Science of the Total Environment 912 (2024) 169357

Contents lists available at ScienceDirect

Science of the Total Environment

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

Costs and benefits of synthetic nitrogen for global cereal production in 2015 and in 2050 under contrasting scenarios

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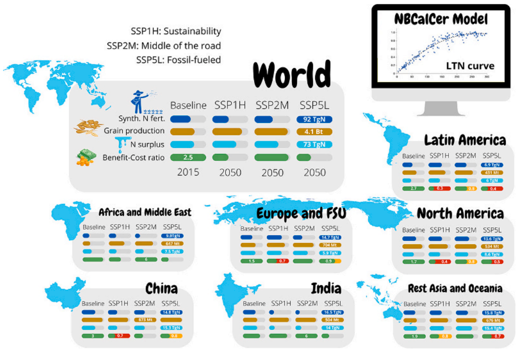
HIGHLIGHTS

- Direct use of synthetic nitrogen (N) contributes 44 % to global grain production.
- Global N surplus projected to decrease in sustainable scenarios but insufficiently.
- Ratio of N-benefits over N-costs projected to be below 1 for many regions in 2050.
- Produce enough grains with little N pollution needs vast change in global use of N.
- Sustainable food systems need structural shifts in cereal production and consumption.

GRAPHICAL ABSTRACT



ARTICLE INFO

Guest Editor: Estela Romero

Keywords:
Grain
Nitrogen
Fertilizer
Cost-benefit assessment
Cereal sufficiency
Modelling

ABSTRACT

Cereals are the most important global staple crop and use more than half of global cropland and synthetic nitrogen (N) fertilizer. While this synthetic N may feed half of the current global population, it has led to a massive increase in reactive N loss to the environment, causing a suite of impacts, offsetting the benefits of N fertilizers for food security and agricultural economy. To address these complex issues, the NBCalCer model was developed to quantify the global effects of N input on crop yields, N budgets and environmental impacts and to assess the associated social benefits and costs. Three Shared Socioeconomic Pathway scenarios (SSPs) were considered with decreasing N agri-environmental ambitions, through contrasting climate and N policy ambitions: sustainability (SSP1H), middle-of-the-road (SSP2M) and fossil-fueled development (SSP5L). In the base year the contribution of synthetic N fertilizer to global cereal production was 44 %. Global modelled grain yield was projected to increase under all scenarios while the use of synthetic N fertilizer decreases under all scenarios except SSP5L. The total N surplus was projected to be reduced up to 20 % under SSP1H but to increase under SSP5L. The Benefit-Cost-Ratio (BCR) was calculated as the ratio between the market benefit of increased grain production by synthetic N and the summed cost of fertilizer purchase and the external cost of the N losses. In base year the BCR was well above one in all regions, but in 2050 under SSP1H and SSP5L decreased to below one in most regions. Given the

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https://doi.org/10.1016/j.scitotenv.2023.169357
Received 31 May 2023; Received in revised form 1 November 2023; Accepted 11 December 2023

concerns about food security, environmental quality and its interaction with biodiversity loss, human health and climate change, the new paradigm for global cereal production is producing sufficient food with minimum N pollution. Our results indicate that achieving this goal would require a massive change in global volume and distribution of synthetic N.

1. Introduction

At the UN Food Summit in July 2021, it was concluded that, "*Ensuring sustainable food systems requires vastly reducing its environmental and health costs while making healthy and sustainable food affordable to all. One of the central problems of current food systems is that many of the environmental costs of harmful practices and health costs related to poor food access or choices are externalized, so they are not reflected in market prices*" (Hendriks et al., 2021). The external cost of current practices in the global agri-food system may exceed its market value of 10 trillion US $\$_{2018}$ which infers that current food prices on average only represent half of the real cost (Pharo et al., 2019). Within this overarching problem of imbalance between the benefits and costs of the global food system, a derived challenge is to achieve a balance between the benefits of N fertilizer to increase food production and the environmental costs of agricultural N pollution (Chen et al., 2014; Zhang et al., 2021). Current global anthropogenic addition of new N from the Haber-Bosch process may feed up to half of the global population (Erisman et al., 2008). The downside of this global benefit is that the use of synthetic fertilizer, together with the generation of new reactive N by cultivation of N fixing crops and N deposition from combustion of fossil fuels now is twice the natural input of reactive N (Liang et al., 2021; Sutton et al., 2013). It cannot be surprising that this increase of input and loss of N cannot be without huge effects on both terrestrial and aquatic ecosystems. Steffen et al. (2015) concluded that subsequent global N losses to the environment exceed the assumed planetary boundary of N (Rockström et al., 2023) and Van Grinsven et al. (2013) concluded that these impacts cause unaffordable environmental costs. The use of synthetic fertilizers and manures across the nearly 40 % of Earth's ice free land devoted to agriculture, comprises the largest source of ammonia, nitrate and nitrous oxide pollution globally, with severe impacts on ecosystems, human health and climate change (Foley et al., 2011; Gu et al., 2021; Schulte-Uebbing et al., 2022; Sutton et al., 2011; Thompson et al., 2019; van Grinsven et al., 2022).

Cultivation of wheat, maize, rice and barley covers about half of the global crop area, with area shares of 16 %, 14 %, 13 % and 3.4 %, respectively (mean land use for 2013–2017; FAOSTAT (2019)). It is estimated that 57.3 TgN/yr of synthetic fertilizers were applied to these four cereals in 2014–2015, representing 55.9 % of its global consumption (IFA-IPNI, 2017). Wheat was the main crop receiving N fertilizers, with 18.2 % of global use, followed by maize with 17.8 % and rice with 15.2 %. Other cereals accounted for 4.7 % of the world total. Therefore, reconciling the benefits and costs of N use in cereal systems is one of the keys to more sustainable future agri-food systems (Ladha et al., 2016; Lassaletta et al., 2014). A more judicious and balanced use of N fertilizers should not be carried out in isolation, but within a redesign of overall crop management by crop nutrition, pest control and irrigation, and taking a long term and global perspective on sustainable land use and planning for food and livestock (Bai et al., 2022; Billen et al., 2021), and on food security in relation to dietary choice (Westhoek et al., 2014; Willett et al., 2019). Close to 40 % of the global land and cereal production are used to feed livestock (Manceron et al., 2014; Our Word in Data, 2023) and in many regions people consume more proteins and calories than in dietary guidelines (Leip et al., 2022).

In this paper we quantify grain yields and N budgets resulting from changing N inputs and potential yields for cereal systems in global regions for 2015 and 2050 under three contrasting Shared Socioeconomic Pathway scenarios (SSPs) (Mogollon et al., 2018; Riahi et al., 2017). We also quantify and value the changes of major environmental impacts of the N losses, for confrontation against the economic benefits of N for grain yields and grain sufficiency for humans and livestock. As shown in van Grinsven et al. (2022), the study on which our approach builds, internalizing the external cost of current fertilizer use would lead to reduction of N rates in intensive cropland of high-income countries. Therefore, the objective of this study is to perform a global social cost benefit analysis for nitrogen use in cereal production under contrasting future scenarios, illustrating the pathways more desirable for the society.

2. Materials and methods

2.1. Impact-pathway approach

Our assessment approach derives from the impact-pathway approach as applied for energy generation by Bickel and Friedrich (2005) and adopted by Van Grinsven and Gu (2024a) for N cost-benefit analysis in the INMS project (Towards the establishment of an International Nitrogen Management System; https://www.inms.international/). The essence of the approach is to model the chain from activities to emission, to dispersion, to exposure, to impact, and finally to cost (see flow scheme in Fig. S1). For this case the activity is cultivation of cereals. Emission refers to the release of reactive forms of N (nitrate, ammonia etc.) resulting from use of N organic and synthetic fertilizers. For nitrate, dispersion-exposure refers to reactive transport of nitrates in surface runoff and groundwaters, to rivers and seas causing exposure of organisms (including humans) to harmful concentrations, eutrophication sometimes causing anoxia. Aquatic impacts include human disease from high nitrate in drinking water and loss of biodiversity and ecosystem services (e.g. recreation) both in fresh water and marine systems. For ammonia, dispersion-exposure refers to reactive transport of ammonia in air causing, firstly, exposure of organisms (incl. humans) to ammonia derived harmful ambient air pollution levels and, secondly, to ammonia derived atmospheric N deposition exposing terrestrial nature to loads exceeding critical loads. Air pollution impacts include human disease and premature mortality and terrestrial biodiversity loss. Finally, all the impacts are converted to economic costs to allow comparison and addition of impacts and cost-benefit analysis.

2.2. NBCalCer model for response of grain production and N budgets to N input

We applied the NBCalCer model (Nitrogen Benefit Calculator for Cereals, Rodriguez et al. (2022)) to quantify the global effects of contrasting future N input scenarios on grain yields in rainfed and irrigated wheat, maize, rice and barley, associated N budgets and environmental impacts, and finally the associated economic benefits and costs for farming and society (see Fig. S2 for a flow scheme of the model). The model operates at the country scale, and for the USA and China at the scale of states and provinces, respectively. Results are here presented for seven global regions derived from thirteen AgMIP (The Agricultural Model Intercomparison and Improvement Project, Ruane et al. (2017); https://agmip.org/) regions (Table 1, Fig. S3) which have comparable global shares in population and GDP (Table S2).

NBCalCer quantifies the long-term response of global cereal grain yields to nitrogen fertilizer application, in terms of grain mass and of gross and net, absolute and marginal, economic output per hectare of cultivated land. Key relations in NBCalCer describe the long-term effect of N input on grain yield and on grain N content. Long-term responses

Table 1
Aggregation of 13 AgMIP regions to 7 global regions for presentation of NBCalCer results.

World region code	World region	Region/s
AFM	Africa and Middle East	Africa+Middle East
CHN	China	China
EFS	Europe and Former Soviet Union	Europe+Former Soviet Union
IND	India	India
LAM	Latin America	South + Central America
NAM	North America	Canada+USA
RAA	Rest of Asia, Australia, and New Zealand	Rest of Asia + Australia + New Zealand

are not biased by the effect of temporary net delivery or retention of N in soils and represents a situation where the soil N pool is in near steady state with the N input.

These relations were derived by van Grinsven et al. (2022) and for wheat, maize and barley take the form of Eq. (1) and for low land rice of Eq. (2).

$$Yr = -1.87 \times 10^{-5} \times Nav^2 + 8.768 \times 10^{-3} \times Nav \quad \left(R^2 = 0.82, S = 132\right) \tag{1}$$

$$Yr = -4.396 \times 10^{-6} \times Nav^2 + 4.261 \times 10^{-3} \times Nav \quad \left(R^2 = 0.95, S = 16\right) \tag{2}$$

where *Yr* (unitless) is grain yield (*Y* in kg/ha/yr) relative to the maximum achievable yield (*Ymax* in kg/ha/yr) and where *Nav* (kg N/ha/yr) is the total availability of N from fertilizer, manure, atmospheric deposition and biological fixation and where *S* is the number of underlying datasets. Hereafter, for simplicity, we omit /yr for the different rates. To convert *Yr* to yields (t/ha), *Yr* is multiplied by *Ymax*. *Ymax* was based on potential yields (*Yp in t/ha*) for irrigated systems and for rainfed systems on the water-limited yield *(Yw in t/ha)* from the Global Yield Gap Atlas (GYGA; https://www.yieldgap.org/, van Ittersum et al. (2013)). For rainfed cereals *Yp* is the water-limited yield from GYGA *(Yw in t/ha)*. *Ymax* was set to 80 % of *Yp*. For the combination of countries and cereal crops (except for barley) not yet covered by GYGA, *Yp* and *Yw* values per climate zone level (i.e., geographic region characterized by homogeneous climate conditions) were extrapolated and only when the harvested area of the specific cereal in a country was larger than 50,000 ha (Van Loon et al., 2021).

A linear response of N content in grain (*N%*) to Nav was derived from long term trials on winter wheat in Broadbalk UK and scaled to the other cereals based on the difference in mean N% (van Grinsven et al., 2022).

$$N\% = 1.873 + 3.26 \times 10^{-3} \times Nav - 6.20 \times 10^{-2} \times Ymax \quad \left(R^2 = 0.743, S = 224\right) \tag{3}$$

N surplus was calculated as:

$$\text{Nsurplus} = \text{Nav–Nremoval} \tag{4}$$

where *Nsurplus* is the N surplus, *Nav* is total N input from all above-mentioned sources and *Nremoval* is N removal by the crop calculated as: *Y x N%/100.*

2.3. Impact models for human mortality and air pollution and biodiversity loss by N deposition

In the cost-benefit analysis three N pollution impacts were included, namely, increased premature mortality by ambient air pollution of N containing fine particulate matter ($PM_{2.5}$), loss of terrestrial biodiversity by N deposition and loss of marine ecosystem services by N river loads. We did not include impacts of nitrate in drinking water, of freshwater eutrophication by N, of N driven formation of ambient ozone, and of N driven greenhouse gasses emission or carbon sequestration, or N_2O driven depletion of stratospheric ozone. Based on previous studies (Sobota et al., 2015; Van Grinsven et al., 2013) these impacts, and associated costs were judged small for the considered systems of cereal production. The increased mortality by $PM_{2.5}$ from N use in cereal production for the seven global regions was derived from total mortality results from the TM5-FASST model (Van Dingenen et al., 2018). The contribution of cereal production to total increase of $PM_{2.5}$ induced mortality was assumed to be proportional to (1) the share of NH_3 emission from use of urea type fertilizer and manure to total emission of NH_3, as obtained from the IMAGE-GNM model (Beusen et al., 2022), and (2) the contribution of NH_3-N to total $PM_{2.5}$ formation, which was determined by model perturbation (Gu et al., 2021). The total loss of terrestrial biodiversity by N deposition was based on results of the GLOBIO model (Schipper et al., 2020) and the contribution by N use in cereal production was also based on the share of NH_3 emission, as for $PM_{2.5}$ induced mortality. The used impact models are spatially explicit and take into account the effect of location of emission sources on impacts of NH_3 and nitrate on humans and ecosystems. For both mortality effects of $PM_{2.5}$ and biodiversity effects of N deposition, we assumed that the global spatial configuration of NH_3 sources related to cereal production relative to the location, population and terrestrial nature was the same as for overall agriculture. The total marine impacts of N river loads were quantified by Pinto et al. (2021) and the contribution by N use in cereal production was assumed proportional to the share of the N surplus in total agriculture as quantified using the IMAGE-GNM model (Beusen et al., 2022).

2.4. Validation of used impact models

The three impact models IMAGE-GNM, TM5-FASST and GLOBIO are well established and validated against observations of e.g. N river loads, concentration fields and trends of $PM_{2.5}$ or N deposition. Here, specification of impacts of changed N inputs and losses from cereal systems were simple downscaled results based on estimates of contribution of cereals systems to N surplus and losses of NH_3 from total agriculture. National NBCalCer results for cereal productivity (ton grain per hectare) in base year compared well to reported mean national yields by FAOstat and GYGA (Table S3), especially for rainfed wheat and maize with R-squared linear regression exceeding 0.7 and slopes close 0.9. For irrigated maize and (paddy) rice the comparison was quite poor with R-squared around 0.2, which could be problematic for our analysis as globally about 40 % of grain production derives from irrigated systems. In spite of the poorer performance of NBCalCer for irrigated systems, total global production of individual cereals and total grain by NBCalCer is within 10 % of values based on FAOstat. As underlying long-term N response data apply to near steady state of soil N, lower predicted yield can be expected for regions with soil N depletion, and higher yields in case of current soil N build up or in case of high inputs of manure N. The plausibility of N budgets by NBCalCer was checked against N budgets for arable agriculture from IMAGE-GNM. Total grain yield projected by NBCalCer could be validated against national and regional crop production data from Eurostat and FAOstat. In spite of the apparent validity of the used impact models on the scale of countries or states, these models use fairly coarse grid resolutions (typical 0.5–1 latitudinal x longitudinal degrees) which may not capture the effect of the local spatial interactions of sources and receptors of N impacts.

2.5. Shared socioeconomic pathways (SSPs) scenarios

We projected effects of cereal production in 2050 under three contrasting scenarios belonging to the SSPs scenario group (Van Vuuren et al., 2021), with different levels of climate change as the result of contrasting socio-economic development and climate policies, on which N storylines were superimposed (Kanter et al. (2020); Table S1):

1. SSP1 (van Vuuren et al., 2017), RCP2.6 (Representative Concentration Pathway (RCP) leading to radiative forcing of 2.6 W/m^2), policy-high, with high ambitions for climate policy and N-policy and which represents a best-case scenario (referred to as SSP1H hereafter)
2. SSP2 (Riahi et al., 2017), RCP4.5, policy-med, with medium ambitions for climate policy (RCP leading to radiative forcing of 4.5 W/m2) and N-policy and which represents a middle of the road scenario (referred to as SSP2M hereafter)
3. SSP5 (Kriegler et al., 2017), RCP8.5, policy-low, with low ambitions for climate policy (RCP leading to radiative forcing of 8.5 W/m2) and N-policy and which represents a worst-case scenario (referred to as SSP5L hereafter)

2.6. Input data

Nitrogen input to cereal croplands (Table 2) include application of synthetic fertilizer (Syn) which for base year 2015 was taken from IFA-IPNI (2017) and for Europe from Fertilizers Europe (2019), completing the inputs using the IMAGE-GNM model (Beusen et al., 2022; Bouwman et al., 2013). For 2050 for the three SSPs Syn was projected using the IMAGE-GNM model, which was also the source for rates of livestock manure N, biological N fixation and atmospheric N deposition in the base year and 2050 (Table S4). A description of the IMAGE-GNM model is available in Note S1 from supplementary material.

Globally, synthetic N rates in cereal production are projected to decrease in 2050 for SSP1H and SSP2M and strongly increase for SSP5L. In SSP2M, an expansion of cropland and pastureland is projected consistent with Riahi et al. (2017). Higher rates of synthetic N in SSP1H than SSP2M are expected, in view of less N availability from manure associated with a lower livestock production. In SSP5L, due to the absence of environmental policies, there are few incentives to decrease fertilizer use and improve management to increase nitrogen use efficiencies (NUE). Global mean nitrogen input rates from manure are projected to increase due to increased consumption and production of animal products. Differences between 2050 scenarios and base year strongly vary between global regions. We highlight China where under SSP1H and SSP2M the synthetic N rates are projected to almost halve due to more availability and more efficient use of manure, and India where under SSP1H and SSP2M synthetic N rates are projected to decrease even more. This strong decrease is also caused by modest increases of *Ymax*, which leads to modest increases of N requirement which can be almost fully satisfied with the increased availability and efficient use of manure N.

Table 2
Total nitrogen input rates (in kgN/ha/yr) for cereal production, as sum of synthetic fertilization, manure, N deposition and biological fixation, and the percentage that synthetic fertilization (Syn) represents from the total, in global regions in base year and for 2050 under SSP1H, SSP2M and SSP5L. World region codes can be found in Table 1.

	Base year		SSP1H		SSP2M		SSP5L	
	Total	Syn (%)	Total	Syn (%)	Total	Syn (%)	Total	Syn (%)
World	142	61	140	49	134	41	204	64
AFM	78	45	73	36	69	22	113	56
CHN	220	60	202	35	204	30	334	54
EFS	99	67	123	75	120	68	166	76
IND	174	67	129	22	117	4	269	71
LAM	142	51	184	51	174	41	225	54
NAM	184	68	206	67	205	62	282	72
RAA	128	58	141	50	134	45	174	65

Base year prices for cereals (Table S5) and fertilizer (Table S6) were derived from the Chatham House Resource Trade Database (http://resourcetrade.earth/) and projections for 2050 for the three SSPs from the Modular Applied General Equilibrium Tool (MAGNET) model (van Meijl et al., 2020; Woltjer et al., 2014). The MAGNET model is a multi-regional, multi-sectoral, applied general equilibrium model based on the Global Trade Analysis Project (GTAP) database (Hertel, 1997) in which input and output prices are endogenously determined to achieve equilibrium between supply and demand. The model has a relatively detailed description of the agricultural sector with land modelled as an explicit production factor described by a land-supply curve (Dixon et al., 2016). It has been applied extensively for the development of scenario projections as part of the IMAGE integrated assessment model framework (Stehfest et al., 2014), among others for the SSP scenarios (Doelman et al., 2018). *Ymax* in 2050 for the three SSPs was also based on MAGNET projections.

Global fertilizer prices are projected to increase modestly and with small differences between the SSPs and lowest prices in North America (Fig. S4). Projected prices in India and China are twice as high (around 1US$\$_{2020}$ in NAM and around 2.2US$\$_{2020}$ for India and China) reflecting high regional energy prices and problems meeting regional fertilizer demands. Future concerns especially are the high and increasing grain prices in India, and South Asia in general (around 5US$\$_{2020}$ in RAA), which in SSP2M does not keep up with increasing purchasing power (van Meijl et al., 2020).

2.7. Valuation

The changes in market benefits of N were based on the changes in grain yields and prices, and use and prices of synthetic fertilizer. The calculation of costs of impacts of N loss were based on Van Grinsven and Gu (2024a) using functions that value a change of risks of premature mortality, loss of biodiversity or ecosystem services. These functions take the general form of.

$$\Delta \mathrm{Value}_{i,j} = \Delta \mathrm{Impact}_{i,j} \times \mathrm{WTP}_{i,j} \times \left(\mathrm{GDP}_{i,j}\right)^{\varepsilon} \times \mathrm{Pop}_{i,j} \tag{5}$$

where Δ is a change in time (or between scenarios), the subscripts "i,j" refer to place and time, *Value* is the economic value in monetary units, *Impact* is the (risk of a) physical effect by a change in N pressure, *WTP* is the willingness (see e.g. Jacobsen and Hanley (2009)) to pay to prevent this risk, *GDP* is the gross domestic product per capita, ε is the income elasticity of the *WTP* and *Pop* is the population. The GDP elasticity (ε) for increased risk of premature mortality by N driven air pollution of $PM_{2.5}$ was 0.8–1.2 (ε depends on GDP, Narain and Sall (2016)), for increased risk of loss of terrestrial biodiversity by N deposition 0.45 and for increased risk of loss of marine ecosystem services (recreation and eutrophication) 0.97 (Van Grinsven and Gu, 2024a). We expressed the benefit and cost values as a percentage of GDP which is a simple approximation of discounting (Van Grinsven and Gu, 2024a; Van Grinsven and Gu, 2024b). Global mean GDP per capita is projected to almost double in 2050 for SSP2M to a factor of three under the different SSPs (Table S2) and in China even by a factor up to eight. Benefits and costs of changed use and loss of reactive nitrogen (Nr) expressed as a percentage of GDP are proxies for the relative gain or loss of welfare in contrasting regions and scenarios.

2.8. Social cost benefits analysis

A social cost-benefit analysis (SCBA) is a tool to inform decision-making which is based on objective grounds as much as possible. A nitrogen SCBA aims to provide an overview of the resulting benefits and

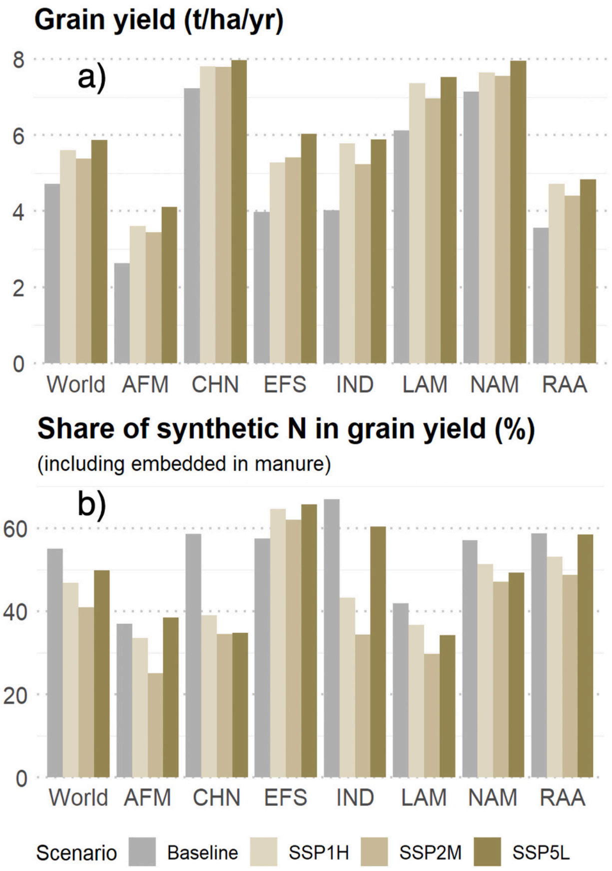

Fig. 1. Mean area weighted average yield per hectare for wheat, maize, barley and rice (a), and contribution of synthetic N fertilizer to cereal production, including synthetic N embedded in manure originating fertilizer use on feed crops (b) in base year and 2050.

disbenefits (costs) of a N policy or measure to society as a whole. By quantifying these benefits and disbenefits to the best of abilities and by expressing them in monetary terms, the SCBA provides information on the effect on social prosperity. In addition to effects on yield and the three N pollution impacts our SCBA also considers the change in cost of N fertilizer and the fixed and variable costs of farming not related to N input (e.g. costs of seeds, tillage, labour and land rental). SCBA can inform policy decisions on interventions which have the largest chance to deliver net future welfare gains. SCBA can also help to raise awareness of farmers and the agricultural industry about the societal cost of their current practices.

2.9. *Uncertainty analysis*

To assess the degree of robustness of the presented results of NBCalCer, an uncertainty analysis was performed using the Monte Carlo method to generate random samples from a set of 16 model inputs and parameters. The analysis is not based on a thorough assessment of uncertainties of the included parameters but rather a mix of expert judgement, published uncertainty analysis (Beusen et al., 2008; Le Noë et al., 2017) and a default uncertainty value (see Note S2 and Table S9 for details). We generated a distribution of the main outputs of the model by bootstrapping the Monte Carlo simulation with replacement for a total of 500 replicates. The uncertainty for each outcome was analysed using the median and the Q1 and Q3 quartiles.

3. Results

3.1. *Yield response*

For all SSPs, cereal productivity (ton grain per hectare) is projected to increase in 2050 in all regions, as compared to the base year, with a global increase from 14 % to 25 %, and with largest increases from 30 % to 47 % in India, 33 % to 52 % in region Europe and the Former Soviet Union and from 31 % to 56 % in region Africa and Middle East (Fig. 1, Fig. S5).

Global cereal production is projected to increase by 23 %, 38 % and 48 % under SSP1H, SSP2M and SSP5L, respectively (Fig. 2). Production increases are the combined effect of changes in crop area, Ymax and availability and utilization of N. For example, in SSP1H these three factors contributed 14 %, 27 % and 59 %, respectively, as opposed to 53 %, 23 % and 44 % in SSP2M and 39 %, 17 % and 44 % in SSP5L. Relative contributions of the three factors are very different in world regions (Table S7). Differences reflect that in the sustainability scenario food sufficiency in 2050 with a smaller crop land expansion is only possible when combined with higher yielding cultivars and increased NUE. Depending on the country and scenario, there are some production decreases projected, for example, in China, Mexico and United States and some countries in Europe (see Fig. S6). A detailed table showing areas and production for each cereal, for both rainfed and irrigated, for each world region and globally, and under each scenario is available in Table S8 from supplementary material.

In the base year, using our model NBCalCer, the relative contribution of the direct use of synthetic N fertilizer to global grain production (the N-share, Van Grinsven et al. (2021)) was estimated at 44 % ranging between 20 % in Sub-Saharan-Africa to over 70 % in Canada and Australia (Fig. S7). Lower N-shares apply to regions with low use of synthetic N (Sub-Saharan-Africa) and regions where cereals are grown in rotation with soybean (e.g., USA and Brazil). If we include the contribution of embedded synthetic N in manure (see for explanation in; Van Grinsven and Gu (2024a), Chapter 9.2), the global N-share increases to 56 % (Fig. 1). The global N-shares are projected to decrease somewhat in the future and foremost in SSP2M. This decrease is the net effect of decreased use of synthetic N in e.g. China, Europe, North America and India, and the increased inputs and NUEs of manure in China and India (See Chapter 10 in Sutton (2023)).

3.2. *N budget and NUE*

Under SSP1H and SSP2M, the total N availability at global scale remains similar to the base year, N surplus is reduced by around 25 % and therefore NUE is improved by the same range. In most regions, in

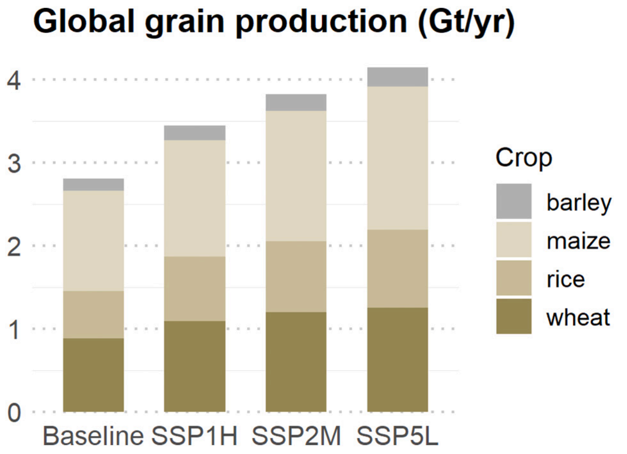

Fig. 2. Global production in base year and 2050 of wheat, rice, maize and barley in base year and 2050.

Table 3
Input of total N (in kgN/ha/yr) from all sources (Nav), resulting N surplus (Nsurp) and Nitrogen Use Efficiency (NUE; calculated by N removal / Nav) for cereal production in global regions in base year and for 2050 under SSP1H, SSP2M and SSP5L. World region codes can be found in Table 1.

Scenario	Base year			SSP1H			SSP2M			SSP5L		
Region	Nav	Nsurp	NUE	Nav	Nsurp	NUE	Nav	Nsurp	NUE	Nav	Nsurp	NUE
World	134	69	53	134	54	66	130	52	65	191	103	54
AFM	74	36	54	71	21	74	68	19	72	107	48	64
CHN	210	108	51	196	81	59	199	84	58	320	188	43
EFS	97	29	72	120	27	85	118	24	85	162	49	76
IND	155	112	34	125	45	64	117	42	64	239	164	37
LAM	133	54	62	173	70	64	167	69	64	212	104	55
NAM	178	67	63	199	75	64	199	76	63	272	129	54
RAA	116	83	35	132	83	47	125	80	46	157	110	40

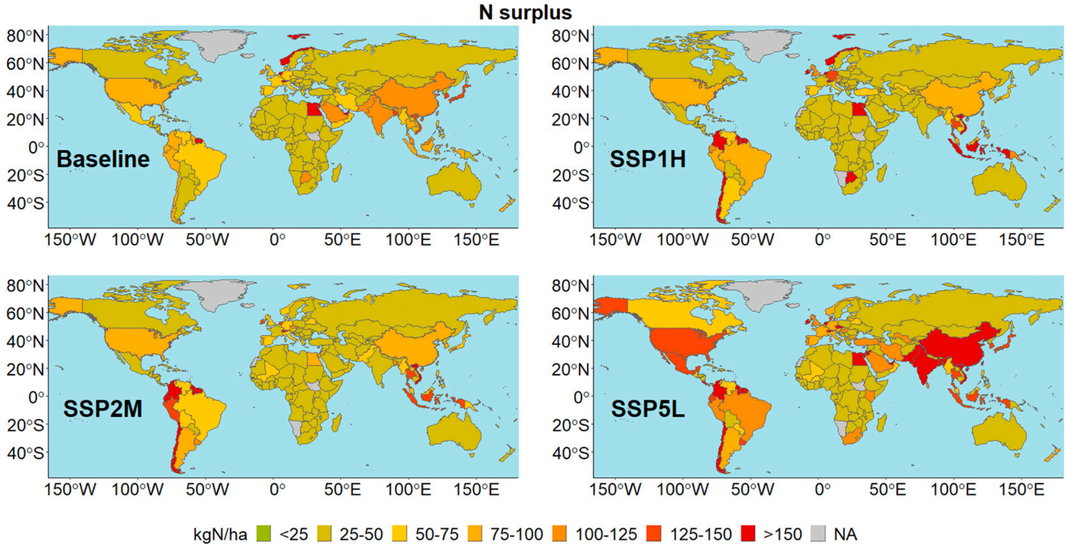

Fig. 3. N surplus (kgN/ha/yr) at country level in the base year (around 2015) and for 2050 for the three SSPs scenarios. NA values stand for missing values.

Europe, America, Rest of Asia and Oceania, increases of N input rates are projected, increasing N surplus by around 30 % in Latin America and 12 % in North America. Projections for India and China show a modest decrease of N inputs by 19 %–25 % and, 5–7 % respectively, as a result of the scenario assumption on a more efficient use of manure. This reduces the N surplus by around 60 % in India and 25 % in China while increasing the overall NUE. Under SSP5L and in every region there is an increase of the total available N and an increase of the N surplus (ranging from a 33 % in Africa-Middle East region, to a 93 % increase in the American regions) (Table 3, Fig. 3, and Figs. S8 to S12).

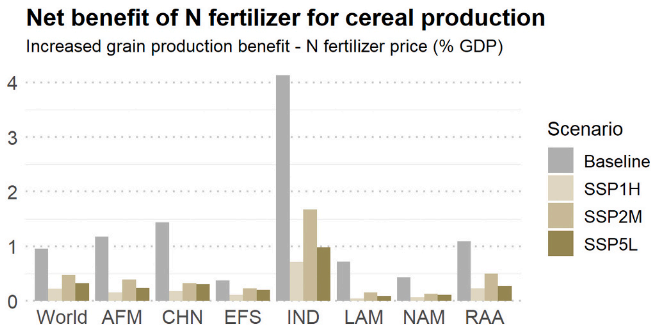

Fig. 4. Net economic benefit of application of purchased synthetic N fertilizer for cereal production in base year and 2050 under three SSPs expressed as percentage of GDP without considering social costs.

3.3. *Benefits and costs*

3.3.1. *Benefits*

The global benefit of increased cereal production by the use of synthetic N represents a net value (corrected for the purchasing cost of synthetic N) of close to 1 % of GDP (i.e. around 800 million US$_{2015}$), in base year (Fig. 4). The net benefit (in absolute terms) without considering purchasing costs of synthetic N is sustained and slightly increased in 2050 under SSP2M, decreases by one third under SSP1H and increases by 30 % under SSP5L, while, if considering purchasing costs of synthetic N, just slightly decreases under SSP1H and increases around 50 % under SSP2M and SSP5L. The variation of economic value in global regions is the combined effect of different changes in cereal production and cereal and fertilizer prices as projected by the economic model MAGNET. While projected cereal prices in 2050 for Europe and the USA are not much higher than in base year, they are projected to almost double in India under SSP2M (e.g. rice costing over 1800 US$_{2020}$ per ton) and SSP5L, and in China under SSP5L (e.g. maize costing over 1100 US$_{2020}$ per ton), due to the large increase of demand for cereals for both food and feed.

Global gross benefits of N fertilizer for cereal production decrease to 0.2 %, 0.5 % and 0.3 % of GDP in in 2050 for SSP1H, SSP2M and SSP5L, respectively (Fig. 4). The cause of this decrease is that GDP is projected to increase more strongly than the combined effect of increasing volumes and prices of cereals in all global regions. Benefits of N fertilizer for cereal production are higher in developing regions than in high-income regions (Fig. S13), with the highest value of 4.1 % in India in base year.

The net benefits of synthetic N for cereal production are somewhat offset by yield reduction due to damage by NO_x derived from ground-level ozone and yield increase by N deposition. The global average yield loss due to ground-level ozone derived from NO_x in base year is 1.4 % (with a highest value of 4 % in North America), which loss is outweighed by the yield increase due to N deposition representing a global average yield gain in base year of 3.2 % (and with highest value of 6 % in the AFM region (Van Grinsven and Gu, 2024b; van Grinsven and Gu, 2023)). The net yield change caused by atmospheric N pollution (both NO_x-induced ozone and N deposition) in base year ranges between -3 % in North America to $+5$ % in the regions AFM and EFS, and a global mean of $+2$ %. In 2050 under all SSPs, the net global yield change decreases due to decreasing N deposition and increasing NO_x-derived ozone formation in China and India, which will be the dominant economies in 2050.

3.3.2. *Costs*

We quantified the environmental costs of N losses from cereal production resulting from the volatilization of NH_3 and from the N surplus from application of fertilizer and manure and its impact (1) on premature mortality by NH_3 induced secondary $PM_{2.5}$ formation, (2) on loss of terrestrial biodiversity by NH_3 induced N deposition, and (3) N surplus related eutrophication of marine waters (Van Grinsven and Gu, 2024b; van Grinsven and Gu, 2023) in Sutton (2023). In the base year, the total N pollution cost by cereal production amounts to 0.20 % of global GDP, with the largest contribution of 0.10 %-point by increased loss of marine ecosystem services and smaller contributions of 0.07 %-point by biodiversity loss and 0.04 %-point by increased premature mortality (Table 4). The dominant contribution of the cost of the eutrophication of marine waters to the total environmental cost of N losses is caused by the relatively large contribution of cereal systems to N surplus in agriculture and total N river loads which is related to the fact that cereal cultivation receives 60 % of the global use of synthetic N fertilizer and contribute 40 % to the N surplus of total agricultural land, while the contribution of the global emissions of NH_3 is around 10 %. N

Table 4
External costs and Benefit-Cost Ratios (BCR) of global production of cereal crops in the baseline year (2015) and 2050 for three SSPs expressed as % of GDP. World region codes can be found in Table 1.

		Total external cost	YLL-PM_Nr	MSA	N marine	Synth fertilizer purchase cost	Fixed cost	BCR
Base year	**World**	**0.20%**	**0.04%**	**0.07%**	**0.10%**	**0.18%**	**0.15%**	2.49
	AFM	0.07%	0.02%	0.04%	0.01%	0.15%	0.11%	5.50
	CHN	0.32%	0.08%	0.09%	0.16%	0.16%	0.11%	2.98
	EFS	0.15%	0.03%	0.03%	0.09%	0.09%	0.28%	1.51
	IND	0.45%	0.09%	0.27%	0.09%	0.45%	0.11%	4.59
	LAM	0.09%	0.02%	0.04%	0.03%	0.18%	0.14%	2.68
	NAM	0.17%	0.01%	0.03%	0.13%	0.08%	0.36%	1.73
	RAA	0.26%	0.04%	0.10%	0.12%	0.31%	0.16%	1.93
SSP1H	**World**	**0.15%**	**0.02%**	**0.02%**	**0.12%**	**0.05%**	**0.13%**	1.13
	AFM	0.02%	0.00%	0.01%	0.01%	0.03%	0.10%	2.98
	CHN	0.25%	0.02%	0.02%	0.21%	0.02%	0.12%	0.70
	EFS	0.11%	0.01%	0.02%	0.09%	0.06%	0.25%	0.69
	IND	0.13%	0.04%	0.02%	0.07%	0.01%	0.09%	4.93
	LAM	0.06%	0.00%	0.01%	0.04%	0.10%	0.12%	0.28
	NAM	0.15%	0.01%	0.01%	0.13%	0.03%	0.25%	0.39
	RAA	0.19%	0.01%	0.03%	0.15%	0.09%	0.14%	0.82
SSP2M	**World**	**0.14%**	**0.01%**	**0.02%**	**0.11%**	**0.05%**	**0.14%**	2.39
	AFM	0.02%	0.00%	0.01%	0.01%	0.03%	0.11%	6.00
	CHN	0.25%	0.02%	0.04%	0.19%	0.02%	0.13%	1.21
	EFS	0.10%	0.01%	0.02%	0.07%	0.07%	0.28%	1.40
	IND	0.11%	0.03%	0.02%	0.06%	0.00%	0.09%	6.00
	LAM	0.06%	0.01%	0.02%	0.04%	0.10%	0.12%	1.03
	NAM	0.13%	0.01%	0.01%	0.11%	0.04%	0.29%	0.77
	RAA	0.19%	0.01%	0.03%	0.15%	0.12%	0.16%	1.58
SSP5L	**World**	**0.24%**	**0.07%**	**0.04%**	**0.14%**	**0.08%**	**0.15%**	1.00
	AFM	0.05%	0.01%	0.02%	0.01%	0.07%	0.13%	1.98
	CHN	0.35%	0.08%	0.03%	0.24%	0.04%	0.13%	0.78
	EFS	0.17%	0.04%	0.03%	0.11%	0.06%	0.25%	0.87
	IND	0.38%	0.20%	0.07%	0.12%	0.09%	0.10%	2.09
	LAM	0.10%	0.02%	0.03%	0.05%	0.14%	0.16%	0.36
	NAM	0.18%	0.05%	0.03%	0.11%	0.04%	0.24%	0.51
	RAA	0.26%	0.05%	0.06%	0.15%	0.15%	0.17%	0.65

NB: YLL-PM_nr: Increased premature mortality by ambient air pollution of N containing fine particulate matter ($PM_{2.5}$) calculated using Years of Life Lost. MSA: loss of terrestrial biodiversity by N deposition calculated using the Mean Species Abundance. N marine: loss of marine ecosystem services by N river loads.
The used colours for BCR highlight were: ● <0.5 ● 1.0 ● >2.0.

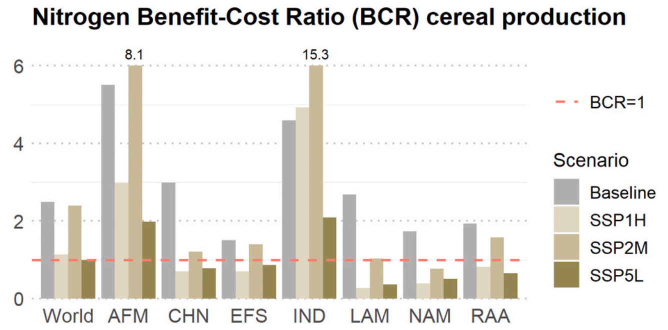

Fig. 5. Ratio of net benefits of N for cereal production and over the sum of the costs of N impacts and N fertilizer costs (note that the BCRs for Africa and Middle East and India under SSP2M are 8.1 and 15.3 respectively).

pollution costs in base year expressed as percentage of GDP are highest for China (0.32 %) and India (0.45 %) reflecting high N intensities and N losses and low GDP. Costs are lowest in Africa and Middle East (0.07 %) and in Latin America (0.09 %), related to low N intensities and N losses. The N pollution costs in %GDP in the high-income regions EFS and North America take an intermediate position, which is the combined effect of high N intensities but also higher NUEs among others due to higher yields and more N policies in place, but also to higher GDP. The relative shares of the three impacts vary strongly between world regions (Table 4). While marine pollution is dominant in China, EFS and North America, terrestrial biodiversity loss is the largest cost in AME, India, and Latin America. In 2050 under SSP1H and SSP2M the N pollution cost in %GDP decreases globally and in all global regions, but mainly because GDP increases more strongly than N pollution cost. The latter is the effect of the GDP elasticities in Eq. (5), which are always <1. This means that the WTP to prevent risk of N pollution increases less than proportionally with GDP. Total global N pollution cost in 2050 under SSP5L is similar to that in base year, because of the projected large increase of the use of synthetic N fertilizer in cereals; from 51 TgN in base year to 92 TgN in 2050. This is the major driver of an increase of the N surplus from 41 TgN to 73 TgN and of the NH_3 loss at application of synthetic fertilizer and manure from 10 TgN to 17 TgN. In 2050 in all three SSPs the N pollution cost in China will represent about 45 % of the global N pollution cost, twice as much as in base year. In 2050 in the Asian regions, with both a strong increase in GDP and population, the cost of increased mortality by air population in %GDP is also projected to increase, most strongly in India. In India this cost share increases from 20 % of the total N pollution cost in base year, to around 30 % in 2050 under SSP1H and SSP2M to nearly 60 % under SSP5L. The cost share of N driven MSA loss terrestrial systems in most regions is projected to decrease in 2050 mainly because the low GDP elasticity (0.45), but it remains to be the dominant cost item in Africa and South America which regions harbor the largest terrestrial ecosystems.

3.3.3. Benefit-cost ratio

In our Social Cost-Benefit Assessment (SCBA) one objective is to find a combination of inputs of N, production of grain and loss of N that delivers a ratio of Benefits over Costs (BCR) as high as possible or at least exceeding a value of one. A value far below one would represent a cereal production system causing an unacceptable cost for society. In our analysis achieving a BCR exceeding one should not be taken too strictly in view of uncertainties and possible incompatibilities of the value functions. Therefore we focus on changes of BCR rather than absolute values. The SSP2M scenario (the middle of the road scenario), comes out as the pathway with the highest BCRs, with globally in 2050 the same value as in base year and with a substantial increase of BCR in India which then is the most populous global region (Fig. 5). The fact that BCR in 2050 under SSP2M is in par with BCR in base year could be interpreted as that in 2050 the benefit of meeting the cereal demand of the population of 9.3 billion people is in balance with an increase of N pollution cost, similarly to in base year feeding a population 7 billion people. With the exceptions of India and AFM, BCR in 2050 under SSP2M in all other regions is lower than in base year, indicating that the increased market value of the cereal production cannot keep up with the increased cost of pollution. BCRs in SSP1H (sustainability) and SSP5L (conventional development, no policy intensification compared to base year) are, except for India, much lower, indicating that from a perspective of both controlling pollution N and producing sufficient cereals, these pathways are sub-optimal for society.

3.4. Implications for cereal sufficiency

The BCR approach appreciates the benefits of increased cereal grain production only in terms of market value. To illustrate the societal consequences of N induced changes in grain production, related to N use in another way than financially, cereal sufficiency is an insightful indicator. Cereal sufficiency reflects the balance between regional supply and demand. For this we compared regional grain production per capita to grain demand under different dietary assumptions. Globally, cereal supply in the base year is close to 400 kg per capita per year for the sum of wheat, maize, barley and rice (Fig. 6) including direct and indirect consumption. While all cereals, theoretically, are suitable for human consumption, particularly maize is used more for feed than directly for food, while rice is hardly used for feed. Currently, as compared to the mean global grain production per capita, North America and EFS are regions with large grain surpluses, while AFM, India and China tend to have grain shortages.

We distinguished three contrasting diets, (1) Western lifestyle with meats every day, (2) Demitarian with meats half of the days and (3) a vegetarian diet satisfying the FAO recommendation of a required protein intake of 50 g/day, and assuming that half of the protein is coming from grain. If we assume a fixed grain waste of 20 %, the gross grain demand would be 830, 550 and 160 kg grain per capita per year for the three respective diets (Table 5). Given a mean grain yield of 5 t/ha, this infers that on average one hectare of cereal can feed 6–16 persons.

Current global grain production, under optimal trade and access to grains, would allow a diet in between a demitarian and vegetarian food choice (Fig. 6). Global mean supply of cereal per capita (for all uses) is projected to not increase in 2050 under SSP1H and SSP2M and slightly for SSP5L to 470 kg. Given projected diet changes to more western type diets, this confirms expectations of increasing grain insufficiency, and which underlines the urgency to curb current diet trends.

3.5. Uncertainty results

The outputs from the NBCalCer model with less uncertainty in terms of the interquartile range (IQR) are the shares of synthetic N, followed by NUE and N surplus, then followed by the total N pollution cost, the grain yields, and finally by the net benefit of synthetic fertilizer for grain production, and the BCR and the individual N pollution costs (Fig. 7). The key outputs of NBCalCer for policy support are total N pollution cost (expressed as percentage of GDP) and BCR which both are reasonably robust (generally limited by +/− 15 % or less) globally and in contrasting regions.

For the world, the IQR is lower than 25 % and the maximum difference from Q1 and Q3 to the reference value was lower than 15 % for all outputs (Table 6) except for the pollution cost calculation by NH_3 emission to $PM_{2.5}$ and human mortality (with IQR of 29.9 % and a maximum difference of 15.3 %). The differences from the median to the reference value are both positive and negative and differences from Q1 and Q2 and from Q2 and Q3 vary up to 23.9 % (for the case of the net benefit of synthetic fertilizer for grain production) reflecting the existing non-linearities of the model.

This general behavior applies to every region, with the outputs of N

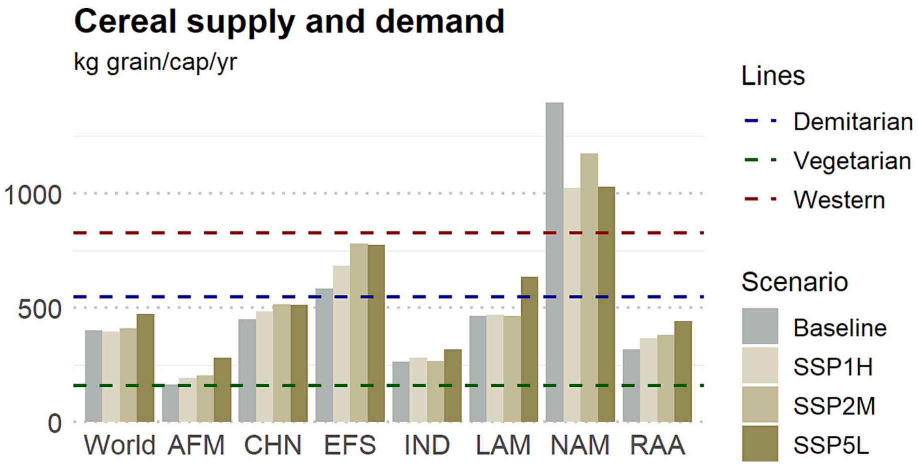

Fig. 6. Production of grain per capita in world regions (bars) as compared to grain demand for different food choices (horizontal dashed lines).

Table 5
Required cereal production for food and feed per global citizen for different diets.

Global Diet	Description	kg/cap/year
Western lifestyle	meat every day, with 50 % over consumption of protein	830
Demitarian	50 % animal protein assuming 40 % feed conversion efficiency	550
Vegetarian	50 % protein supply from cereals, rest from legumes	160

surplus and pollution costs the ones varying the most among regions (see Fig. S14).

4. Discussion

4.1. *Cereal production and sufficiency*

Projected increases of global cereal production in 2050 are almost one quarter (SSP1H) up to a half (SSP2M, SSP5L) higher than in the base year. This increase somewhat exceeds the growth of global population. This is also the case in most of the considered global AgMIP regions, with the exception of Africa and Middle East. Achievement of this increase of cereal production requires substantial increases of yield potential (*Ymax*), availability of N (synthetic N), utilization of N (NUE), and in several regions also some increase of crop area. We also find that currently, under given regional potential yields and crop areas for cereals, about half of the global grain production can be attributed to use of synthetic N fertilizer, which is consistent with Erisman et al. (2008). In spite of a small projected increase of grain supply per capita in most regions, the mean global supply would allow close to a demitarian diet, with modest portions of meat 2–3 days a week. In view of concerns about environment and biodiversity, increase of crop area and N input intensity is not a sustainable option to increase cereal supply per capita. While the metric of cereal sufficiency provides insight in risks of food insecurity and measures to prevent food insecurity by adjusting supply and demand, eradicating hunger is far more complex, depending also on global trade, differences in regional demand for food and other uses, and within regions, on local access and availability for grain.

4.2. *Nitrogen balance and environmental performance*

One key to produce more grain with less pollution is increasing potential yields (Mogollon et al., 2018; van Grinsven et al., 2022) combined with increased availability (so not input) and utilization of N, both by improved N management and regional redistribution of synthetic N fertilizer (Mueller et al., 2017; Smerald et al., 2023). Even our projection in the Sustainability scenario SSP1H does not show an increase of NUE nor a redistribution of synthetic N in cereal production. This indicates that even SSP1H does not use the theoretical potential of nitrogen productivity and efficiency. Only projections for India show a strong increase of NUE, which is the result of a strong increase of availability and efficiency of manure.

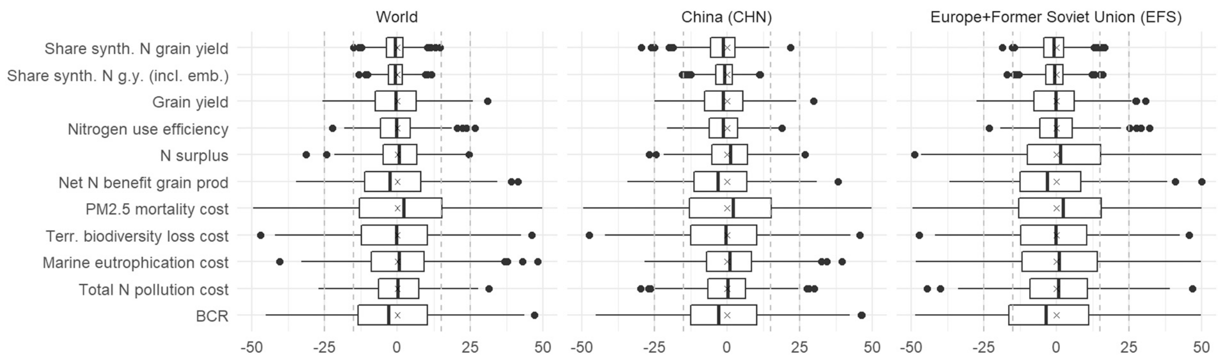

Fig. 7. Uncertainty results for all cereals and for both rainfed and irrigated for the base year, for the world and two contrasting regions, China (CHN) and Europe and Former Soviet Union (EFS), with boxplots expressing the percentual change of each variable with respect to the used value (represented at 0 % x). Vertical dotted lines are plotted at 15 % and 25 % distances.

Table 6

Reference value (Base) used for each variable, after aggregating all cereals, both rainfed and irrigated, for the base year scenario for the world, and the quartiles Q1, Q2 (median) and Q3 extracted from the 500 simulations at the Monte-Carlo analysis, both in relative and in absolute (in between brackets) terms.

Output	Base	Q1	Median	Q3
Share synth. N grain yield	0.44	−3.72 % (0.43)	−0.85 % (0.44)	1.9 % (0.45)
Share synth. N grain yield (incl. embedded)	0.55	−3.03 % (0.53)	−0.7 % (0.55)	1.78 % (0.56)
Grain yield	4.71	−7.52 % (4.36)	−0.47 % (4.69)	6.51 % (5.02)
Nitrogen use efficiency	0.53	−5.9 % (0.5)	−0.41 % (0.52)	4.52 % (0.55)
N surplus	69.16	−4.98 % (65.71)	0.64 % (69.6)	6.69 % (73.78)
Net N benefit grain prod	0.96	−11.26 % (0.85)	−2.65 % (0.94)	8.03 % (1.04)
PM2.5 mortality cost	25.84	−14.62 % (22.06)	1.14 % (26.13)	15.25 % (29.78)
Terr. biodiversity loss cost	45.53	−12.43 % (39.87)	−0.27 % (45.41)	10.46 % (50.29)
Marine eutrophication cost	70.80	−8.89 % (64.5)	0.49 % (71.14)	9.22 % (77.33)
Total N pollution cost	142.17	−6.58 % (132.81)	0.02 % (142.19)	7.35 % (152.61)
BCR	2.49	−13.28 % (2.16)	−2.83 % (2.42)	11.17 % (2.76)

The environmental performance of global cereal cultivation is best under the Middle of the road (SSP2M) scenario and surprisingly not in the SSP1H scenario. The latter likely is the effect of the lower projected grain prices in 2050 under SSP1H. Therefore, also cereal sufficiency is an additional indicator for benefits of increased cereal production. Cereal supply in 2050 increases in all SSPs in all global regions. This does not necessarily increase cereal sufficiency, which depends on dietary choice and its impact in the share of cereals used for feed. Under SSP1H one would expect that the consumer preference for animal products is lower than under SSP2M and SSP5L.

4.3. Uncertainty of scenario results

Based on our uncertainty analysis, we can conclude that our central results are quite robust supported with uncertainties generally <15 %. Our two key outputs are (1) N pollution cost expressed as a ratio with GDP and (2) Benefit – Costs ratios, which are especially robust as future changes of the numerator and denominator of both ratios are causally linked. However, uncertainties in results for 2050 could be higher than in base year, especially due to uncertainty of future prices of fertilizer and grain and future willingness-to-pay values underlying the marginal pollution damage costs. Also, the underlying assumptions for the used SSPs are uncertain. It should be kept in mind that widely used scenario sets like the SSPs are meant to explore contrasting long-term developments and do not represent unpredictable events like wars, pandemics and energy crises.

4.4. Reflection on cost-benefit assessment

Valuation data were mostly from European and North America studies and not available for other global regions. Therefore, valuation results for tropical low-income regions are more uncertain. Further, using GDP as the main variable to project future marginal costs per unit of N pollution may not be accurate as it is based on current variation of preferences across global regions. Future attitudes may change strongly, for example in the case of socio-economic disruptive effects of climate change, biodiversity loss, new pandemics, or food insecurity.

When comparing the costs to the benefits of N for cereal production in a SCBA, one could question if the net market benefits for farming are the proper counterweight for the social cost of N pollution caused by cultivation of cereals. One would tend to think that the social benefit of increased grain production should also include benefits for consumers, businesses, and the public sector. A simple first step could be to use an approximation of what a consumer pays for a unit of grain in cereal products (which could be referred to as the “food plate price”) instead of what a farmer receives (referred to as the “farm gate price”). However, there is no consensus on definition and no record on quantification of this hypothetical food plate price of a kg of grain (van Grinsven et al., 2022). The extension of a SCBA on N use in cereal systems to society as a whole, introduces a plethora of new questions and dilemmas. For example, there can be both public health costs and benefits related to a change in the supply of cereals. In the case of under-supply, typical for food insecure regions, there are effects on hunger and diseases caused by protein and other diet related deficiencies. In case of a change in over-supply, there are effects on incidence of obesity, diabetes and cardiovascular disease. In a SCBA for the global food system by Pharo et al. (2019) the global societal cost by obesity and hunger exceeded those from pollution, biodiversity loss and climate change by a factor of two. Regarding our partial SCBA for N and cereal production, one could argue that availability of cheap fossil energy and synthetic N fertilizer is one cause of availability of cheap cereal products, but quantifying the contribution of N to over-use of cereal products, obesity and related diseases would be a challenge beyond the scope of this analysis.

4.5. Use of social cost-benefit analysis for policy support and communication

A prominent use of SCBA in policy is for the revisions of the EU Ambient Air Quality Directive and its standards for $PM_{2.5}$. Valuation of air pollution mortality is well established and a SCBA for revision of this directive in 2022 concluded that the health benefits of stricter standards outweighed the mitigation cost by a factor of seven (EC, 2022). In addition to $PM_{2.5}$ mortality, our SCBA also includes costs for marine pollution and loss of terrestrial biodiversity by N losses, which are less well established than the cost of increased human mortality. Moreover, there is an ongoing public and political debate on the acceptability of a slower increase in future agricultural production as result of stricter N policies, given that 9 million people are dying each year from hunger and growing populations (WFP, 2021). Our SCBA approach however can help to design policies to reduce N losses from cereals systems and to evaluate cost and benefits of specific N mitigation projects including N emission application and buffer strips, with most chance of success in high income regions. Finally, our SCBA can also be applied for true pricing (Hendriks et al., 2021) or to establish nitrogen taxes (Johne et al., 2023).

5. Conclusions

To our knowledge this is the first global social cost benefit analysis for nitrogen use in cereal production under contrasting future scenarios for economic development, and climate and nitrogen policies (here the Shared Socio-Economic Pathways). This SCBA shows that the externalities of current and future N use for ecosystems and human health in the European continent and in North America are high and are close to outweighing the net market benefits of increased yields of cereals by N fertilizer use. In 2050 this likely also will become the case under the Sustainability (SSP1H) and the Conventional (SSP5L) scenario, in other global regions, foremost in Latin and North America. Our SCBA results also provide support for the recent policy ambitions in the EU (EC, 2020) and by the UN (UNEP, 2019) to halve N waste, as SCBA can turn this ambition into a financial case highlighting the welfare gains and fertilizer savings. In policy, perhaps unfortunately, "money tends to speak louder than words".

CRediT authorship contribution statement

A. Rodríguez and H. van Grinsven designed the study. A. Rodríguez: Software, Data Curation; A. Rodríguez, H. van Grinsven: Conceptualization, Validation, Formal analysis, Investigation; A. Rodríguez, H. van Grinsven, L. Lassaletta: Writing – Original Draft; All the authors gave conceptual advice and commented on the manuscript at all stages. All authors discussed these methods, as well as the results and their implications.

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.

Data availability

Data will be made available on request.

Acknowledgements

We acknowledge the International Nitrogen Management System project (INMS, http://www.inms.international/) funded by the Global Environment Facility (GEF) through the United Nations Environment Programme (UNEP). We are grateful to the Spanish Ministry of Science, Innovation and Universities (AgroSceNA-UP, PID2019-107972RB-I00).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2023.169357.

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