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Integrated modelling of fertilizer and climate change scenario impacts on agricultural production and nitrogen losses in Austria

Elisabeth Jost [a,*], Martin Schönhart [b], Hermine Mitter [a,c], Ottavia Zoboli [d], Erwin Schmid [a]

[a] University of Natural Resources and Life Sciences, Feistmantelstraße 4, 1180 Wien, Austria
[b] Federal Institute of Agricultural Economics, Rural and Mountain Research, Dietrichgasse 27, 1030 Wien, Austria
[c] University of Graz, Department of Environmental Systems Sciences, Universitaetsplatz 3, 8010 Graz, Austria
[d] Institute for Water Quality and Resource Management, TU Wien, Karlsplatz 13/226, 1040 Wien, Austria

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ABSTRACT

The European Commission's Farm to Fork strategy aims at reducing nutrient losses and fertilizer use, but has been criticized for its expected negative impacts on European economy, agriculture, and food supply. We apply an integrated modelling framework to analyze potential effects of fertilizer reductions on land use, nitrogen losses, and agricultural output of two fertilizer and four climate change scenarios. The fertilizer scenarios comprise a uniform 20 % reduction of mineral N fertilizer (f20) and a combination of several fertilizer restrictions (fcm). The model results indicate that the restrictions in fertilization lead to decreases in crop production of 6 to 9 %, whereas intensive and extensive grassland production increases. N losses to air, water, and soil are substantially reduced by 9 % (f20) and 20 % (fcm), yet fall short of the intended 50 % reduction. The regional heterogeneity of the model results shows that tailored measures need to be elaborated by taking climate change developments, the regional heterogeneity of prevalent farming systems, and bio-physical conditions into account. Uniform measures applied to the national policy context fall short to attain policy targets cost-effectively. N emission capping, taxes or managerial measures such as crop rotational N balancing are options to be explored in future research.

1. Introduction

The European Commission (EC) has launched an ambitious political process – the Green Deal – aiming to make "Europe the first climate-neutral continent" (European Commission, 2023a). A suite of policy strategies tackling key sectors and topics has been introduced, seeking to support goal achievement by 2050. One of these is the Farm to Fork (F2F) strategy, which aims to make food systems "fair, healthy and environmentally-friendly" (European Commission, 2023b). Key quantitative and qualitative targets have been defined such as the EC "will act to reduce nutrient losses by at least 50%, while ensuring that there is no deterioration of soil fertility" (European Commission, 2020, p. 7). Hence, the EC expects a reduction of fertilizer use by at least 20 % until 2030, compared to a three-year baseline comprising the average of 2015, 2016, and 2017.

The F2F strategy has been criticized for a perceived lack of ex-ante impact assessments, especially with regard to its effects on the agricultural sector and global food supply (cf. Wesseler, 2022). Several research and modelling efforts have responded to this critique. In particular, they have analyzed and quantified potential impacts of the formalized policy targets on the European economy, its agricultural sector, and international trade (Barreiro-Hurle et al., 2021; Bremmer et al., 2021; Henning et al., 2021; Schiavo et al., 2021). We add to this by providing analyses with higher spatial resolution and a modelling approach taking Austrian national framework conditions into account.

We respond to this policy planning problem by developing and applying an integrated modelling framework. It combines a crop rotation model, a bio-physical process model, a spatially explicit bottom-up economic land use optimization model, and a range of land use indicators in order to analyze the impacts of fertilizer and climate change scenarios on agricultural production in terms of yields, land use and management, on the net benefits of crop and grassland production as well as on the environment in Austria. Hence, we explore the nexus of climate change, agriculture and nitrogen (N) in terms of reactive N losses in agricultural production into air (i.e. nitrous oxide - N_2O and ammonia - NH_3), into water via leaching or runoff (i.e. nitrate - NO_3^- and

* Corresponding author.
E-mail address: elisabeth.jost@boku.ac.at (E. Jost).

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ammonium - NH_4^+) and into soil via sediment transport (i.e. organic N - N_{org}). The model results shall support national policy actors in developing cost-effective and spatially tailored measures to reduce nitrogen losses in agriculture.

Reactive N inputs into the environment mainly originate from fertilizer application and to a lesser extent from biological fixation and deposition (Pan et al., 2022). Hence, agriculture is the key sector responsible for N inputs. It is estimated that globally roughly 50 % of mineral and organic fertilizers applied to agricultural land is lost to the surroundings (Erisman et al., 2013). A wide range of concerns relates to this: the production and use of nitrogen fertilizers is energy intensive and generates approximately 5 % of global greenhouse gas (GHG) emissions (Gao and Cabrera Serrenho, 2023), NH_3 causes air pollution and impairs human respiratory health, and leaching of NO_3^- or NH_4^+ causes acidification and eutrophication of both marine and terrestrial ecosystems and deterioration of groundwater bodies. With regard to NO_3^-, it is assumed that roughly 50 % of total global NO_3^- lost to water bodies originate from agriculture (UNEP, 2019). N_2O is a potent GHG contributing to climate change. N loss via sediment transport may cause N accumulation in natural ecosystems (leading to changes in fungal and microbial communities or decreases in soil biodiversity), and cause changing rates of N and C (carbon) cycling reducing nutrient persistance (Berhe et al., 2018; Quinton et al., 2010; Velthof, 2011). Economic analyses estimated a total social cost associated with pollution by agricultural N in the EU between 75 and 485 billion € per year (van Grinsven et al., 2013, see also Leip et al., 2022; de Vries et al., 2021). For the EU, Sutton (2011) estimated that costs of annual N-related damage range between 70 and 320 billion €, which is more than twice as much as N fertilizers create in income. A detailed summary on the case of N in Austrian agriculture can be found in the appendix section A-1.

Considering the high societal stakes and the strong spatial heterogeneity of relationships between N management and the environment (cf. Billen et al., 2024), this study contributes to prevalent research gaps in three ways. First, it considers N loss via air, water and soil through sediment transport by accounting for the heterogeneity of spatial conditions and bio-physical processes as well as management practices. Second, it goes beyond catchment or case-study area extents (Kasper et al., 2019; Schroeck et al., 2019) to the level of agricultural production regions and EU member state analysis, which is key for policy design. Austria, i.e. the national level, is the typical spatial and administrative unit for implementation of the European Union's Common Agricultural Policy (CAP) such as the agri-environmental programme ÖPUL. The programme comprises compensatory payments for voluntary measures taken by farmers (BML, 2024). Third, it provides results for cropland, extensive and intensive grassland, and it models not only representative crops per crop group but differentiates 23 crops which are cultivated on about 90 % of Austrian cropland. We also provide results of uncertain climate futures by exploring four climate change scenarios. This accounts for the relevance of climate change in agricultural production and helps to understand the long-term consequences of policy decisions taken now (Riahi et al., 2017). The fertilizer scenarios support the F2F strategy implementation with respect to alternative policy designs and the spatial influences of soil, land use and fertilizer management.

2. Data and methods

2.1. The integrated modelling framework

The integrated modelling framework (IMF) applied in this study consists of the crop rotation model CropRota (Schönhart et al., 2011), the biophysical process model EPIC (Izaurralde et al., 2017; Izaurralde et al., 2006; Williams, 1995), and the spatially explicit bottom-up economic land use optimization model BiomAT (Karner et al., 2019). It provides results at 1 km grid resolution of agricultural land by comparing a historic reference period (1981–2010) to a future period (2041–2070). Besides other bio-physical and economic datasets, we employ information provided by a recently updated N-balance calculation for Austria (BMLRT, 2020, see section 2.2). The IMF has been successfully applied and validated in different study contexts of Austrian agriculture (cf. Karner et al., 2019; Feusthuber et al., 2017; Mitter et al., 2015; Stürmer et al., 2013). An overview of the IMF and model interfaces are provided in Fig. 1. Details regarding model features, employed datasets and scenario formulation are described in the following sections.

CropRota is applied to obtain typical shares of crop rotations for each municipality in Austria (Schönhart et al., 2011). CropRota uses reported land use data from the Integrated Administration and Control System (IACS, 2012–2014) and an expert-based agronomic score matrix that values pre-crop and main-crop sequences of 23 crops by its agronomic suitability. CropRota is a linear programming model maximizing the total value of agronomic suitability over all crop rotations at municipal level subject to reported crop shares and crop rotation restrictions. By considering crop rotations, we acknowledge the fact that average annual fertilization and irrigation differs between crops influencing plant growth and nutrient flows. The crop rotations are proportionally and spatially assigned to 1 km cropland grid cells. The reference and two alternative crop rotations feed into the bio-physical process model EPIC and land use optimization model BiomAT.

EPIC (version EPIC0810) is a bio-physical process model, which simulates major processes of agro-ecosystems at a daily time step. It is applied at a spatial resolution of 1 km for agricultural land in Austria. The model is driven by daily weather data (min/max temperatures, precipitation, solar radiation, humidity, wind speed), geomorphological conditions (e.g. soil type, elevation, slope) as well as data on agricultural management practices (e.g. planting, harvesting, tillage, fertilization, crop protection, irrigation and crop rotations). EPIC simulates important hydrological processes such as evapotranspiration, surface runoff including volume and peak rate, and subsurface flow in the root zone including lateral flow and percolation to shallow groundwater as well as groundwater table dynamics, return flow and deep percolation. EPIC simulates wind and water erosion by offering six erosion equations including, for instance, USLE (universal soil loss equation) and RUSLE (revised universal soil loss equation). Nutrient dynamics of N and P (phosphorus) mirror several processes. Modelled N processes include mineralization, immobilization, denitrification, volatilization, nitrification and crop nutrient uptake as well as soluble and adsorbed N in surface runoff, and lateral and vertical subsurface flow. Plant growth including root growth can be simulated for more than 100 parameterized crops. Potential daily growth is based on radiation and a leaf-area-index whereas actual growth is constrained by available water, temperature, nutrients and aeration. Carbon dioxide (CO_2) affects both plant growth and water use. In addition, plant competition is modelled for water, nutrients and light as a function of the leaf-area-index and plant height. Crop yield (either grain yield or total harvestable biomass) removed from the field, is a function of a harvest index and above-ground biomass. Hence, supply and demand of nutrients and water is calculated for every day, which drives, inter alia, plant growth including above-ground biomass and roots. Modelling of C dynamics include three major components such as C—N transformations, crop growth and management. The C—N transformations are modelled by five pools including structural litter, metabolic litter, soil microbial biomass, slow humus and passive humus. This includes modelling of driving factors of transformation such as temperature, soil water, oxygen and tillage. Actual C and N transformation is based on N supply and demand as well as on the demand established by the potential C transformation of the source and the C/N ratio of the receiving compartment.

EPIC provides annual outputs – inter alia – on crop yields as well as on mineral (N_{min}) and organic (N_{org}) N flows including losses into air, water as well as soil through sediment transport. In particular, we consider the loss of mineral NH_3-N and N_2O-N to the atmosphere. The loss of N_{min} to surface and groundwater includes runoff, percolate, and lateral subsurface flow mainly as NO_3^--N and NH_4^+-N. In addition, we

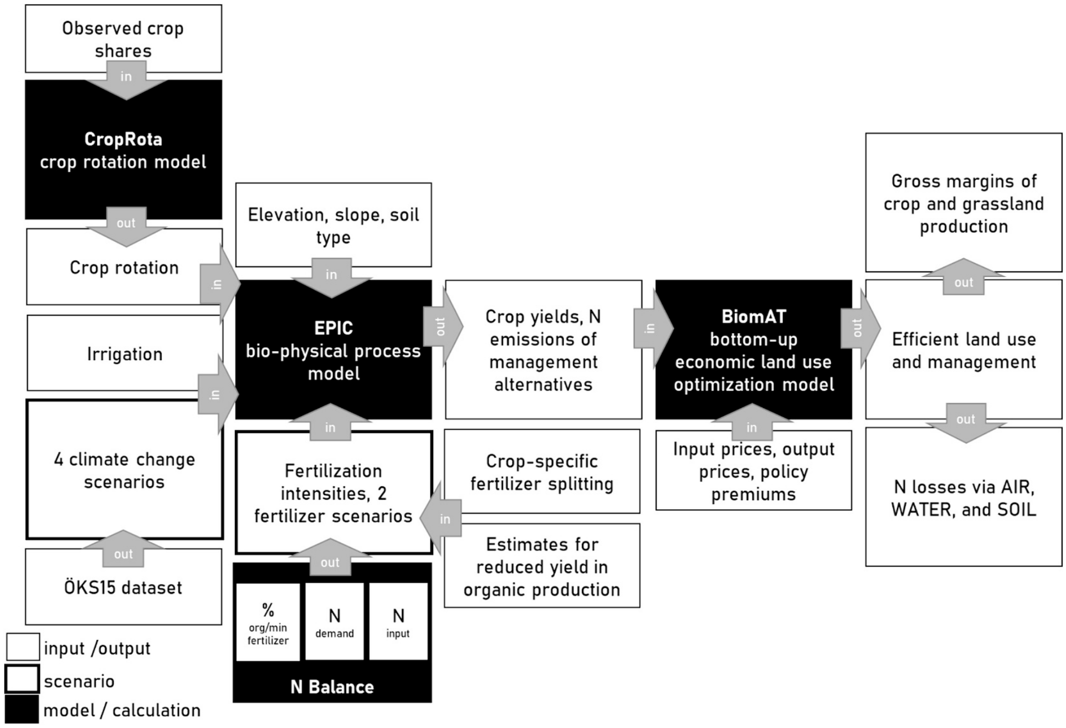

Fig. 1. Schematic illustration of the integrated modelling framework (IMF).

consider N_{org} lost through sediment transport. Hence, a nutrient loss in EPIC means that the nutrient is not available for plant growth. Since EPIC is a plot scale model and individually applied to each grid cell of agricultural land in Austria, transport of water, nutrients and sediment across grid cells are not considered in the analysis. Therefore, the total N loss is the sum of individual loss categories and grid cells in a region.

The EPIC outputs by grid cell and for specific crop management options are input to BiomAT. BiomAT is a bottom-up, spatially explicit agricultural land use optimization model that maximizes total net benefits of crop and grassland production subject to agricultural land endowments at 1 km grid resolution in Austria. BiomAT seeks to find efficient combinations of agricultural land use and management options and is applied to fertilizer and climate change scenarios (see section 2.3). Results are given as the mean of a 30-year timespan for both the historic reference period (1981–2010) and the future period (2041–2070). BiomAT is calibrated to the historic reference period employing the duality theory in mathematical programming (Karner et al., 2021; Mitter and Schmid, 2021; Feusthuber et al., 2017). The objective function is stated as follows:

$$max\ NB = \sum_{i,j,k} GM_{i,j,k} x_{i,j,k} - \begin{cases} \sum_{i,j} \frac{\eta_{i,j} \widetilde{x}_{i,j}^{\alpha}}{\alpha \left(x_{i,j}^{0}\right)^{(\alpha-1)}}, & x_{i,j}^{0} > 0 \\ \sum_{i,j} \eta_{i,j} \widetilde{x}_{i,j} & x_{i,j}^{0} = 0 \end{cases} \tag{1}$$

In the objective function (eq. 1), which maximizes net benefit of agricultural production (NB_{max}, in €), GM refers to gross margins (in €/ha), and x is land use (in ha). The index i denotes the grid cell, with I = 71,604, j the land cover type, with J = 4 (cropland, intensive grassland, extensive grassland, and alpine pastures), and k represents land management practices, with K = 13 (including three alternative crop rotations; three tillage systems such as conventional tillage, reduced tillage, and conventional tillage with winter cover crops; three fertilizer application levels of which one is the reference level derived from N-balance calculations (see section 2.2) and two scenario based levels; rainfed and irrigated cropland and grassland; two mowing frequencies and pasturing). Specific land management practices k are attributed to specific land cover types j (e.g. tillage is not available for grassland but becomes available after land cover conversion from grassland to cropland). Related assumptions are i) no additional costs for land cover transitions, e.g. from cropland to grassland, which adds flexibility to the model, ii) the sum of grassland types (i.e. intensive and extensive grassland, and alpine pastures) does not decline in the grid cell, which is in accordance with national regulations, iii) land cover change within each 1 km grid cell is restricted to land cover types of grassland and cropland available in the historical reference period (1981–2010), and iv) agricultural land cannot be abandoned.

The first term of the objective function sums the product of gross margins and land use for each i, j, and k. GM includes a linear (i.e. variable) cost component from standard gross margin calculations. The second term represents the non-linear cost function. The product of the marginal value η for each i,j and modelled land use $\widetilde{x}$ (defined by Eq. 3) to the power of the coefficient α is divided by observed reported land use from the calibration period x^0 and summed over grid cell i and land cover type j. The coefficient α is assumed to be 2 representing a quadratic cost function, which is usually used if further information is not available (see e.g., Howitt, 1995). For technical reasons, the quadratic part of the cost function is used if the observed land cover type is greater than zero, otherwise the linear part is used in the model. It is assured that the model is also calibrated to the reference crop rotation in each cropland grid cell i.

The equality eqs. 2 and 3 ensure that land use $\widetilde{x}_{i,j}$ summed over management practices k equals total land endowment b by land cover type j and grid cell i.

$$\sum_{j} \widetilde{x}_{i,j} = b_{i,j} \forall i,j \tag{2}$$

$$\widetilde{x}_{i,j} = \sum_{k} x_{i,j,k} \forall i,j \tag{3}$$

Gross margins of crop and grassland production are calculated considering simulated yields from the EPIC model, variable production costs derived from standardized gross margins (AWI, 2016), commodity prices representing three-year average from Statistics Austria (2015–2017), and the CAP premiums comprising direct payments and the agri-environmental programme.

The IMF provides all results on the level of 1 km grid cells and aggregated units such as regional and national sums and means as well as for the historic reference period (1981–2010) and the future period (2041–2070). We report the results at the level of eight agricultural production regions (landwirtschaftliche Produktionsgebiete) in Austria: the Alpenostrand (AOR), the Alpenvorland (AVL), the Kärntner Becken (KB), the Hochalpen (HA), the Nordöstliche Flach- und Hügelland (NFH), the Südöstliche Flach- und Hügelland (SFH), the Voralpen (VA), and the Wald- und Mühlviertel (WMV). The agricultural production regions comprise similarities in landscape, topography and altitude in high alpine (Hochalpen), alpine (Voralpen, Alpenostrand), to non-alpine (Alpenvorland, Wald- und Mühlviertel, Nördöstliches Flach- und Hügelland, Südöstliches Flach- und Hügelland) regions. The categorization of Austrian national territory into the eight agricultural production regions was derived from a cluster analysis for improving the basis for national agricultural statistics (Wagner, 1990a, 1990b). It is widely used (e.g. Strenge et al., 2023) and improves the comparability of different studies. Topographic and soil characteristics of each region are summarized in Table 1. The regions' geographic locations can be retrieved from appendix Fig. A-1.

We further deploy Getis-Ord-Gi* hotspot analysis (Esri, 2023) to provide detailed spatially explicit insights on N losses. Getis-Ord-Gi* hotspot analysis is a spatial statistics technique, assessing the concentration of high and low values within a geographic dataset by statistically evaluating levels of N loss of each spatial grid cell based on the values of neighboring locations. As an advantage to other alternatives like Moran's I or Geary's C, it identifies areas with statistically significant hotspots (clusters of high values) and coldspots (clusters of low values) to reveal spatial patterns and trends in the data (cf. Braithwaite and Li, 2007). The method is widely used for local hotspot identification across scientific fields from research on agricultural water management (Mitter and Schmid, 2019), environmental radioactivity (Mtshawu et al., 2023) to tectonic activity (Pal et al., 2023).

2.2. Using nitrogen balance data in the biophysical process model EPIC

We use the N-balance calculations by the Austrian Federal Ministry of Agriculture, Regions and Tourism for the years 2015–2018 (cf. Strenge et al., 2023; BMLRT, 2020) to differentiate for regional fertilization intensities on cropland and grassland as well as for crop-specific types of fertilizers.

With an R routine (The R Foundation, 2023), we transfer the N-balance data to the national territory based on regional yield potentials. Yield potentials are derived from yield estimates of Statistics Austria at district level (Statistik Austria, 2023), which in combination with official crop and yield-specific recommendations for N fertilization (BMLRT, 2017) serve to define an associated crop-specific N-demand at the municipal level (disaggregated from the district level). The novel calculation method further employs the N-balance data to derive crop-specific shares of mineral and organic fertilizer. We use the available data on the mean annual amount of applied N fertilizer from manure (organic) and commercial (mineral) fertilizers. We have defined three organic fertilizer regimes such as a 0 %, 50 % or 100 % share of manure fertilizer, based on the N-balance calculations of regionally available amounts of manure from livestock production and the associated crop-specific N demand and application (cf BMLRT, 2017). For example, field beans, field peas, soybeans and winter rape do not receive any manure fertilizer, whereas extensively managed grasslands receive 100 % N from manure fertilization.

The number of N-fertilizer applications (i.e. splitting) and the corresponding N-levels are determined based on crop- and climate-specific recommendations (Sinaj et al., 2017). Single applications below 20 kg N ha^{-1} are added to the previous application. Single applications of manure on cropland may not exceed 100 kg N ha^{-1}. On grassland, a partial application is limited to max. 70 kg N ha^{-1} from manure. It is also assumed that manure is applied first, i.e. before mineral fertilizer. Timing of fertilization is determined crop-specific in EPIC using heat unit scheduling of plant growth stages.

Finally, the mean annual amount (2015–2018) of applied N fertilizer provided from the N-balance calculation is used to define the reference fertilization level from which the two fertilizer scenarios are derived (see section 2.3).

2.3. Socio-economic conditions and scenarios of fertilization and climate change

IMF setup and implementation requires assumptions regarding the socio-economic conditions and their future developments. We keep socio-economic conditions, i.e. costs of agricultural inputs, prices of agricultural commodities, and subsidy levels, constant in all scenarios (see section 2.1). Similarly, livestock production levels and utilizable agricultural land are kept constant in all scenarios. These assumptions serve the analytical purpose of the present study to model the effects of climate change and fertilizer management on N losses and agricultural production.

Table 1
Characteristics of the agricultural production regions in Austria regarding area size, average annual mean temperature and precipitation as well as average slope, soil clay content, soil pH, soil bulk density, and soil organic carbon content. Values in brackets depict standard deviations. (Source: eBOD (cf. Aust, 2007)).

Name (in German)	Acronym	Area (km^2)	⌀ annual mean temperature (°C)	⌀ annual precipitation (mm)	⌀ slope (%)	⌀ soil clay content (%)	⌀ soil pH	⌀ soil bulk density (t m^{-3})	⌀ soil organic carbon in plough layer (t ha^{-1})
Alpenostrand	AOR	10,971	7.1 (±1.6)	1013 (±211)	24 (±12)	10 (±5)	5.4 (±0.8)	1.4 (±0.2)	52 (±19)
Alpenvorland	AVL	8588	9.2 (±0.5)	1039 (±237)	8 (±7)	17 (±7)	5.9 (±0.8)	1.3 (±0.2)	40 (±22)
Hochalpen	HA	29,742	4.2 (±2.8)	1355 (±325)	39 (±17)	12 (±7)	5.7 (±1)	1.3 (±0.2)	67 (±24)
Kärntner Becken	KB	2497	8.2 (±1.2)	1015 (±155)	14 (±11)	11 (±6)	5.5 (±0.9)	1.3 (±0.3)	52 (±25)
Nö. Flach- u. Hügelland	NFH	10,185	10.1 (±0.5)	591 (±62)	4 (±4)	22 (±9)	7.0 (±0.8)	1.4 (±0.1)	30 (±12)
Sö. Flach- u. Hügelland	SFH	5023	9.8 (±0.4)	851 (±100)	9 (±7)	19 (±8)	5.4 (±0.7)	1.4 (±0.1)	37 (±13)
Voralpen	VA	9251	7.6 (±1.4)	1498 (±387)	24 (±12)	22 (±9)	6.0 (±0.9)	1.2 (±0.2)	63 (±25)
Wald- u. Mühlviertel	WMV	7547	7.8 (±0.7)	791 (±132)	10 (±6)	11 (±5)	5.1 (±0.7)	1.4 (±0.2)	47 (±22)

Based on the F2F policy targets of 50 % reduction in nutrient losses via 20 % reduction in mineral N fertilization (European Commission, 2023b), two scenarios are implemented encompassing measures for adapted fertilizer application. These scenario specifications replace model parameters of the reference fertilization scenario as specified in 2.2. The first fertilizer scenario (f20) implements a uniform 20 % reduction of mineral N fertilizer, whereas the second fertilizer scenario (fcm) comprises several combined fertilizer restrictions: −20 % mineral N fertilizer application (= f20) combined with maximum application of 175 kg N ha^{-1} on crops, except for temporary grassland (BMLRT, 2017), and no mineral N fertilizer application on permanent grassland. Fig. 2 shows the amount of N fertilizer applied on cropland and grassland in the reference scenario as well as the f20 and fcm scenarios at 1 km grid resolution in Austria.

Furthermore, we use four contrasting, regionally downscaled climate change scenarios for a reference period (1981–2010) and a future period (2041–2070). These were chosen to represent moderate (ICHEC45, ICHEC85), dry (MOHC45) and wet (IPSL85) conditions as well as moderate (RCP4.5: MOCH45, ICHEC45) and strong (RCP8.5: ICHEC85, IPSL85) climate forcing in Austria. Details on the respective climate change scenarios can be found in appendix section A-2.

We apply two procedures to differentiate the impacts of climate change and fertilizer scenarios: i) climate change impacts for the future period under reference fertilization (2041–2070) are analyzed in comparison to a historical reference period (1981–2010); ii) the fertilizer scenario impacts are analyzed by comparing the situation with reference fertilization to the situation with fertilizer scenarios fcm and f20 in the same (future) time period (see Table 2).

The IMF offers several land use indicators, which help draw policy-relevant conclusions for the implementation of measures in attaining F2F policy targets. Results are provided on fertilizer use amounts, N losses to water and air as well as soil, agricultural production, land use and management choices, as well as total net benefits of agricultural production.

3. Results

3.1. Fertilizer and climate change scenario effects on yields, agricultural land use and management

EPIC and BiomAT provide results on crop yield developments as well as land use changes for the fertilizer and climate change scenarios at 1 km grid resolution. When comparing the historic reference and future period under reference fertilization, changes in yields and land use are visible across all climate change scenarios, yet most prominently for the more pronounced climate change scenarios MOHC45 (dry, moderate forcing) and IPSL85 (wet, strong forcing). The modelling results suggest yield increases for soybeans (4–17 %), alpine pastures (~ 5 %), intensively managed grasslands (15–29 %) as well as winter wheat (~ 2 %). On Austrian average, they show a decrease in cropland area (MOHC45: -10 %, IPSL85: -10 %, ICHEC85: -9 %, ICHEC45: −8 %) as well as in area of extensive grasslands and alpine pastures, whereas intensively managed grassland area increases through cropland conversion (see Table 3). Largest areas of extensive grassland and alpine pastures are modelled for the IPSL85 climate change scenario with wet conditions and strong climate forcing.

In the fertilizer scenarios f20 and fcm, model results indicate a further increase in extensively managed grassland area (7 % with IPSL85) accompanied by further decreases in cropland area (f20: ∅ -3 %, fcm: ∅ -3 %), compared to the situation with reference fertilization. More specifically, BiomAT results indicate a decrease in cultivation area for forage crops, cereals, root crops, and oilseeds in all fertilizer scenarios and climate change scenarios. Relative area decreases for these crop groups range between 1 % (fcm, oilseeds in MOHC45/IPSL85 and grain legumes in ICHEC85) and 7 % (fcm, forage crops in ICHEC85).

The BiomAT model entails information on irrigated area for the respective climate change and fertilizer scenarios. Please note that the model results presented in the following, show the potential irrigation requirement regardless of the actual water availability in a region or area. During the historical reference period (1981–2010), only 1 % of the total agricultural land is irrigated, of which 99.7 % are located in the non-alpine, cropland dominated Nordöstliches Flach- und Hügelland (NFH) region. For the future period, model results suggest a reduction in irrigated area to 0.1 % (IPSL85), 0.6 % (ICHEC85), and 0.9 %

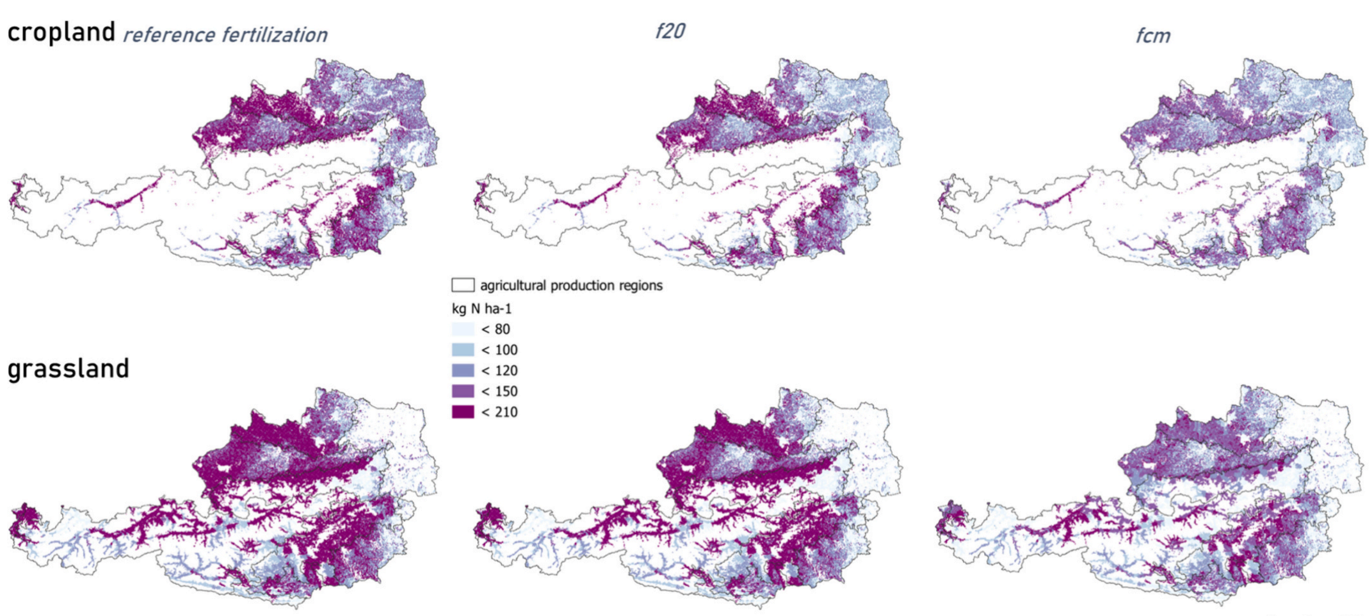

Fig. 2. Calculated N fertilizer applications on cropland (above) and permanent grassland (below) in kg N ha^{-1} for reference fertilization, f20 and fcm fertilizer scenarios in Austria.

Table 2
Overview on characteristics and data sources of applied climate change and fertilizer scenarios.

Scenarios	Characteristics	Sources / Data
Climate change		
• **impact analysis: relative changes derived from comparing the historic reference period (1981–2010) to the future period (2041–2070) under reference fertilization (i)**		
a) MOHC45	• Representative Concentration Pathway 4.5 (moderate forcing) • Temperature increase (from reference period 1971–2000) until end of century: 1.8–3.5 °C (Austria) • Dry (Austria) • Simulation: MOHC-HadGEM2-ES_rcp45_r1i1p1_CLMcom-CCLM4–8-17 • Resolution: 1 km, daily	ÖKS15 (EURO-CORDEX, Chimani et al., 2016)
b) ICHEC45	• Representative Concentration Pathway 4.5 (moderate forcing) • Temperature increase (from reference period 1971–2000) until end of century: 1.8–3.5 °C (Austria) • Moderately dry (Austria) • Simulation: ICHEC-EC-EARTH_rcp45_r1i1p1_KNMI-RACMO22E • Resolution: 1 km, daily	ÖKS15 (EURO-CORDEX, Chimani et al., 2016)
c) ICHEC85	• Representative Concentration Pathway 8.5 (strong forcing) • Temperature increase (from reference period 1971–2000) until end of century: 3.3–5.3 °C (Austria) • Moderately dry (Austria) • Simulation: ICHEC-EC-EARTH_rcp85_r1i1p1_KNMI-RACMO22E • Resolution: 1 km, daily	ÖKS15 (EURO-CORDEX, Chimani et al., 2016)
d) IPSL85	• Representative Concentration Pathway 8.5 (strong forcing) • Temperature increase (from reference period 1971–2000) until end of century: 3.3–5.3 °C (Austria) • Wet (Austria) • Simulation: IPSL-CM5A-MR_rcp85_r1i1p1_IPSL-INERIS-WRF331F • Resolution: 1 km, daily	ÖKS15 (EURO-CORDEX, Chimani et al., 2016)
Fertilization		
• **impact analysis: relative change derived from comparing reference fertilization (i) to fertilization scenarios (ii,iii) with the same climate change scenario in future time period (2041–2070)**		
i) reference fertilization	• Crop-specific N fertilizer applied (based on livestock numbers, yield statistics and fertilization recommendations) • Resolution: municipality level	BMLRT, 2020 Statistik Austria, 2023 BMLRT, 2017
ii) f20 (uniform measure)	• Uniform −20 % mineral N fertilizer application	Own calculation BMLRT, 2017
iii) fcm (combined measures)	• −20 % mineral N fertilizer application (= f20) • maximum application of 175 kg N ha^{-1} on crops, except for temporary grassland • no mineral N fertilizer application on permanent grassland	Own calculation BMLRT, 2017

(ICHEC45), respectively. In climate change scenario MOHC45 where reductions in precipitation are most pronounced, irrigated area increases to approximately 5 % of the total agricultural land (see Fig. 3) and expands into all agricultural production regions. Of the total irrigated area in MOHC45, 36 % are located in the WMV, another 36 % in the NFH, and 9 % in the AOR region, all located in the eastern parts of Austria. The reduction of irrigated agricultural land by about 20 % is almost equal in f20 and fcm, compared to reference fertilization. These changes take place in the NFH region only. Relative changes in irrigation in f20 and fcm scenarios compared to reference fertilization range between −6 % and − 1 % (MOHC45), −22 % and − 20 % (ICHEC85), and − 28 % and − 27 % (ICHEC45).

3.2. Fertilizer and climate change scenario effects on total net benefits of crop and grassland production

The economic implications of responses in agricultural production to the climate and fertilizer scenarios from BiomAT are summarized in Table 4.

Compared to the historic reference period with reference fertilization, total net benefits of crop and grassland production increase across all climate change scenarios between 20 % – 64 %. Fertilizer scenarios f20 and fcm show opposite effects on total net benefits from agricultural production. Compared to reference fertilization in the respective (i.e. unchanged) climate scenario, fertilizer scenario f20 shows a reduction in net benefits between 2 % (MOHC45) and 4 % (IPSL85). Fertilizer scenario fcm yields higher total net benefits than the scenario with reference fertilization across all climate change scenarios. Yet, increases are small. They range between 0.1 % (ICHEC85) and 1 % (IPSL85).

3.3. Fertilizer and climate change scenario effects on N fertilizer input and N losses via air, water, and soil

BiomAT results show an increase in N fertilizer application between 3 % (IPSL85) and 7 % (ICHEC85) when comparing the climate change scenarios with the historic reference period (114.9 kg N ha^{-1} a^{-1}). In fertilizer scenarios f20 and fcm, total N inputs are reduced by around 9 % and 20 %, compared to the reference fertilization.

In the historic reference period, the largest share of N is lost in water, i.e. either through percolation (67.5 %), surface runoff (13 %) or lateral subsurface flow (4 %). Gaseous N losses account for 15 % of total N losses, with N volatilization in the form of NH_3^--N accounting for 14 % and N_2O-N for 0.8 % of total N losses. A rest of 0.6 % is lost as N_{org} through soil sediment transport (appendix table A-6). Fig. 4 depicts the differences between spatially-explicit hotspots of N loss in air, water and soil for the historic reference period and their climate change induced changes in the dry scenario MOHC45 (figures for climate change scenarios ICHEC45, ICHEC85, and IPSL85 can be found in the appendix, section A-6).

With reference fertilization, the climate change scenarios MOHC45 and ICHEC45 result in decreases of total N loss (−8.4 % and − 0.3 %, compared to the historic reference period), wherase the climate change scenarios ICHEC85 and IPSL85 result in increases of total N loss (+0.1 % and 9 %, compared to the historic reference period). Losses of NO_3^- in surface runoff either increase (IPSL85, ICHEC85) or decrease (MOHC45, ICHEC45), depending on altered precipitation and temperature regimes induced by the climate change scenarios. Magnitudes of change differ widely among the climate change scenarios. For N losses in percolate, increases are simulated for IPSL85 and ICHEC45, whereas decreases are simulated for MOHC45 and ICHEC85. N losses in lateral subsurface flow increase in the scenarios with higher precipitation, i.e. ICHEC45, ICHEC85, and IPSL85 by 5–14 % but decrease in the dry MOHC45 scenario by 10 %, compared to the reference period. N_2O-N losses decrease across all climate change scenarios. NH_3-N losses increase in IPSL85, ICHEC85, and ICHEC45, whereas they decrease in MOHC45. N_{org} losses through soil sediment transport increase in all climate change scenarios with largest relative increases of 136 % in IPSL85. Overall N loss is largest in the wet IPSL85 and lowest in the dry MOHC45.

Compared to the situation with reference fertilization for the future period, the implemented fertilizer scenarios result in an overall decrease of total N loss (Table 5). In fertilizer scenario f20, N losses to air increase in ICHEC45 and ICHEC85 but decrease by 4.6 % in MOHC45 and by 0.2 % in IPSL85. N losses via water increase in both fertilizer scenarios in the wet climate change scenario IPSL85. In f20, largest decreases (−11 %)

Table 3
Relative changes (%) in area extents of land cover and crop groups by climate change scenarios MOHC45, ICHEC45, ICHEC85, and IPSL85 (reference fertilization, historic reference period vs. future period) and fertilizer scenarios f20 and fcm (future period, reference fertilization vs. fertilizer scenario with the respective climate change scenario).

	Cereals	Forage crops	Grain legumes	Oilseeds	Root crops	Intensive grassland	Extensive grassland and alpine pasture	Others
Reference fertilization*								
MOHC45 dry/moderate forcing	−9.6	−16	−4.9	3.2	−10	23	−10.7	−15
ICHEC45 moderately dry/moderate forcing	−7.0	−13	−14	−1.6	0.1	23	−2.4	−5.8
ICHEC85 moderately dry/strong forcing	−8.6	−15	−14	−2.5	1.7	25	−17.1	−7.7
IPSL85 wet/strong forcing	−9.5	−14	−10	−4.3	−4.7	17	−16.3	−12
*f20 (uniform)***								
MOHC45	−3.2	−2.0	0.3	−1.6	−2.2	1.1	4.6	1.8
ICHEC45	−3.1	−2.7	−0.6	−3.6	−1.4	1.6	2.6	1.3
ICHEC85	−4.6	−4.1	−0.4	−3.0	−2.5	1.4	3.3	0.7
IPSL85	−3.3	−1.7	0.4	−1.8	−2.5	1.5	6.0	1.8
*Fcm (combined)***								
MOHC45	−3.3	−3.9	−0.4	−1.1	−2.4	0.5	6.0	1.6
ICHEC45	−2.9	−3.4	−0.9	−3.2	−1.6	1.8	3.7	1.3
ICHEC85	−5.1	−7.0	−1.1	−3.1	−2.8	1.6	4.6	0.3
IPSL85	−3.5	−3.8	−0.2	−1.1	−2.7	2.4	6.8	1.7

* relative change derived from comparing historic climate (1981–2010) to future climate (2041–2070) without changes in fertilization.
** relative change derived from comparing reference fertilization to fertilizer scenarios with the same climate change scenario for the future time period (2041–2070).

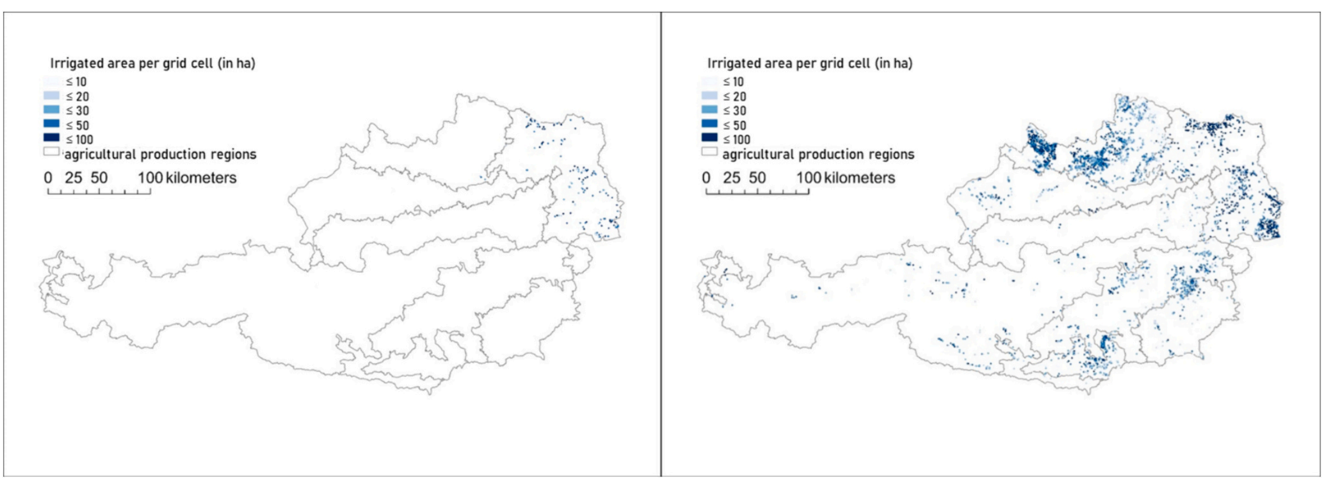

Fig. 3. Irrigated area per grid cell (ha) with reference fertilization for the historic reference period (left) and the future period in climate change scenario MOHC45 (right).

are modelled for drier conditions such as with MOHC45 for N losses via water. In fcm, largest overall reductions of 18 % are reached for N loss to water in climate change scenario MOHC45, compared to reference fertilization.

Fig. 5 depicts the relative change of N losses to air, water and soil through sediment transport, compared to the relative changes in N fertilizer application rates (FTN) by climate change scenarios and regions. Relative changes indicate differences between the historic reference period and the future period. Increase in N fertilizer inputs between the historic reference period and the future period is largest in regions HA, AOR, and WMV, i.e. across high alpine, alpine and non-alpine landscapes. Regional decreases in N inputs are modelled for three non-alpine regions, i.e. SFH in the wet IPSL85 and dry MOHC45, for NFH in dry conditions (MOHC45), and for AVL in the wetIPSL85 climate change scenario. Except for N losses to air, we see that higher N fertilizer input does not necessarily increase N losses. Climate change induced differences in N losses between the historic reference and the future period are comparably small for N losses to air and large for N losses to water. N losses to soil show different regional responses with regard to climate change scenarios. For example, in the dry MOHC45 scenario, increases in N losses are substantially lower in the non-alpine SFH, KB and high alpine HA regions, whereas substantially higher in the cropland dominated NFH region.

As for climate change induced variability between the historic reference and the future scenario period, regional peculiarities are also evident for changes in N losses as results of the reductions in N fertilizer inputs in fertilizer scenarios f20 and fcm (Fig. 6). Fertilizer scenario f20, for example, yields a −16 % change in N-fertilization intensity for the non-alpine NFH, whereas a reduction of merely 4 % is reached in the high alpine HA region, where hotspots of N losses to air and water are located (cf. Fig. 4). Reductions in N applied as fertilizer are larger for fcm than f20, with highest reductions in the alpine VA region, where

Table 4
Relative changes (%) in total net benefits of crop and grassland production by climate change scenarios MOHC45, ICHEC45, ICHEC85, and IPSL85 (reference fertilization, historic reference vs. future period) and fertilizer scenarios f20 and fcm (future period, reference fertilization vs. fertilizer scenario for the respective climate change scenario).

	*Reference fertilization**	*f20 (uniform)***	*fcm (combined)***
MOHC45 dry/moderate forcing	29.9	−1.95	0.61
ICHEC45 moderately dry/ moderate forcing	53.9	−3.07	0.32
ICHEC85 moderately dry/strong forcing	64.2	−3.14	0.14
IPSL85 wet/strong forcing	19.6	−3.70	1.14

* relative change derived from comparing historic climate (1981–2010) to future climate (2041–2070) without changes in fertilization.
** relative change derived from comparing reference fertilization to fertilizer scenarios with the same climate change scenario for the future time period (2041–2070).

modelled decreases in cropland area are large (f20: −7 %, fcm: −35 % compared to reference fertilization), whereas almost no further reductions are reached for the cropland dominated regions of NFH and SFH, when moving from f20 to fcm. The model results again highlight regional specificities regarding the extent to which fertilizer scenarios fcm and f20 yield reductions in N losses to water, soil, and air. Higher reductions of N losses to air can be reached in all regions in fertilizer scenario fcm, compared to f20. This holds true, except for the non-alpine NFH and SFH regions, where differences between the two fertilizer scenarios are small. As stated above, climate change scenario induced variability is highest for N losses to water. Particularly the combinations of fertilizer scenario fcm and the dry climate change scenario MOHC45 yield high reductions in N losses to water. Despite higher reductions in applied amounts of N fertilizer, reductions of N losses to water in the high alpine, grassland dominated HA region are low compared to the non-alpine, cropland dominated NFH region, where only small reductions in applied amount of N fertilizer are induced by fcm compared to f20. Differences are less pronounced for N losses through soil sediment transport.

Using correlation analysis, we have tested for relationships between the N losses and several environmental indicators, i.e. applied N fertilization intensity, terrain slope, maximum temperature, mean annual precipitation, as well as soil-related indicators being topsoil organic C contents, bulk densities, pH-values and clay contents. Mean regional levels for each assessed indicator can be reviewed in Table 1. Conducted analysis (see appendix Fig. A-9) on the national level support discussion of the obtained model results (section 4.2).

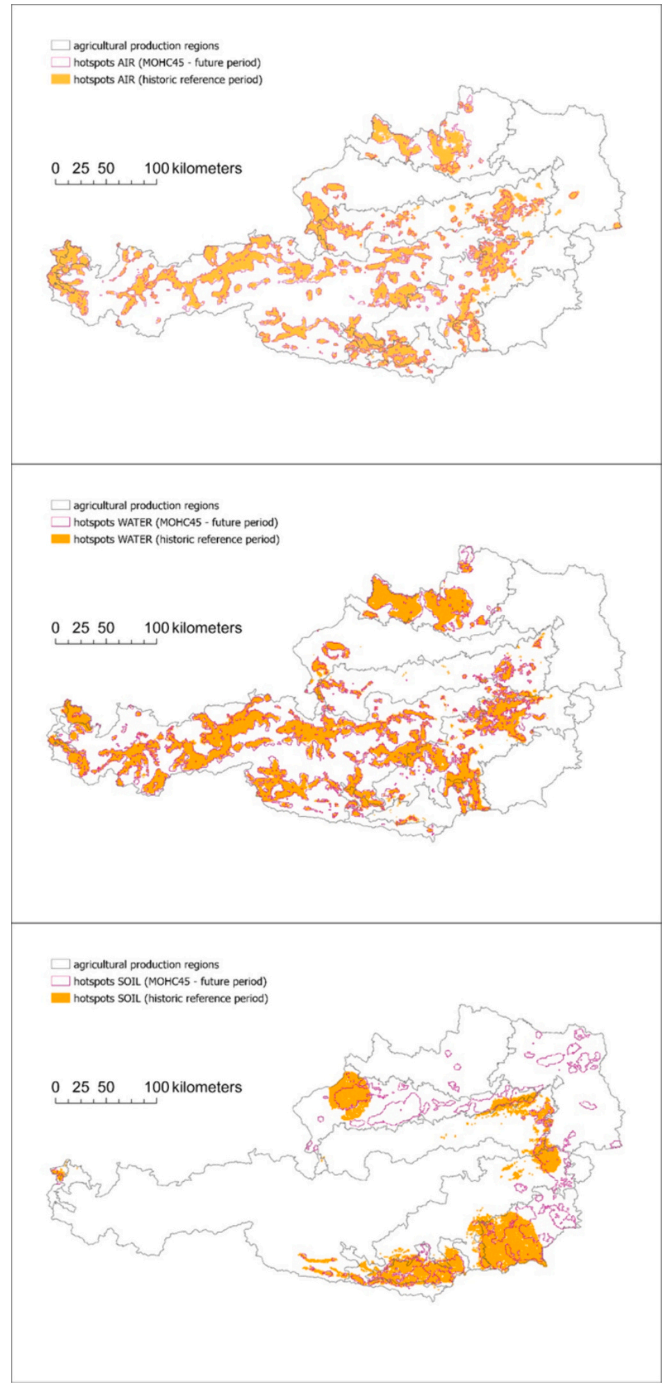

Fig. 4. Hotspots of N loss in air, water, and soil for the historic reference period (1981–2010) and the future period (2041–2070) in climate change scenario MOHC45 and reference fertilization (hotspot analysis: Getis-Ord-Gi*, cf. Esri, 2023).

4. Discussion

4.1. Modelled responses of agricultural production and management to induced changes in fertilization under climate change in Austria

Our model results show that restrictions in fertilization as proposed in the F2F strategy will most probably lead to a decrease in crop production between 6 % and 9 %. This is in line with other modelling studies, mostly conducted with EU-wide or global economic models, which model decreases in production between 7 % to 12 % (Beckman et al., 2020) and 15 % (Bremmer et al., 2021).

In our analysis, modelled impacts are largest on cereal crops, where production decreases between 7 % and 10 %. Other modelling studies of the F2F target implementation show decreases in cereal crop production between 10 % (20 % for Germany; Bremmer et al., 2021) and 49 % for the EU (Beckman et al., 2020). The model results differ for several reasons. While our analysis focuses on the isolated effects of fertilizer reductions others, e.g. combine fertilizer and pesticide use restrictions set as F2F targets (Bremmer et al., 2021). Furthermore, some assessments consider wheat as representative for all cereal crops, whereas our crop group category "cereals" subsumes several crops: winter wheat, durum wheat, winter rye, barley, spring barley, oats, triticale, sorghum, millet, and grain maize.

Oilseed crops, i.e. rapeseed, sunflowers and soybeans, are also prone to decreases in production by F2F strategy target implementation.

Table 5
Relative changes (%) of N losses to air, water and soil through sediment transport in climate change scenarios MOHC45, ICHEC45, ICHEC85, and IPSL85 and the fertilizer scenarios f20 and fcm (reference fertilization vs. fertilizer scenario for the future period and the respective climate change scenario).

	AIR	WATER	SOIL	total N loss
*f20 (uniform)**				
MOHC45 dry/moderate forcing	−4.6	−11.3	−6.6	−1.9
ICHEC45 moderately dry/moderate forcing	0.1	−2.3	−5.0	−1.3
ICHEC85 moderately dry/strong forcing	0.7	−2.0	−5.4	−1.6
IPSL85 wet/strong forcing	−0.2	7.8	−5.4	−1.7
*fcm (combined)**				
MOHC45 dry/moderate forcing	−7.8	−17.8	−9.3	−8.5
ICHEC45 moderately dry/moderate forcing	−3.1	−9.0	−4.9	−7.8
ICHEC85 moderately dry/strong forcing	−2.6	−8.9	−6.7	−7.9
IPSL85 wet/strong forcing	−3.2	0.9	−7.5	−7.4

* relative change derived from comparing reference fertilization to fertilizer scenarios with the same climate change scenario for the future time period (2041–2070).

Depending on the climate change scenario, our results range between −4 % and − 5 %, relative to the production levels with reference fertilization. The production decrease is in line with previous findings, even though the magnitude of overall oilseed production decreases in other studies ranges between 61 % (Beckman et al., 2020) and 11 % (Bremmer et al., 2021).

In the combined fcm scenario with restricting fertilization to a maximum of 175 kg N ha^{-1}, our model results show a decrease for forage crops, i.e. alfalfa, clover and silage maize, between 5 % and 8 %. Comparing this result is hardly possible as most of the other studies do not consider forage crops as a distinct category. Henning et al. (2021) expect a reduction of 30 % with regard to forage crop production, which lies well above our model results. Barreiro-Hurle et al. (2021) find joint reductions in area shares of soybean and forage production on cropland. Yet again, both modelling studies implement several F2F-targets, which goes beyond tackling N input reductions only.

Total relative change in production per crop group and our considered fertilizer scenarios fcm and f20 differs between 0.3 % points for oilseeds and − 2 % points for forage crops. Crop groups with larger differences contain crops, which tend to be fertilized at levels above 175 kg N ha^{-1} (such as silage maize in forage). These crops are subject to larger N input reductions for the combined fcm scenario than for the uniform f20 scenario. However, the modelled changes in total crop production are a result of the combined effects of yield and land use change.

With regard to permanent grasslands, our fertilizer scenarios yield an overall increase in both intensive and extensive grassland area as well as in grassland production, compared to reference fertilization. Few studies estimated grassland yields and to what extent grassland area might change due to F2F measures. Henning et al. (2021) model an increase in grassland area, yet do not differentiate between extensive and intensive management. Barreiro-Hurle et al. (2021) model reductions in area shares of intensive grassland in total arable land. The fcm scenario results in a stronger increase in extensively managed grassland area relative to f20, because f20 offers more economically viable alternatives. Second, the area shares of intensive grassland are larger in the fcm than in the f20 scenario due to the strong impacts of fcm on cropland production, which increases the relative competitiveness of grasslands. In national statistics we see a two-fold trend: i) grassland management tends to be abandoned or partly extensified in steep, alpine and marginalized areas where cultivation is difficult or where intensification does not seem economically viable; and ii) grassland management tends to be intensified in regions favorable for dairy cattle production that requires energy- and protein-rich forages (SUSKE Consulting, 2019). The overall increase in grassland production in the fertilizer and climate change scenarios (especially dry MOHC45, wet IPSL85 with strongest effects on precipitation; see appendix section A-2), highlights the importance of grassland for Austrian agricultural production (SUSKE Consulting, 2019). It is in line with potential grassland productivity increases in locations with favorable production conditions under climate change (Schaumberger et al., 2021). Profitability of grassland production might additionally increase as a source for livestock forage to attenuate dependencies on concentrated feedstuffs (Billen et al., 2024; Schils et al., 2022).

We also find that climate change scenarios with most pronounced effects on temperature and precipitation, i.e. MOHC45 and IPSL85, lead to stronger land use and land cover changes towards grassland production and extensification, whereas the moderately dry ICHEC85 and ICHEC45 scenarios maintain a high cropland productivity and fertilizer application. Further decreases in agricultural productivity under conditions of decreased precipitation or strong temperature increase can only be prevented by adaptation in management, such as irrigation (MOHC45).

The uncertainty associated with future world market price developments as well as the reaction of agricultural markets to regional shocks hampers the estimation of economic costs and benefits associated with F2F policy implementation (European Commission, 2023c). Hence, we keep socio-economic framework conditions such as input and output prices constant to reveal the effects of two fertilizer scenarios under climate change. It results in a decrease of total net benefits from agricultural production between −2 % and − 4 % in scenario f20 (and an increase of between 0.1 % and 1 % in scenario fcm), compared to reference fertilization levels. Total net benefit reductions in scenario f20

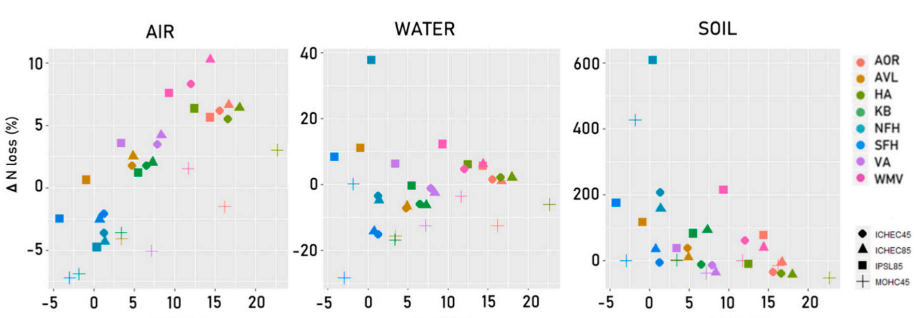

Fig. 5. Relative change (%) of N losses to air, water and soil plotted against relative change (%) in N fertilizer application rates (FTN) between the historic reference period and the future period by climate change scenario and region.

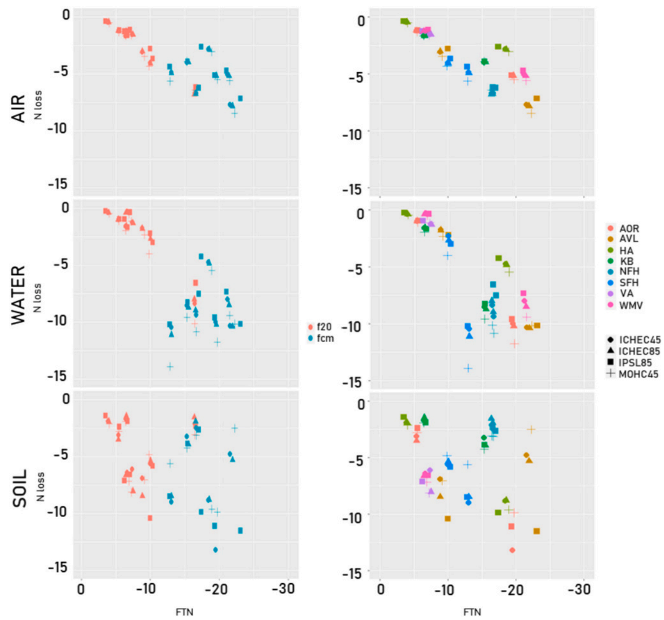

Fig. 6. Relative change (%) in N loss to air, water and soil plotted against relative change (%) in N fertilizer application rates (FTN) by climate change scenario, region, and fertilizer scenarios f20 and fcm (f20 and fcm in the left plot with identical symbols but different colors and in the right plot with identical colors but different position).

are most pronounced with climate change scenarios IPSL85, ICHEC85 and ICHEC45. This is mostly due to stronger decreases of cropland production than in the dry MOHC45. Higher total net benefits of agricultural production in scenario fcm can be explained by lower average costs of inputs (in particular for N fertilizer) compared to scenario f20. The results indicate that fcm fertilization levels are more efficient than the reference fertilization level considering climate change and an aggregated level of analysis.

The results on net benefits of agricultural production differ between studies, mainly due to the scale of modelling (EU cf. Bremmer et al., 2021; global cf. Beckman et al., 2020), the consideration of potential crop quality losses (cf. Ayadi et al., 2022), and the assumed changes in input and output prices (cf. Henning et al., 2021). The results range from modelled negative impacts of almost 8 billion € (Bremmer et al., 2021) to 21.3 billion € (Henning et al., 2021) on the overall value of agricultural production in the EU.

A further aspect are additional benefits for human and environmental health, biodiversity, and climate change mitigation associated with F2F measures, which may outweigh costs of reduction measures (de Vries, 2021). These benefits and costs need to be taken into account for decision making, which is only done by few of the reviewed impact assessments (e.g. Schiavo et al., 2021). For instance, Henning et al. (2021) estimate that societal net benefits through ecosystem services will increase by 59 billion € (132 € capita^{-1}) when implementing the complete F2F strategy.

4.2. Impacts of regional farming systems, soil and climate on N inputs and N losses

We have analyzed two fertilizer scenarios (i.e. f20 and fcm) as of the F2F strategy in order to quantify the effects on N losses to air, water and soil through sediment transport. The F2F strategy aims to reduce nutrient losses by 50 % based on reductions in mineral N fertilization of 20 %. The two fertilizer scenarios allow us to investigate the relationship between N mineral fertilizer reduction levels and N losses by bio-physical conditions and farming systems at regional scales (cf. Strenge et al., 2023). A uniform −20 % reduction of mineral N fertilizer application (i.e. f20) results in an overall reduction of N fertilizer application of about 9 % due to unchanged amounts of organic N fertilizer from livestock production. The combined fcm scenario does not allow mineral N fertilizer applications on permanent grasslands and limits the maximum applied amounts to 175 N kg ha^{-1}. This scenario leads to an overall 20 % reduction of N fertilizer applied in Austria. N loss reductions in scenario f20 range between 1.3 % and 1.9 % and in scenario fcm between 7.4 % and 8.5 %. However, both scenarios (i.e. f20 and fcm) do not lead to an overall 50 % reduction in nutrient losses. This is largely in line with other modelling studies. Barreiro-Hurle et al. (2021) and Henning et al. (2021) report GHG emissions reductions (measured in CO_2 equivalents) between 20 % and 29 % for combined fertilizer and pesticide use restrictions. Barreiro-Hurle et al. (2021) show reductions in NH_3 emissions of 33 %, in NO_3^- leaching of 36.2 % and in methane (CH_4) and N_2O emissions of 14.8 %. Henning et al. (2021) estimate a reduction of total GHG-emissions from agriculture of 109 mio. t in CO_2 equivalents, which comprises reductions in N_2O emissions of 37.5 % and CH_4 emissions of 22.7 %. Both studies expect the achieved GHG-emissions reductions to be compensated through large leakage effects driving emissions in the rest of the world. However, attenuating effects of e.g. supportive application technologies might support F2F goal achievement in addition to reductions in N fertilizer inputs.

Our fertilizer scenarios differ with respect to the N inputs and modelled N losses, but both are likely to have beneficial environmental effects. N loss reductions in scenario fcm are higher than in f20 but are still insufficient to reach the F2F target of −50 % nutrient losses into the environment. Hence, the environmental effects of F2F measures are considerably larger in fcm than in f20. More specifically, N loss reductions are highest to water and soil through sediment transport and lowest to air in fcm, with a number of potential desirable environmental effects. Reduced N losses in percolation and runoff prevent potential impairment of ground and surface water bodies (Tyagi et al., 2022), with beneficial effects on water quality. Lower N accumulation potential in soil might yield positive effects on soil biodiversity (Wang et al., 2023). Reduced N loss through soil sediment transport may further prevent the potential of soil acidification (de Vries, 2021). Climate change mitigation through reductions in mineral N fertilizer production (mainly reliant on fossil fuel combustion) is an indirect beneficial effect of the imposed F2F measures.

Our model results suggest that effects on N losses induced by lower mineral N fertilization differ by regional agricultural farming systems and bio-physical conditions. Similar to other studies (cf. Strenge et al., 2023; Henning et al., 2021; Schroeck et al., 2019), we find no linear relationship between N fertilization and N losses and therefore challenge emission factor approaches used in national emission inventories (Eggleston, 2006). Some regions (e.g. the high alpine HA) show low N_{min} input levels but high N losses (e.g. due to high shares of organic fertilizers prone to environmental losses), whereas other regions' fertilization intensities are relatively high with proportionally lower N losses (e.g. the non-alpine NFH, SFH). We further see that the dominance of N losses to either air, water or soil sediment are particularly region-specific.

Only for N losses to air, N input reductions correspond rather linearly to lower N loss, yet specific to regional soil and climate conditions (cf. Strenge et al., 2023). In case of N losses to water and soil sediment, factors beyond N inputs seem to determine N losses. Using correlation analysis (cf. appendix Fig. A-9), we see that N losses to air are predominantly influenced soil organic carbon (SOC), bulk densities, and fertilizer levels (FTN); whereas for N losses to water and soil, climate and topographic factors seem to be more important. This finding is supported by other studies (cf. Kasper et al., 2019). Hence, with some information on bio-physical conditions prevalent within a particular region, ex-ante estimation of regional N loss reduction potentials may be possible.

Regions of high SOC contents, low bulk densities and high precipitation such as the HA, show lower reduction potential of N losses to air, compared to regions such as the NFH or SFH, where low SOC contents and high bulk densities prevail. Levels of N losses to water are higher in the HA region and cannot be reduced substantially with reductions of N inputs in the f20 and fcm scenarios. In the SFH region, however, N losses to water are substantially reduced. These different effects of N input reductions on N losses to water can largely be explained by the steep slopes prevalent in the high alpine HA region. The rather high sensitivity of N losses to water in the non-alpine SFH region to the rather small changes in fertilizer inputs can be explained by low slopes as well as low annual precipitation and high annual temperature. An additional factor, especially with regard to N losses to air, are differences in farming systems as high amounts of organic fertilizer are applied in the grassland-dominated HA region, whereas mainly mineral fertilization and large-scale corn production prevail in the SFH region (cf. Strenge et al., 2023; Pelster et al., 2012). In case of N losses to soil sediment, we see the opposite climate change induced effect than for N losses to water. Climate change scenarios with decreases in annual precipitation, e.g. MOHC45, lead to higher reductions of N loss to water. Climate change scenarios with increases in annual precipitation, e.g. IPSL85, lead to higher reduction in N losses to soil, if fertilization management is changed. Lower annual precipitation support N accumulation in the soil, whereas higher annual precipitation increases N leaching (Zhang et al., 2020; Ruser et al., 2006). This might increase the potential of hot moments of N_2O emissions after rewetting (Wagner-Riddle et al., 2020). Model results reinforce the importance of grassland-targeted measures in order to reduce N losses. This is shown by the strong reductions in N losses to water and air in the combined fcm scenario compared to the uniform f20 scenario, which specifically addresses fertilization restrictions on permanent grassland. Furthermore, an increase in extensive grassland areas has an attenuating effect on N losses through soil sediment transport compared to crop production, as can be seen in the alpine AVL region (cf. Figs. 3 & 6).

4.3. Importance of climate change scenarios in policy impact analysis

Our model results show a climate-induced increases in productivity and fertilization intensity across all the four selected climate change scenarios, which results mainly from increases in grassland yield potentials (cf. Schönhart et al., 2018; Leclère et al., 2013). This attenuates conclusions of previous assessments on the effect of F2F measures on agricultural production and highlights the crucial importance of climate for the cost-effectiveness of F2F measures. The other reviewed studies show a strong decrease in agricultural production as a consequence of F2F measures. Our scenario results suggest higher overall production levels as management impacts are outperformed by the modelled productivity increases on grassland due to climate change. Decreases of cropland productivity are strongest in IPSL85, a climate change scenario that pronounces strong decreases in precipitation and increases in temperature in Austria.

Furthermore, we find that modelled magnitude of N loss reduction strongly depends on the climate change scenario. Hence, our analysis supports conclusions drawn by other studies that precipitation strongly influences soil moisture and therefore N processes such as nitrification and denitrification (cf. Wang et al., 2021; Kasper et al., 2019). Levels of N losses are lowest for climate change scenario MOHC45 with the lowest annual precipitation sums. The climate change scenario IPSL85 yields highest per hectare N losses in all regions, mostly driven by increased N loss with runoff. However, lower levels of N loss with runoff from reduced precipitation may still result in deteriorating groundwater quality if N concentration in leachate remains high or increases due to low groundwater recharge. Similar drivers and processes have been analyzed for surface waters under climate change in Austria (Schönhart et al., 2018). Besides dilution, higher denitrification rates can reduce N in surface water (Zessner et al., 2017). We find that increased fertilization due to more favorable production conditions will not automatically lead to higher nutrient losses as crop nutrient uptake might be improved (Schönhart et al., 2018). This is evident when comparing N losses modelled for ICHEC85 and IPSL85. Even though N fertilization is higher with ICHEC85, N losses dominate with IPSL85 characterized by lowest productivity levels.

4.4. Methodological considerations

The introduced integrated modelling framework delivers results on potential impacts of the F2F strategy on agricultural production and N losses in Austria, considering policy design as well as climate change. However, certain limitations of the modelling framework approach are relevant to note. For instance, does the strong increase in extensive grassland production in the scenario fcm partly result from model assumptions. BiomAT does not model livestock production explicitly, but includes hay production as marketing option. This may overestimate the relative profitability of grassland assuming sufficient processing capacities and marketing options (e.g. development of biomass processing and storage facilities). Furthermore, the model does not allow for abandonment of previously cultivated agricultural land, nor does it allow the conversion of permanent grassland to cropland. Hence, abandonment of permanent grassland due to lacking economic viability or infrastructure development and its transition to cropland or afforestation - as observed in the past (SUSKE Consulting, 2019) - are not explicitly considered in the model.

We use average prices for agricultural inputs and outputs as well as assume constant socio-economic framework conditions. This assumption helps to focus on the isolated effects of climate change and fertilization scenarios, which facilitates the interpretation of results (Mitter et al., 2015). Considering alternative yield, price and emission developments would require another research focus and, in case of stochaastic data even an alternative modelling approach that accounts for risk preferences and uncertainty appraisal of farmers. However, this is beyond the scope of this analysis. Policy premiums to support diversification of crop rotations towards legumes, for example, might further reduce N losses. These crop-specific policy premiums may also compensate for decreased farm revenues from lower production levels.

We acknowledge uncertainties in the modelling framework stemming from various sources such as limited data availability. These are addressed through comprehensive comparison of our results to other research (cf. Strenge et al., 2023), various validation efforts for the applied IMF in previous studies (cf. Kirchner et al., 2021; Schönhart et al., 2011), face validation with experts at various stages of the research (cf. Rykiel, 1996), and the presentation of model results in relative terms.

Alternative N-sensitive crop rotations could be introduced to further develop the applied IMF. These could include a minimum share of legumes or obligatory use of catch crops in order to further reduce N losses (Billen et al., 2024; de Notaris et al., 2018). Considering additional crop rotations and other managerial or technical options would improve the approximation of farmers' opportunity costs and the development of cost-effective policy designs. Finally, linking the IMF with a global agricultural economic land use model would enable the analysis of potential leakage or spill-over effects (cf. Meyfroidt et al., 2020).

5. Conclusions and outlook

Our integrated modelling framework complements the results of other studies on the effect of F2F measures on agricultural production and N losses (cf. Billen et al., 2024). In our Austrian case study analysis, we find that reductions in mineral fertilizer application by 20 % do not suffice to reach the intended reduction target of 50 % nutrient losses. Cropland production, especially cereal and forage crop production, are reduced whereas grassland extent and production increases as a combined effect of fertilizer and climate change scenarios. Our analysis confirms the partial effectiveness of F2F measures targeted at mineral fertilizer in order to reduce N losses in air, water and through soil sediment transport. Yet, it shows that both cost-effectiveness and N loss reduction potentials depend on the regional context of prevalent farming systems, bio-physical conditions including climate change and the pollutant category. We further see a limited effectiveness of measures targeting only mineral fertilizers for the alpine, mostly grassland-dominated regions in Austria.

The regional heterogeneity of our model results supports the conclusion that policies with uniform restrictions at national level fall short to attain policy targets cost-effectively. Tailored measures need to be elaborated by taking climate change as well as regional heterogeneity of prevalent farming systems and bio-physical conditions into account. The provided integrated modelling framework serves as the adequate tool to support ex-ante policy analysis by making trade-offs of policy outcomes visible in order to inform the development of targeted policy measures.

In terms of future research, we suggest the exploration of further policy measures' effects, which can serve to achieve F2F strategy targets. These can range from stricter fertilizer restrictions to reductions above 20 %, inter-regional manure trading or crop rotational specifications.

CRediT authorship contribution statement

Elisabeth Jost: Writing – original draft, Methodology, Formal analysis, Conceptualization. **Martin Schönhart:** Writing – review & editing, Methodology, Conceptualization. **Hermine Mitter:** Writing – review & editing. **Ottavia Zoboli:** Writing – review & editing, Methodology, Formal analysis. **Erwin Schmid:** Writing – review & editing, Supervision, Methodology, Conceptualization.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolecon.2024.108398.

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