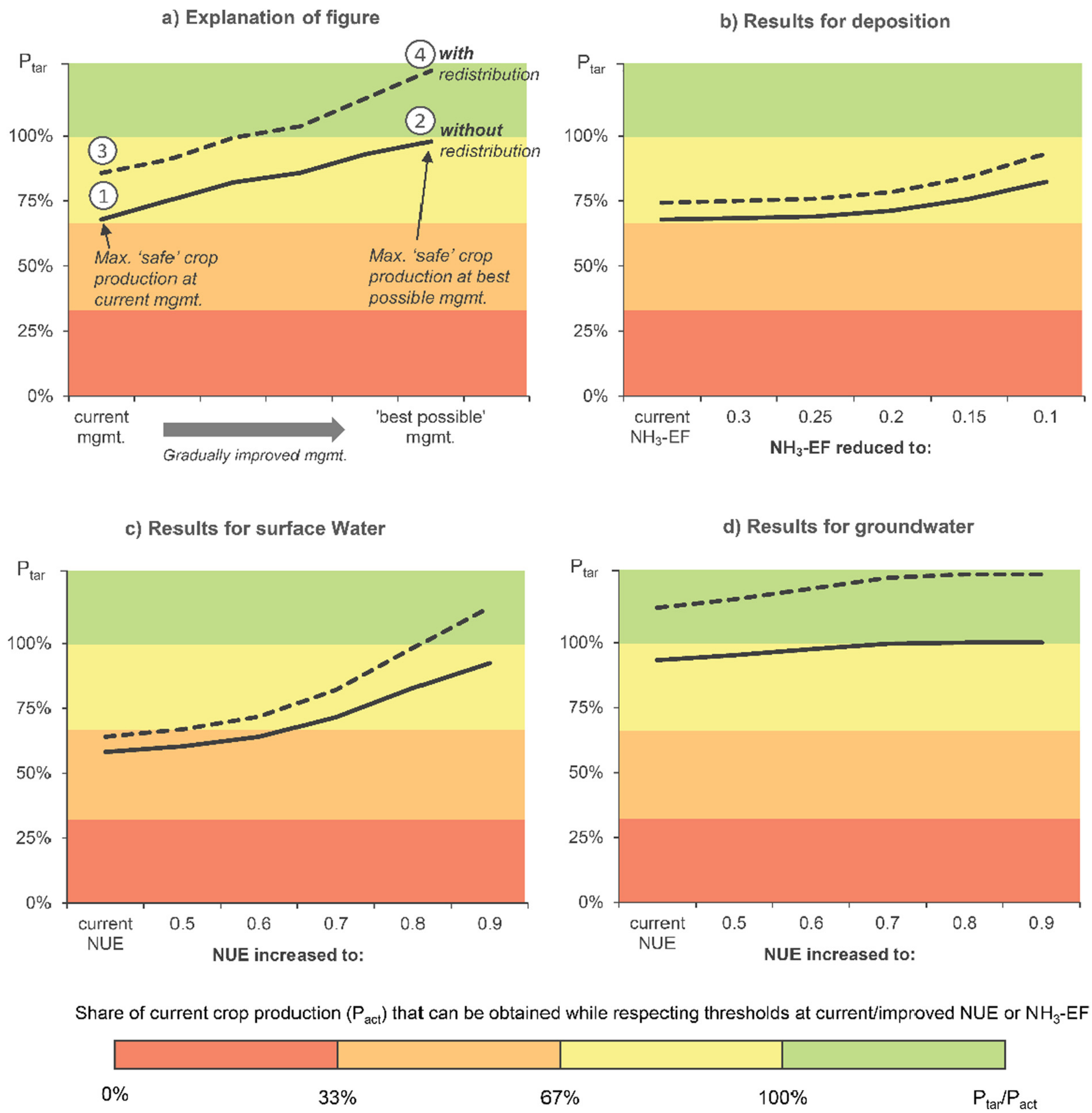

Fig. 6. Maximum crop production that can be obtained while respecting environmental thresholds at current or gradually improved N management factors. Panel (**a**) illustrates the figure concept; panels (**b**)-(**d**) show results for three thresholds. P_{act} = current crop production, P_{tar} = crop production at target yields. (**a**) In this hypothetical example, only two thirds of P_{act} can safely be obtained within threshold at current N management (point ①), while this share increases to almost 100% at 'best possible management' (②). If N inputs are redistributed to regions where this is possible within thresholds (dashed line), ~80% of P_{act} can be obtained within thresholds at current management (③). If redistribution and management improvements are combined, crop production can be increased to P_{tar} without exceeding thresholds (④). (**b**)–(**d**) Maximum crop production (expressed as share of P_{act}) that can be obtained while respecting thresholds at current and gradually reduced manure NH_3 EF (b), and at current and gradually increased NUE (c,d).

crop production with environmental thresholds are above the minimum NUE target of 0.50 for all countries (Fig. 7b). Moreover, at our estimated target level for N input for closing yield gaps and related N output, all countries except one are above the minimum productivity target of 80 kg N ha^{-1} yr^{-1}, while NUEs are between 0.66 and 0.90 (Fig. 7c).

4.1.2. Uncertainties and limitations in calculating critical N inputs and required nitrogen use efficiencies and ammonia emission fractions

In this study, we used a uniform threshold for N concentration in runoff to surface water, similar to previous global studies that used critical N concentrations to assess N water footprints (Mekonnen and Hoekstra, 2015, who used a threshold of 2.9 mg N l^{-1}) or required reductions in agricultural N loads (e.g., Gerten et al., 2020 and Yu et al., 2019; who both used a threshold of 1 mg N l^{-1}). However, such a uniform threshold does does not reflect variation in ecological criteria for different surface water types (e.g., highland or lowland lakes, calcareous or siliceous rivers). Nutrient criteria for surface water used to support 'good ecological status' under the Water Framework Directive vary widely across water body types and across Member States (Poikane et al., 2019). For example, median values for N concentration thresholds in lakes and rivers range between 0.7 and 4.0 mg N l^{-1}, and vary substantially even within shared water body types due to different approaches used to set threshold N concentrations. Some Member States do not define criteria for N concentrations in rivers of lakes at all (Poikane et al., 2019), based on the widely held belief that

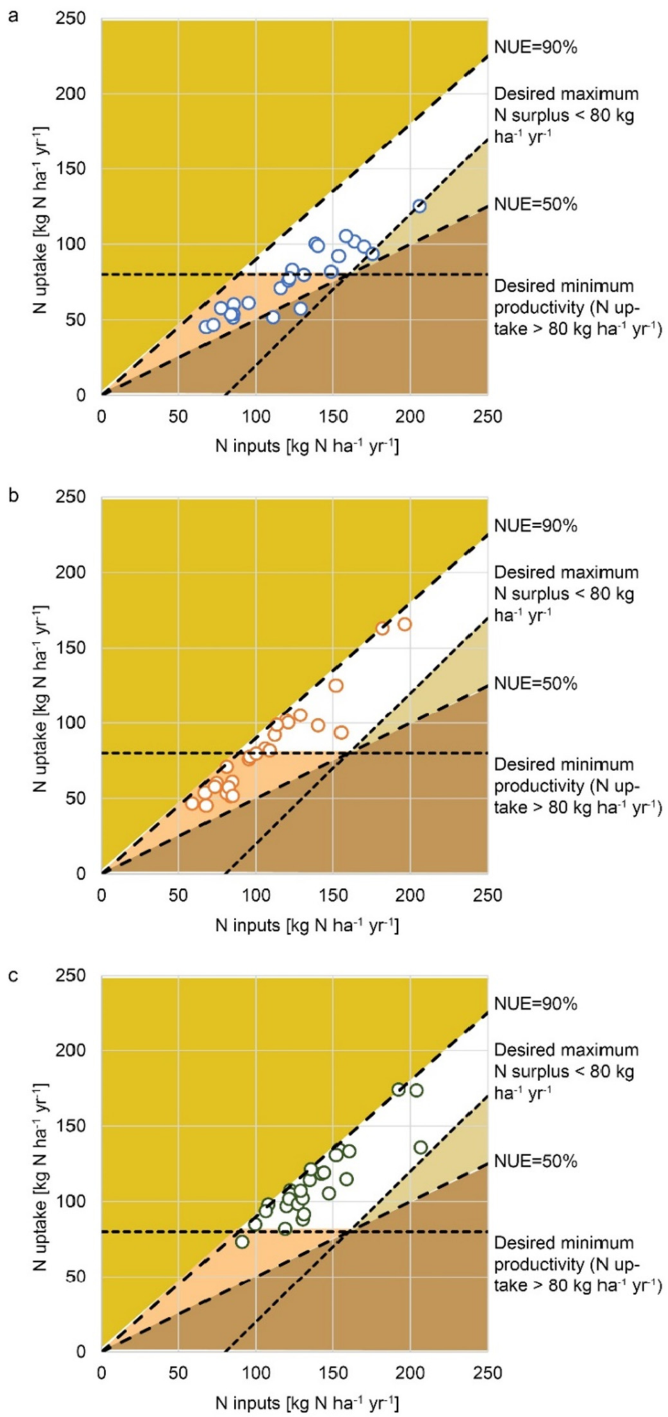

Fig. 7. Country-average nitrogen (N) inputs and N uptake for cereal crops in the EU from INTEGRATOR, following the graphical representation proposed by the EU Nitrogen Expert Panel (2015), (**a**) for the current situation, (**b**) at necessary NUE to remain within thresholds for N runoff to surface water and (**c**) at required N inputs to obtain target yields and necessary NUE to remain within thresholds for N runoff to surface water. The white area delineates the desired range for NUE, N surplus and productivity. In panel (a), Belgium (N input = 356 kg N ha^{-1} yr^{-1}; N uptake =166 kg N ha^{-1} yr^{-1}; NUE = 0.46) and the Netherlands (N input = 328 kg N ha^{-1} yr^{-1}; N uptake =163 kg N ha^{-1} yr^{-1}; NUE = 0.50) fall off the scale.

phosphorus (P) is the primary limiting nutrient in freshwater whereas N is most limiting in coastal waters (Schindler et al., 2016). However, recent evidence shows that N often equally limits primary production in lakes and that reducing both N and P is required to achieve good ecological status (e.g., Dolman et al., 2016; Elser et al., 2007; Paerl et al., 2016).

The threshold for N concentration in *runoff* to surface water used in this study is only a proxy for N concentration in surface water itself, which is also affected by N inputs from other sources (e.g., sewage), legacy N related to fertilization in the past (Bouraoui and Grizzetti, 2014; Van Meter et al., 2016), and removal and retention processes in groundwater, riparian areas and surface waters. We assumed that the effect of ignoring N load from non-agricultural sources roughly compensates for neglecting N removal processes in water bodies (see also De Vries et al., 2021, for further discussion). Further improving the approach could entail using basin-level targets for 'good ecological status' instead of one flat-rate target for all water bodies, as well as including a more detailed representation of other sources contributing to freshwater N pollution. Such detailed assessments have been performed for e.g., the Netherlands (Groenendijk et al., 2016) and the German region of Mecklenburg-Vorpommern (Kunkel et al., 2017). However, obtaining the required data at European level may prove challenging.

Similar to N concentrations in surface water, N deposition on terrestrial ecosystems is also affected by non-agricultural emissions, mainly NO_x emissions from transport and industry. Our approach assumes that these emissions are reduced proportionally with agricultural NH_3 emissions. In reality, in certain situations mitigating N losses from other sources may be easier to achieve, thus reducing the need for changing agricultural practices (see De Vries et al., 2021, for further discussion).

Impacts of N input changes on yields in this study is assessed assuming a constant NUE, i.e. NUE changes linearly with N inputs. Other studies proposed an asymptotic function to describe the relationship between N inputs and yields (N uptake) (Lassaletta et al., 2016, 2014a; Mueller et al., 2014), where yields show a decreasing response to N inputs at increasing fertilization rates. Compared to these studies, our study may underestimate marginal reductions in N losses from input reductions at high inputs as well as N losses caused by increasing current to target N inputs. NUE response to N inputs also strongly depends on other yield-limiting factors (de Wit, 1992), and alleviating these factors may increase NUE without affecting N inputs.

Finally, the assumed values for 'best feasible' and 'best possible' NUE and NH_3 EF used to estimate crop production shares that can be reconciled with N thresholds through improved management are rough estimates. Opportunities to increase NUE or reduce NH_3 EF are affected strongly by local circumstances, such as climate, soil and crop type, manure management system and the availabiltiy of technologies such as manure processing. Where reducing the NH_3 EF of manure is not sufficient to comply with NH_3 emission thresholds, farmers may also substitute manure by nitrate fertilizers, however, this implies that livestock numbers need to be reduced or excess manure needs to be disposed of.

4.2. Redistributing nitrogen inputs

Several studies showed that redistributing N inputs from excess areas to areas where thresholds are not exceeded can reduce N losses substantially while maintaining crop and livestock production. Liu et al. (2016) used a global crop growth model at high spatial and temporal resolution to assess N losses and yields for wheat, rice and maize under different fertilization schemes. They found that distributing global N inputs homogenously over all cropland would decrease N losses by 11% and increase yields by 7%. If, in addition to this redistribution, N was applied continuously throughout the growing season, global N losses decreased by 23% (21% for Europe) and crop production increased by 10% (16% for Europe). Mueller et al. (2012) used regression-based nutrient-yield response curves to assess the global potential for closing yield gaps while reducing nutrient overuse, and found that global N input could be reduced by 28% without yield losses for major cereals. In a follow-up study, Mueller et al. (2014) used a trade-off frontier to reallocate global N inputs to maximise crop production and minimize losses. They found that under optimal allocation, 50% less N fertilizer would be needed to achieve production levels for major cereal crops. For Europe, such an 'optimal' allocation implied redistributing N inputs from Western to Eastern Europe.

All previous studies, however, optimize for overall reductions in N losses without considering region-specific environmental vulnerabilities. While in line with previous studies (see also e.g. Pradhan et al., 2015) we found large potentials to close yield gaps by increasing N fertilization in Eastern Europe, respecting environmental boundaries does not allow for such increases at current NUE. In large regions of Poland, Czech Republic and Romania, for example, thresholds for N pollution are already exceeded and increasing N inputs to close yield gaps would further excarbate N-related problems (e.g., Fig. 3 & Fig. 4).

For the livestock sector, van Grinsven et al. (2018) showed that relocating pig production in the EU could reduce external costs of N pollution and the exceedance of critical N deposition, especially when combined with best-management practices. They also note that such relocations are likely to meet socio-economic barriers, such as national economic interests, stakeholder objections or a lack of infrastructure (van Grinsven et al., 2018). While this equally applies to a redistribution of crop production and associated N inputs, the need to comply with targets set under the Green Deal and other EU directives will likely provide strong policy incentives to reduce N pollution and may stimulate investments that are necessary to overcome such barriers.

4.3. Nitrogen use efficiency targets in policies and scientific literature

Partially as a result of European and national policies aimed at reducing N pollution, average farm-level NUE in European has increased since the 1990s (Van Grinsven et al., 2014; Velthof et al., 2014), though not sufficiently to meet environmental targets (EEA, 2019). To date, however, most policies lacked integration and generally regulated only one type of N compound (Brink et al., 2011), for example nitrate in the Nitrates Directive (EC, 1991) or NO_x and NH_3 emissions in the National Emission Ceilings Directive (EC, 2001). The recently launched "Farm to Fork Strategy" (FFS) as part of the European Green Deal represents a shift away from single-issue policies towards a more holistic approach aimed at reducing all adverse N impacts simultaneously. The FFS has set the Europe-wide target to reduce nutrient losses by 50% and fertilizer use by 20% (European Commission, 2020). Achieving these targets while maintaining current crop production implies an increase in average NUE from currently 0.63 to 0.77 (own calculations). Zhang et al. (2015) estimated target NUEs per world region to meet 2050 food demand while remaining within safe planetary boundaries for N losses, and derived an NUE target of 0.75 for the EU, while Sutton et al. (2013) proposed 0.70 as a long-term target for crop-system NUE. These values agree well with our derived average 'necessary' NUEs to achieve water quality targets at current or target crop production of 0.67 (groundwater) or 0.78 (surface water), see Table 2.

However, no previous study has differentiated the goals by region by accounting for variation in current agricultural systems and in environmental vulnerabilities. By doing this, we show that necessary improvements in N management vary greatly between regions, and that averaged targets thus have limited usefulness. Even if all regions achieve an average target NUE of 0.75, thresholds for N runoff to surface water would still be exceeded on half of all agricultural land (Fig. S2b). Average necessary NUEs vary between countries (Fig. 5) as well as within countries (Fig. 4). In some regions, necessary NUEs exceed 0.90, a level that is difficult, if not impossibe, to obtain (see also Section 4.4). Very high needed NUEs to avoid N impacts were also found for China, where respecting critical N loads to surface water while maintaining crop production required NUE to increase to ~87% (from currently 36%) for the whole of China, and to >95% for several provinces (Yu et al., 2019).

4.4. Approaches to increase nitrogen use efficiency

The most practical way to improve NUE is by tuning the rate, timing, method and type of N application (Snyder, 2017), with the goal to better match N supply with crop demand. Measures to increase NUE can be taken by farmers voluntarily (e.g., to save costs on fertilizers, Houlton et al., 2019), but are often legally required through policies. Policy measures such as maximum N manure application rates (EC, 1991), mandatory incorporation of manure (e.g. in Denmark; Kronvang et al., 2008) or prohibiting manure application during the winter period (Liu et al., 2018) have greatly increased NUE in many European countries.

Several studies have assessed possibilities to increase cropping system NUEs. However, comparison of achievable NUEs with necessary NUEs reported in this study is complicated by different definitions of NUE in the literature. An assessment of options to increase NUE in European farming systems found that implementation of a multitude of technical options can increase NUE to max. 82% (Northern Europe) and 92% (Southern Europe), but the study only considered inputs of 'virgin' N from outside the agricultural system (Hutchings et al., 2020). Nitrogen use efficiencies reported in field trials are often expressed as partial factor productivity (PFP_N). PFP_N is defined as crop uptake divided by fertilizer inputs, and thus PFP_N values are lower than values for NUE that also consider inputs of non-fertilizer N sources (Balasubramanian et al., 2004). Extensive field trials in China have shown that integrated soil management strategies can increase PFP_N of grain cropping systems by 30–45%, to levels of 60% (rice), 78% (wheat) and 67% (maize) (Chen et al., 2014). The PFP_N achieved by the best-performing farmers in a certain region can also be seen as a target value for PFP_N increases. Cui et al. (2014) for example found that grain farmers in China achieved PFP_N of ~40% on average, while best-performing farmers achieved 68–80%. Achievable NUEs also depend on the mix of input sources, e.g. for manure, only 50% of the N is immediately available for crop uptake on average (Webb et al., 2013), though manure use can also increase NUE by improving soil organic carbon content and structure and reducing soil acidification (Duan et al., 2011).

Approaches to increase NUE which are targeted on industry are potentially easier to implement as a smaller number of actors is involved (Kanter and Searchinger, 2018). Increasing sale shares of enhanced-efficiency fertilizers, such as fertilizers amended with N inhibitors or slow-release fertilizers could on average increase NUE while maintaining yields (Abalos et al., 2014; Chen et al., 2018; Krol et al., 2020). Mandatory targets for the fertilizer industry regarding the production, efficiency and sales of enhanced-efficiency fertilizers could thus increase NUE while avoiding high transaction costs associated with regulating millions of farmers (Kanter and Searchinger, 2018).

4.5. Beyond farm-level nitrogen use efficiency

In regions where best possible improvements in N management are insufficient to respect N pollution thresholds (red areas in Fig. 4), environmental targets can only be achieved at reduced N inputs, even if this leads to lower agricultural output. For example, our results show that even at improved N management, N deposition cannot be reduced to critical loads while maintaining current agricultural production levels everywhere, which implies that livestock numbers need to be reduced. This discussion is also at the core of the Dutch 'nitrogen crisis' (Stokstad, 2019), where a high court ruled that the Dutch government needs to take immediate action to reduce NH_3 and NO_x emissions to reverse widespread exceedance of critical loads on terrestrial ecosystems, and to comply with the requirements of the Birds and Habitat Directive. De Vries et al. (2020) estimated that N emissions have to be reduced by 25%, 50% and 80%, respectively, to protect 50%, 75% and 95% of all Dutch Natura 2000 sites (i.e., reach critical N loads), although required emission reductions are slightly lower if reductions focus specifically on NH_3 sources near sensitive terrestrial ecosystems. While reducing NH_3 emission by 25% may be possible with technical measures, more ambitious targets can only be met by also reducing the numbers of cows, pigs and chicken (livestock-related emissions alone account for 75% of Dutch NH_3 emissions, Oenema, 2019).

The avoided costs to society by reducing N pollution by extensification could outweigh the lost income from reduced crop production (van Grinsven et al., 2015). Farmers could be compensated for losses in crop production through price premiums or receive compensation for farm closure. Removing N from the environment in areas with excess N runoff where NUE increases cannot sufficiently mitigate agricultural losses is another way of reducing environmental pressure (Houlton et al., 2019). Examples are wetland and riparian restoration projects aimed at filtering N runoff and leaching flows in landscapes.

This study only analysed the potential to restore a safe operating space for N without losing crop production by increasing NUE and redistributing N inputs on *existing* agricultural land. However, further reductions in N losses without affecting agricultural output may be possible by also allowing for a redistribution of cropland within certain constraints, as shown by previous studies (e.g., Gerten et al., 2020; Heck et al., 2018). Land conversion does not always have adverse effects, for example in the case of restoring abandoned croplands with a low value for biodiversity, which is widespread in Eastern Europe (Alcantara et al., 2013). In each case, negative impacts of land conversion in Europe always have to be weighed against potential impacts of land conversion in high-biodiversity areas in other world regions that might indirectly be triggered by sparing land in Europe as long as global demands remain unchanged (Fuchs et al., 2020). Concerns have been raised that reductions in the use of agricultural input and land proposed by the European Farm to Fork and Biodiversity Strategies may lead to reductions in crop production, possibly driving up global good prices (Beckman et al., 2020). This may in turn drive expansion of agricultural production in other regions, possibly resulting in impacts that outweigh the benefits of more sustainable production in Europe from a global conservation perspective (Fuchs et al., 2020).

As measures taken at the farm level are not sufficient to respect N thresholds and maintain production everywhere, targeting other levels of the food chain to improve overall food-chain NUE is needed to reduce N losses, as has been pointed out by numerous studies (e.g., Bodirsky et al., 2014; Grizzetti et al., 2013; Springmann et al., 2018; Westhoek et al., 2014). Such strategies include reducing food waste and the share of animal protein in diets, and have in common that they reduce the need for crop production and thus associated N inputs and losses. This is also recognized in the FFS, which includes commitments to reduce food waste and inform consumers to support sustainable food choices (European Commission, 2020). The FFS, however, does not explicitly mention targets for reducing consumption of animal products, even though two thirds of EU cereal production (Kelly, 2019) and 80% vegetal protein (Lassaletta et al., 2016) is used as feed for livestock. Reducing consumption of animal products in Europe has many co-benefits next to reducing N losses, such as reducing greenhouse gas emissions (Leip et al., 2015), reducing Europe's reliance on imported N in feedstuffs (Lassaletta et al., 2014b) and health benefits (Willett et al., 2019).

5. Conclusions

Maintaining or increasing Europe's crop producing while meeting targets to improve water quality and halt biodiversity loss requires a mix of strategies. We found that increasing N inputs to close yield gaps (ignoring environmental constraints) could increase European crop production by about 30%. However, as critical N losses are already exceeded on most agricultural land, little of this additional crop production can be realized within safe environmental limits for N losses. Remaining within thresholds for N deposition on terrestrial (semi)natural ecosystems and N concentrations in surface water and groundwater at current NUE requires reducing N inputs by ~50%, with large regional differences. Reducing manure NH_3 EFs or increasing NUE to best possible values (0.10 for NH_3 EF for manure and 0.90 for NUE) allows to respect N pollution thresholds without yield losses in 44% of the area where one or more thresholds are exceeded, and can reconcile approximately 80% of current crop production with N thresholds. Increases in NUE and reductions in NH_3 EF can be achieved by improved agricultural management, such as applying 4R strategies for fertilizer and manure application, better manure management, or by crop and livestock breeding. In hotspot regions, however, required improvements in N management to avoid environmental impacts at current production levels are beyond what is considered technologically feasible. Therefore, to conserve our environment, redistribution of N inputs and improved N management need to be complemented by other strategies, such as reducing crop demand by cutting food waste and animal protein consumption.

CRediT authorship contribution statement

Lena Schulte-Uebbing: Conceptualization, Methodology, Software, Formal analysis, Writing – original draft, Visualization. **Wim de Vries:** Conceptualization, Methodology, Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We are grateful to Lex Bouwman for substantial support in structuring the paper and editing several earlier drafts. This work would not have been possible without Jan Cees Voogd who implemented the code for the INTEGRATOR model. We thankfully acknowledge the European Environment Agency, Fertilizers Europe and the International Fertilizers Association for funding the study. L.S. acknowledges funding by the NWO (project number 022.003.009), provided by a project initiated by the SENSE Research School.

Appendix A. Supplementary information

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2021.147427.

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