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An agent-based model to simulate field-specific nitrogen fertilizer applications in grasslands

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ABSTRACT

Grasslands have a large share of the world's land cover and their sustainable management is important for the protection and provisioning of grassland ecosystem services. The question of how to manage grassland sustainably is becoming increasingly important, especially in view of climate change, which on the one hand extends the vegetation period (and thus potentially allows use intensification) and on the other hand causes yield losses due to droughts. Fertilization plays an important role in grassland management and decisions are usually made at farm level. Data on fertilizer application rates are crucial for an accurate assessment of the effects of grassland management on ecosystem services. However, these are generally not available on farm/field scale. To close this gap, we present an agent-based model for Fertilization In Grasslands (FertIG). Based on animal, land-use, and cutting data, the model estimates grassland yields and calculates field-specific amounts of applied organic and mineral nitrogen on grassland (and partly cropland). Furthermore, the model considers different legal requirements (including fertilization ordinances) and nutrient trade among farms. FertIG was applied to a grassland-dominated region in Bavaria, Germany comparing the effects of changes in the fertilization ordinance as well as nutrient trade. The results show that the consideration of nutrient trade improves organic fertilizer distribution and leads to slightly lower N_{min} applications. On a regional scale, recent legal changes (fertilization ordinance) had limited impacts. Limiting the maximum applicable amount of N_{org} to 170 kg N/ha fertilized area instead of farm area as of 2020 hardly changed fertilizer application rates. No longer considering application losses in the calculation of fertilizer requirements had the strongest effects, leading to lower supplementary N_{min} applications. The model can be applied to other regions in Germany and, with respective adjustments, in Europe. Generally, it allows comparing the effects of policy changes on fertilization management at regional, farm and field scale.

1. Introduction

Agricultural decision-making shapes the cultural landscape of central Europe. Grasslands are a central component of those landscapes, covering roughly one third of the agricultural land in Europe (Eurostat, 2023). Meadows and pastures are economically highly important for producing fodder and feed, as grass provides a high-quality nutrient input for livestock systems (Cocca et al., 2012). Furthermore, grasslands are essential for supplying multiple other ecosystem services (Röder et al., 2015; Schils et al., 2022; Zhao et al., 2020). These include regulating services, such as erosion and climate regulation, as well as cultural services, such as recreation and aesthetics (Bengtsson et al., 2019). Grasslands are also known to be biodiversity hotspots, especially if managed extensively (Habel et al., 2013). Many of the ecosystem services are, however, under pressure due to the simultaneously existing trends of grassland conversion, intensification and abandonment

Abbreviations: ABM, agent-based model; FertIG, Fertilization In Grassland; FO, fertilization ordinance; IACS, Integrated Administration and Control System; LSU, livestock unit.

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(Haensel et al., 2023; Lavorel et al., 2019; Nitsch et al., 2012; Schirpke et al., 2019; Xiao et al., 2015). It is thus crucial to identify sustainable management practices for grasslands to ensure the future provision of these ecosystem services.

An important management aspect of grasslands is the proper use of nitrogen fertilizers. These have positive as well as negative effects on grassland ecosystem services, e.g. fertilization can increase soil organic C stocks, improve forage quality but can also lead to a decline of plant species richness (Jones et al., 2014). Francksen et al. (2022) and Glimskär et al. (2023) highlight the relevance of careful nitrogen management to maintain productivity and sustainability in European grassland systems. Additionally, Zistl-Schlingmann et al. (2020) found that management intensity significantly affects both nitrogen-use efficiency and nitrogen flows in grasslands, highlighting the need for optimized fertilization strategies.

Agricultural production is one of the main drivers of reactive N emissions in the European Union (EU). Thus, efficient nitrogen use is necessary and a key objective of the recent EU Farm to Fork Strategy, which aims to reduce fertilizer use by at least 20 % and nutrient losses by 50 % by 2030. (Löw and Osterburg, 2024). Germany has been sued by the EU Commission because nitrate contamination of groundwater exceeded rates defined in the EU Nitrates Directive (ECJ ruling of June 21, 2018, C-543/16). This made legal changes, including several revisions of the fertilization ordinance (regulating technical details of fertilization, German "Düngeverordnung") necessary to protect water bodies from excessive nitrate pollution and improve nutrient management. The legal basis is provided by the Fertilization Act of 2006 (German "Düngegesetz"). The last major changes in the fertilization ordinance have been effective since 2020. This included, for instance, stricter fertilization rules in nitrate-polluted areas ("red zones"), the immediate incorporation of liquid organic fertilizers into the soil on uncultivated arable land, and requirements for improved application techniques for liquid organic fertilizers. The latter also entailed the elimination of the consideration of application losses. Additionally, the minimum effectiveness of several organic fertilizers was increased. This means that a higher percentage of the nutrients in organic fertilizers must now be considered available for plant uptake when calculating fertilizer requirements.

Various factors drive fertilization management, such as location (e.g. soil quality, slope), farm and field portfolios (e.g. crop types, grassland use types, use intensities, livestock), economic factors (e.g. fertilizer costs), technology (e.g. machines used for application), climate, and of course social norms like regulations for water protection zones, agri-environmental schemes or general legal fertilizer restrictions. Fertilization data is usually not available on a field scale, particularly not for larger areas, and due to the above-mentioned factors, it is also not easy to calculate them. However, fertilizer application rates are an important input factor of many agricultural and biophysical models, e.g. for the Soil and Water Assessment Tool SWAT (Abbaspour et al., 2015; Uniyal et al., 2023) or LandscapeDNDC (Petersen et al., 2021), which are widely used to derive policy recommendations.

In the absence of available datasets on actual application rates, one way to obtain data is to query farmers, e.g. in surveys as done by Coulter et al. (2002) or You et al. (2023). Another way is to estimate them using the plant's fertilizer requirement as a proxy (e.g. Abbaspour et al., 2015). Another source of information can be recommended N fertilization rates. However, most available studies focus on cropland (Cai et al., 2023; Holland and Schepers, 2010; Liu et al., 2023; McNunn et al., 2019; Solie et al., 2012; Sulik et al., 2023). One of the few grassland examples is a decision-support tool that derives optimal N fertilization rates on field scale for British grasslands developed by Brown et al. (2005).

Studies that estimate spatially explicit actual nitrogen fertilizer application rates are rare. For instance, nitrogen application was modelled globally with a low spatial resolution of 0.5°, which equals ca. 50 km near the equator (Nishina et al., 2017; Potter et al., 2010) and on a country scale for Germany on a county level (Häußermann et al., 2019). Huffman et al. (2008) calculated available amounts of organic nitrogen fertilizer based on livestock data. Here, the amount of mineral N fertilizer was estimated by annual fertilizer sales. Based on fertilizer recommendation rates, the authors calculated the total applied N fertilizer per crop and for pasture for different soil landscapes in Canada. At a 30 m resolution, Luscz et al. (2015) developed a nutrient source model using GIS for Michigan (USA), including manure application based on farm-level livestock numbers. However, without knowledge of the exact field locations of each farm, they assumed a buffer around the farm operation to distribute the manure on the fields. The scales used in these examples are less suitable for decision making in agricultural management, which usually requires a high resolution such as field scale. Here, agent-based models (ABM) allow the needed level of detail.

To model management decisions on agricultural land, including grasslands, ABMs are frequently used since these allow the simulation of interactions, e.g. amongst different agents like farms, farmers, or fields (e.g. Bayram et al., 2023; Perello-Moragues et al., 2019; Zhan et al., 2015). ABMs are also often used to model farmers' reactions to changes, e.g. adopting new practices or technologies motivated by policy incentives (e.g. Burg et al., 2021; Liu and Xie, 2019; Perello-Moragues et al., 2019). Most of the above-mentioned approaches focus on cropland or specific crops and are thus less useful for deriving fertilizer management recommendations for grassland-dominated areas. So far, no model combines grassland fertilization recommendations with the benefits of ABMs.

In this study, we aim to close this gap by proposing an ABM for Fertilization In Grassland (FertIG). The model simulates the spatially explicit distribution of organic and mineral nitrogen fertilizer at the field scale, including nutrient trade among farms and legal restrictions (e.g. thresholds, water protection zones, agri-environmental schemes). The model provides fertilizer application rates on the field level for grassland that can support decision-makers in allocating measures that regulate fertilization in the analyzed region. For example, it can help analyze the impact of changes in the fertilization ordinance, e.g. how the amount of applied organic and mineral fertilizer as well as nutrient trade vary in the region if application rates are more restricted. Additionally, intensification or extensification scenarios can be analyzed by altering the cattle numbers or number of cutting events in the input data. Also, the effect of droughts on application rates can be simulated if climate-adapted yield data is provided as input data to the model instead of using the model's internal calculation. Furthermore, the resulting nitrogen application rates can be valuable input data for other models. These can further simulate the effect of fertilization management on ecosystem services and thus help derive recommendations for sustainable grassland management.

In the following sections, we first introduce the structure and functionality of the FertIG model and describe the stakeholders' role in its development. We then apply FertIG to the grassland-dominated Ammer region in Bavaria, Germany. To demonstrate one of the model's key features, we estimate the quantity and spatial distribution of nitrogen fertilizer in the Ammer region for 2019. Additionally, we simulate the impacts of the 2020 amendments to the German fertilization ordinance on fertilization management practices.

2. Materials & methods

2.1. Study area & input data

The Ammer study region is located in Southern Bavaria, Germany and is roughly based on the hydrological boundary of the Ammer River catchment (Fig. 1). The area's topography ranges from the hilly north (average of 881 m.a.s.l.) to the Alpine south with mountains of up to 2969 m.a.s.l. The region is characterized by agricultural land (36 %), forest (41 %), water bodies (5 %), urban settlements (4 %), and other land uses, i.e. alpine rock formations and peatlands (14 %) (LDBV, 2016). Overall, agricultural land is dominated by grassland (88 %).

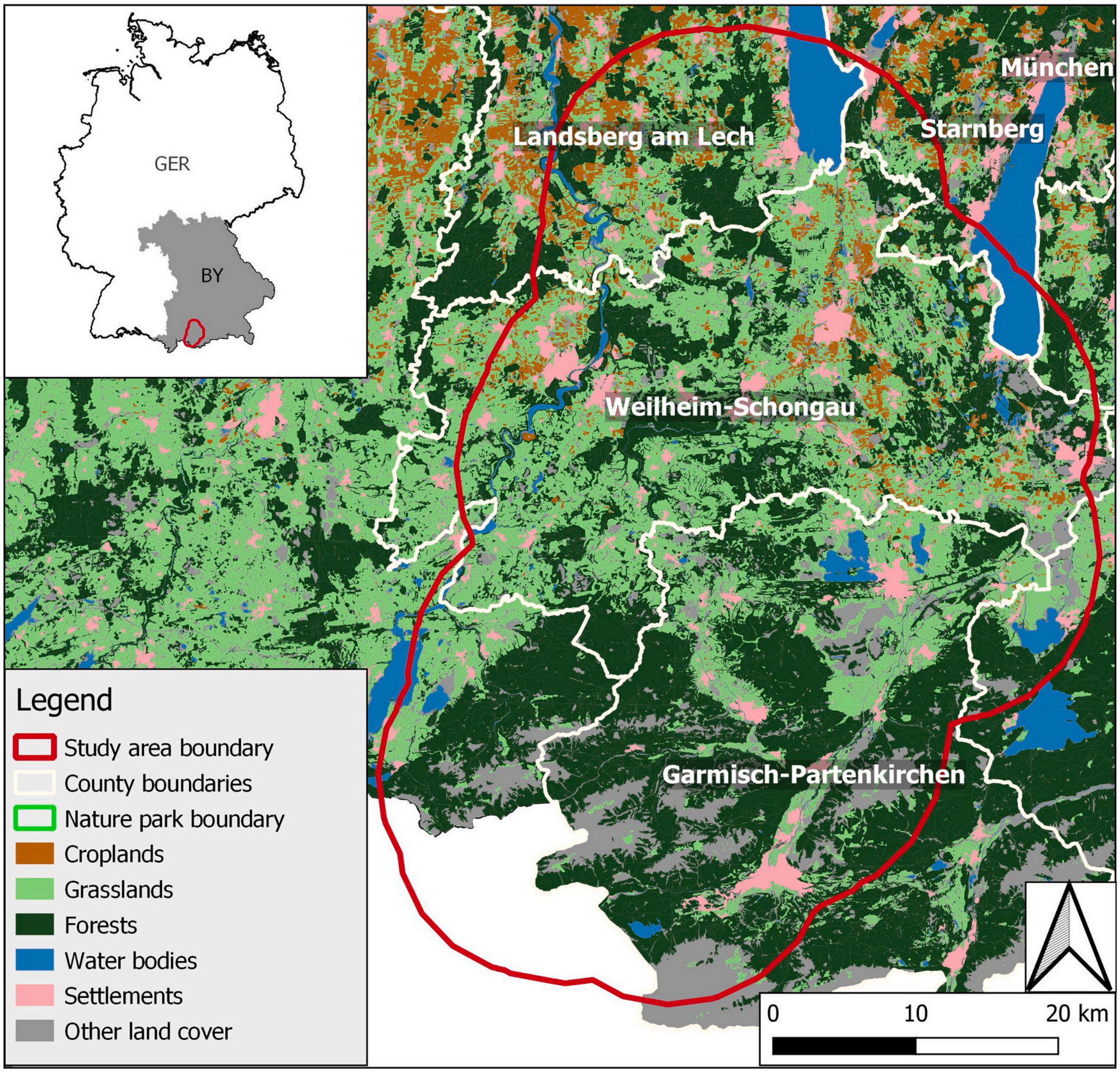

Fig. 1. Location and land use of the study area (GER = Germany, BY = Bavaria). Based on ATKIS land-cover data (LDBV, 2016).

Following the landscape gradient, grassland in the north accounts for 50 % of agricultural land and consists mainly of meadows and mowing pastures with a higher use intensity, while agricultural land in the south consists almost exclusively (99 %) of less intensively used grasslands, such as Alpine pastures. On average, 18 % of the grassland area is cut twice per year, 44 % three times and 31 % four times (Reinermann et al., 2023). Grasslands in the study region provide multiple important ecosystem services, particularly fodder production for cattle, water regulation, erosion regulation, and recreation (Schmitt et al., 2021). Dairy and meat production is very important in the region, with mainly part-time farming in the south and full-time farming in the north.

In our model, we used land-use and farm data from 2019, considering only the agricultural land of the study area, which is 914 km^2. In total, we modelled 3174 farms. Overall, farm sizes were on average 28.74 ha, with average field sizes of 1.8 ha and a mean of 47 livestock units (LSU) per farm (only farms with cattle). The model requires two mandatory and one optional input data sets: (i) field data, (ii) farm data, and optionally (iii) yield data. Data sets (i) and (ii) are spatial data, i.e. shape files, whereas (iii) is a table in CSV format that allocates yields to each grassland field. The spatial data sets were created by joining different spatial input data (Table 1) with GIS software.

The basis of the field data set was the 2019 data set from the EU's Integrated Administration and Control System (IACS), which allocates field polygons to anonymous ownership information, land use, and

Table 1
Summary of model input data sets.

Group	Variable names	Source	Year
Farm	Field portfolios per farm	IACS	2019
Farm	Animal data per farm	IACS	2019
Fields	Field margins & location	IACS	2019
Fields	Land use [grass; crop]	IACS	2019
Fields	Cutting events [no.]	Remote sensing data (Reinermann et al., 2023)	2019
Landscape	Soil (grassland index)	Land appraisal data (LDBV, 2018)	2018
Landscape	Soil (humus)	LfU	2022 developed from profile data of the Bavarian State Office for the Environment (LfU)
Landscape	Slope	ASTER GDEM 3 3 3, (2019)	2019
Norms	Agri-environmental schemes	IACS	2019
Norms	Water protection zones	LfU (2014)	2019

participation in agri-environmental schemes. We intersected the field polygons with the land appraisal data set (LDBV, 2018) to retrieve grassland indices (German "Grünlandzahl") for each field. This index reflects the location's quality for grassland production considering soil type, soil characteristics (yield potential), climate, and water level (water availability). It ranges from 1 to 100 (poor – best). Since the grassland index can vary within each field, we assigned the value with the highest share in the field area. Similarly, fields were assigned to water protection zones, if applicable. These range from zones I (very high protection) to III (protected). For slope, we used the maximum slope of each field assuming that as soon as the slope of the terrain in a section of the field is steep, its traversability with machinery for fertilization and harvesting is more difficult thus leading to a lower yield level. Further, we assigned humus data based on soil profile data of the Bavarian State Office for the Environment (LfU).

Though the provided IACS data includes ownership information (i.e. which fields belong to the same farm), it does not include the locations of the farms. Therefore, as a rough approximation, we used field centroids of each farm's fields and defined the centroid of the field centroids as the farm location when creating the field input data. From the IACS data set, we then allocated cattle numbers and types to each estimated farm location.

2.2. Model

The agent-based model FertIG (Fertilization In Grassland) is implemented in the programming language NetLogo (Wilensky, 1999). It starts with (i) a model setup ("Setup") before (ii) the model run "Go" (Fig. 2). In (i), input data is loaded into the model, and the spatial world (map of the study area), including farm and field agents, is created. This step also identifies fields where legal requirements do not allow any fertilizer application ("fertilization veto"). These fields are located in a water protection zone, or farms participate in agri-environmental schemes restricting fertilization (see Appendix 1). The second step (ii) first calculates fertilizer requirement and the amount of available farm fertilizer. Then, the available organic fertilizer is traded among farms before it is distributed on the respective farm's fields. Fertilized meadows and intensively used mowing pastures are also applicable for supplementary mineral fertilization if the amount of organic fertilizer is insufficient. In the model interface, the user can select between the fertilization ordinance of 2017 (FO, 2017) or its revised version of 2020 (FO, 2020). In the Introduction, we mentioned several differences between the two versions. For our study, only the following changes are relevant: in the FO, 2017, the hectares for the application limit of 170 kg N_{org}/ha and year are based on total farm area, whereas the 2020 revision is stricter, limiting the hectares to fertilized farm area only. Additionally, in the FO, 2020, the minimum effectiveness of cattle manure was increased from 50 % to 60 % in cropland while remaining at 50 % in grassland, and the consideration of application losses (applicable for FO, 2017) of 17.6 % was eliminated. We did not account for special restrictions applicable to nitrate-polluted areas, as none exist in our study region. We neglected requirements concerning necessary distances from water courses because of the small overall area concerned. In the following, each step of the model is described in detail. Information on

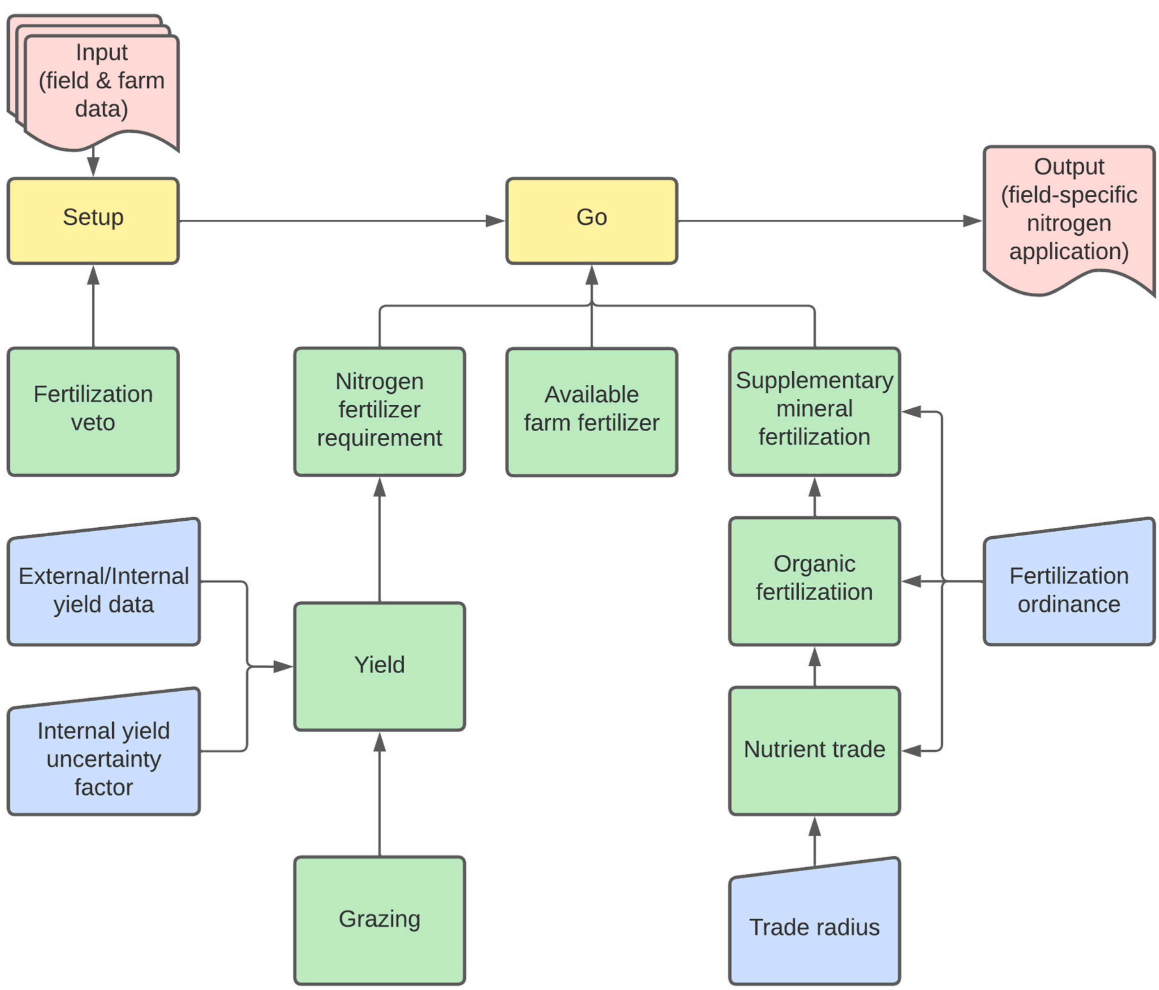

Fig. 2. Flowchart of the agent-based grassland management model. Input and output data are marked in red, main steps in yellow with green sub-steps, and manual input data selected in user interface are blue.

the format of the output data is provided in Appendix 2.

2.2.1. Nitrogen fertilizer requirement

In the model, cropland plays only a secondary role due to the low share of the study area's land use. Furthermore, in Germany, usually organic fertilizer is applied on cropland fields in spring while the rest of the main crop's nitrogen requirement is covered by mineral fertilization. Generally, the application of fertilizers containing a significant amount of nitrogen on cropland is banned from the main crop's harvest until the end of winter (i.e., January 31). There are, however, exceptions, such as the application of specific types of solid manure or the fertilization of cover or catch crops in autumn. Due to the above-mentioned low relevance of cropland in the study region, we simplified the organic fertilization rules for cropland by considering only the potential organic fertilization of main crops in spring. We used an average N requirement of 119 kg N/ha for silage maize and 54 kg N/ha for all other crops (including forage crops) per year (see Appendix 3 for more information).

For fertilized grassland fields, we distinguish between the use categories meadows (including newly sown grassland), mowing pastures, and pastures (including Alpine pastures – IACS categories "Almen und Alpen", and "Hutungen"). Other grasslands such as litter meadows ("Streuwiesen") and meadow orchards ("Streuobstwiesen") are not fertilized in general and thus excluded from the modelling. This study uses methods, assumptions, and numbers published in the official guidelines for fertilization of crop- and grassland by the Bavarian State Institute for Agriculture (LfL), hence referred to as LfL guidelines, that contain condensed information on good professional practice (LfL, 2018). Numbers given in the LfL guidelines can (if applicable) also be used by farmers to calculate their official fertilizer requirement. The LfL guidelines are updated every few years, i.e. a revised version is available, but as we modelled the year 2019, we still used the version of 2018, which was available to farmers at that time. In the following, the grassland fertilizer requirement is calculated based on the official framework outlined in the 2018 LfL guidelines, which aligns with the scheme provided by the fertilization ordinance.

To identify the organic nitrogen requirement of grasslands, the plant's nitrogen requirement is estimated based on yield, the nitrogen content of the mown grass, and the grassland's use type. As additional nitrogen is provided by the soil, legumes, and organic fertilizer from the previous year, the nitrogen requirement has to be reduced by this amount as a next step. We extended the LfL scheme considering of the minimum effectiveness of cattle manure and application losses, as these are necessary to calculate organic fertilization rates (Fig. 3).

Nitrogen removal

In the model interface, the user can define whether grassland yields should be calculated internally or provide their own field-specific yield data. In case the provided yield data includes data gaps, these are complemented by internally calculated yields. The internal yield calculation is based on average yield data for Bavaria, Germany, as provided by LfL (2018). The look-up table differentiates between grassland categories, management intensities (number of cutting events, low/medium/high grazing intensity), and yield levels (low, medium, high). The first two attributes are provided in the input data, whereas the yield level needs to be identified based on the grassland index, slope, or stocking rate.

Meadows

The yield level of meadows depends on location-specific factors (e.g. soil type, yield potential, water availability, climate) reflected by the grassland index that is provided by the land appraisal data set (LDBV, 2018). However, this index is not available for all fields. In these cases, we approximate the yield level according to the field's maximum slope (Table 2).

Pastures

Equally to meadows, the yield level of pastures depends on the grassland index or slope. Instead of cutting information, we approximate the use intensity by the farm's stocking rate (SR, Table 2), which is defined as $SR := LSU/P$, with LSU being the number of cattle per farm in livestock units and P the farm's total grazing area. The transformation of total cattle numbers into LSU is given in Appendix 4.

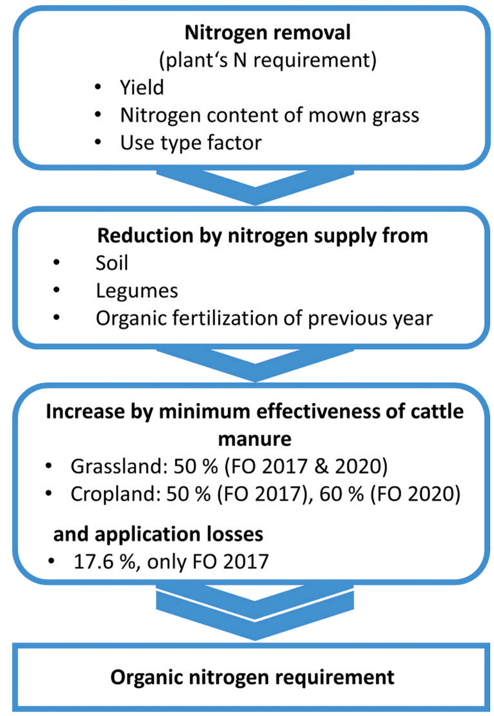

Fig. 3. Calculation workflow of organic nitrogen requirement of grasslands.

Table 2
Definition of grassland yield level (/grazing intensity) based on grassland index or slope (/stocking rate).

Grassland index (GI)	Slope	Stocking rate (SR)	Yield level / grazing intensity
$0 \leq GI \leq 33$	$50\ \% \leq$ slope	$0 = SR \leq 1.5$	Low
$33 < GI \leq 67$	$25\ \% \leq$ slope $< 50\ \%$	$1.5 < SR \leq 3$	Medium
$67 < GI \leq 100$	$0\ \% \leq$ slope $< 25\ \%$	$3 < SR$	High

Mowing pastures

Mowing pastures are used for cutting as well as grazing. To define the use type of a mowing pasture, the share of grazing needs to be identified first. We assume that mowing pastures with no cutting events are pastures, with one cutting event used up to 60 % for grazing, and those with at least two cutting events used up to 20 % for grazing. The use intensity is according to SR for all fields from zero to three cuts, and a high use intensity (independent from SR) is assumed for fields with more than three cuts. The yield level is again defined by either the grassland index or slope.

Once yield level and use intensity are defined, yield is multiplied by the nitrogen content of the harvested grass according to the LfL look-up table. The nitrogen removal is then calculated by multiplying the resulting value with the respective use factor (Table 3, Eq. 1).

Table 3
Use type factors according to grassland use category (LfL, 2017).

Use category	Use type factor
Cutting (100 %)	1.0
Mowing pasture (20 %)	0.9
Mowing pasture (60 %)	0.7
Pasture (100 %)	0.5

$$N\ removal\ [\mathrm{kg\ N/ha}] = yield\ [\mathrm{dt\ DM/ha}] \times N\ content\ [\mathrm{kg\ N/dt\ DM}] \times use\ type\ factor \quad (1)$$

Reduction by nitrogen supply from soil, legumes, and prior fertilization

The nitrogen removed from the grassland field must be adjusted by subtracting the nitrogen supplied through humic soils, legumes, and the ongoing mineralization of organic fertilizers applied in the previous year, which are already available for plant uptake. The N supply from the soil is measured by the soil's humus content (Table 4), whereas the supply from legumes depends on the share of legumes in the grassland. We assume that extensively used grasslands (up to two cuts per year/SR ≤ 1.5) have a higher share of legumes (10–20 %) than intensively used grasslands with (more than two cuts/SR > 1.5, 5–10 %) which equals a reduction by 40 kg N/ha and 20 kg N/ha, respectively (LfL, 2017). Since no data is available on the organic fertilization from the previous year, we assume that each farm applied the maximum allowed amount of 170 kg N/ha of organic fertilizer. According to the fertilization ordinance, a share of 10 %, i.e. 17 kg N/ha, needs to be considered (Section 4 (5) of the fertilization ordinance from 2017). Here, it has to be taken into account that according to the FO 2017, the 170 kg N/ha are related to the entire farm area, i.e. they also include fields that are not fertilized increasing the amount of N that can be applied to fertilized fields. Therefore, if the FO 2017 is selected, we calculate the reduction by Eq. 2.

$$R_{FO2017}\ [\mathrm{kg\ N/ha}] := \frac{170\ [\mathrm{kg\ N/ha}] \times 0.1 \times farm\ area\ [\mathrm{ha}]}{fertilized\ farm\ area\ [\mathrm{ha}]} \quad (2)$$

Minimum effectiveness of organic fertilizers and application losses

When calculating a field's nitrogen requirement, it needs to be considered that when applying organic fertilizers, some of the nutrients will not become available for the plants within the year of application or are lost during the application process (e.g. by volatilization). Therefore, the nitrogen requirement must be corrected (i.e. increased) by the respective organic fertilizer's minimum effectiveness and application losses. Based on the specifications of the FO 2017, we assume a minimum effectiveness of cattle manure of 50 % for grassland and cropland, and 17.6 % application losses. In the FO 2020, the minimum effectiveness of cattle manure increases to 60 % for cropland, and application losses are no longer considered.

In the case of meadows with a nitrogen requirement < 20 kg N/ha, the nitrogen requirement is set to 0 because, according to the consulted stakeholders (see Section 2.3), in practice, farmers would at least apply 20 kg N/ha during a fertilization event.

2.2.2. Available farm fertilizer

For simplicity, we assume that all farms only use a semi-liquid manure system. The amount of available organic nitrogen (N) fertilizer per farm is calculated based on cattle types and yearly average livestock numbers. According to an Excel program provided by the LfL for farmers (LfL, 2019a), the different cattle types produce the amount of nitrogen per year as given in Table A4 assuming an average milk yield of 7000 kg per cow and year (rounded value for the administrative district of Upper Bavaria, German "Oberbayern", LfL, 2019b). The available amount of organic N fertilizer per farm is then calculated by the sum of the products of the number of cattle and the respective amount of nitrogen produced by each cattle type.

Table 4
Reduction of nitrogen requirement by N provision from soil (organic matter) in grasslands.

Humus class (organic matter - OM)	Reduction [kg N/ha]
Very weak to strong humic soils (OM $<$ 8 %)	10
Strong to very strong humic soils (8 % $\leq$ OM $<$ 15 %)	30
Muck (15 % $\leq$ OM $<$ 30 %)	50
Low moor (OM $>$ 30 %)	80

2.2.3. Nutrient trade & fertilizer distribution

There may be a discrepancy between available N from organic fertilizer and required N per farm, either due to uncertainty in input data, simplistic model assumptions, rounding effects or due to farm structures. Farms can have high stocking rates and an organic fertilizer surplus whereas other farms do not have any cattle and may be potential importers of organic fertilizer. The stakeholders confirmed that some farmers are trading organic fertilizer in the study area. However, they also recommended that our model should exclusively allow farms without cattle to receive organic fertilizer from other farms, as this was the most likely case in the study region. Other farms that keep cattle but do not produce enough organic fertilizer to cover their field's fertilizer requirement would usually compensate for this lack with supplementary mineral fertilization. Therefore, we implemented a nutrient trade in the model where only farms without cattle are allowed to receive organic fertilizer from other farms with a surplus. These importers select their trade partners within a predefined radius and start trading with the partner with the highest surplus. Organic farms prefer trading with other organic farms first.

In the model interface, the user can define the trade radius within which each farm can trade with other farms (see Appendix 5 for the translation of km to NetLogo units). Generally, modelled farms are only allowed to trade as much organic fertilizer as the fertilization ordinance allows for application, i.e. 170 kg N/ha in total. An exception are non-organic farms that trade organic fertilizer to organic farms. According to the EU fertilization ordinance (EU Bio Label) (LfL, 2022), they must follow stricter rules, i.e. the selling non-organic farm must not keep more than 2.5 LSU/ha and organic farms are only allowed to receive a maximum of 40 kg N/ha in total from non-organic farms. For simplicity, we applied this limit to all organic farms, despite the stricter rules some of the other organic certification schemes have in the study area.

Distribution of organic and mineral fertilizer (fertilization rates)

When distributing the farm's organic fertilizer, the applied amount must not exceed the previously calculated fertilizer requirement (Section 3 (3) FO 2017), and must comply with the legal limit of 170 kg N_{org}/ha (fertilized) farm area. The model calculates yearly application rates, i.e. it does not differentiate single application events. First, cropland is served on a 'first come, first served' basis, meaning that if insufficient fertilizer is available, some fields will not receive any/enough fertilizer. What remains in stock is then distributed on the farm's grassland fields. In doing so, the algorithm defines a fertilizer application rate (Eq. 3). In case enough fertilizer is in stock, each field receives its required N amount. Otherwise, only a percental share of what is still available will be distributed on the fields (i.e. $R_{fert} \times N_{required}$).

$$R_{fert} := \begin{cases} 1, & N_{stock} \geq N_{required} \\ \frac{N_{stock}}{N_{required}}, & N_{stock} < N_{required} \end{cases} \quad (3)$$

During a workshop, the stakeholders communicated that most non-organic farms use supplementary mineral fertilization on their grasslands. Therefore, we implemented mineral fertilization for meadows and intensively used mowing pastures (i.e. 20 % grazing/cuts ≥ 4) that supplements the organic fertilization if the nitrogen requirement has not been fully covered. Grassland fields with agri-environmental schemes B10, B20-B23, F31, F32, H31, and H32 are excluded from the mineral fertilization (see Appendix 1 for a more detailed description of the measures).

2.3. Stakeholder engagement

The model's concept was discussed at various stages of development with experts from the Office of Food, Agriculture and Forestry (AELF) Weilheim, Germany and at an advanced stage with scientists from the University of Göttingen, Institute of Grassland Science, Germany. Additionally, it was presented and discussed during a stakeholder workshop and conferences/project-internal workshops. Generally, the evaluation consisted of a detailed presentation of model assumptions and workflows (or only specific parts of it), which were then open to discussion or specifically addressed for discussion by the authors, e.g. information about nutrient trade, estimation of grazing intensity, algorithm of nutrient distribution. Afterwards, the model was refined based on the results of these meetings. Intermediate and final model results were mainly validated and discussed with AELF Weilheim as these experts have an excellent overview of the study area and the local farming practices. An overview of the different stakeholder meetings can be found in Appendix 6. Additionally, the NetLogo code was reviewed by two of the co-authors and is available to the public (see Data Availability).

3. Results

We applied the model to the Ammer region running three different settings: (A) FO, 2017, trade radius = 0 km, (B) FO, 2017, trade radius = 30 km, and (C) FO, 2020, trade radius = 30 km. All runs used internal yield calculation and no yield uncertainty has been considered (Appendix 7). Furthermore, we conducted sensitivity analyses for trade radius and yield uncertainty. The detailed results are provided in Appendix 7.

Overall, there are 8436 t N_{org} in the form of semi-liquid cattle manure available in the study region (92 kg N_{org}/ha agricultural land, Figure A3). Of the 3174 farms modelled, 891 farms do not have any cattle and thus no farm fertilizer. The farms with excess fertilizer are homogeneously distributed across the study region. Table 5 summarizes the results of runs (A)-(C). Fig. 4 shows the spatial fertilizer distribution for run (B), which represents the most realistic scenario for the status quo in 2019. The maps reveal that fields with low and high application rates are distributed rather homogeneously in the central and northern part of the study region. Here, only some fields in the far north are not fertilized. These are mainly cropland and belong to farms that do not have any own farm fertilizer and cannot fully cover their nitrogen requirement by nutrient trade. In the grassland-dominated south, where elevation becomes higher, most of the grassland is managed with low intensity, visible by low to no fertilizer application amounts. Overall, mineral fertilization plays only a supplementary role on grassland (apart from some fields in the north) and is most prominent in the centre and the northern part of the study region. Here, elevation is lower than in the south, which allows for a more intensive management, and the share of cropland, where available farm fertilizer is applied first, is higher.

In run (B), an average amount of 117 kg N_{org}/ha field area is distributed on organically fertilized grasslands. However, 502 fields that make up 1.2 % of the total study area receive more than 300 kg N_{org}/ha field area, the highest amount is even 521 N_{org}/ha field area (Figure A4). Most of these are mowing pastures (476 ha) and the remaining fields are meadows (204 ha). Both are used rather intensively with mainly 3–5 cuts (Figure A5) and have comparatively high yields (mean of 92 dt/ha vs. 74 dt/ha overall mean of mowing pastures; mean of 84 dt/ha vs. 60 dt/ha overall mean of meadows, Figure A6) with a grass index ranging mainly from 35 to 60 (Figure A7, the highest value in the study region is 70).

Comparing run (B) with the scenarios in runs (A) and (C), the results show that in run (A), ca. 4 kg N_{org}/ha agricultural land remain in stock after fertilization. This outcome is due to farms in the study region that have more available farm fertilizer than the legal limit of 170 kg N_{org}/ha farm area allows for distribution. Runs (B) and (C), on the other hand, allowed nutrient trade in a radius of 30 km around each farm. In these runs, 23–35 % of the farms without cattle received nutrients from other farms and all available organic fertilizer was distributed in the area. If all fertilized grasslands and partly cropland (see Material & Methods) were to be fertilized with organic N, then the difference between available and required N_{org} (i.e. including minimum effectiveness and application losses) would be −131 kg N_{org}/ha fertilized agricultural land (FO 2017) or −89 kg N_{org}/ha fertilized agricultural land (FO 2020), respectively. Considering the legal application limit of 170 kg N_{org}/ha (fertilized) agricultural land, the total available amount of organic fertilizer from cattle manure remains well below this threshold at a regional scale, amounting to 92 kg N_{org}/ha (based on FO 2017) and 103 kg N_{org}/ha (based on FO 2020). This means, that from a regional perspective, supplementary mineral fertilization is necessary.

In total, for all runs, about 24–25 % of the grassland receives N_{min} but the amount per ha decreases from run (A) to (C). This is also the only noticeable difference in the spatial patterns of fertilizer distribution across the three runs (see Figure A8). In run (B) less mineral fertilizer is applied compared to (A) since nutrient trade allows for a better regional distribution of organic fertilizer and what remained in stock in run (A) after fertilization, compensates parts of the supplementary mineral fertilization in run (B). In run (C), the hectares in the 170 kg N_{org}/ha limitation of the FO 2020 are related to fertilized farm area (FO 2017: total farm area), i.e. at farm level, generally, less N_{org} can be applied. This also increased the number of farms participating in nutrient trade from runs (B) to (C). Nevertheless, there is still a gap between available and required N_{org} though significantly smaller. This means that even when considering only fertilized farm area, the available amount of N_{org} is not sufficient to cover the overall nitrogen requirement. However, the biggest effect of FO 2020 on grassland fertilization is that application losses are no longer considered when calculating the nutrient requirement, which leads to a strong reduction in the required N_{org}. Also, in this case, the remaining N_{org} compensates partly for supplementary mineral fertilization.

Table 5
Summary of the results for model runs (A), (B), and (C); FO – fertilization ordinance.

	Scale	(A) FO 2017, trade radius = 0 km	(B) FO 2017, trade radius = 30 km	(C) FO 2020, trade radius = 30 km
Total available N_{org}/ha agricultural land	regional	92 kg N_{org}/ha	92 kg N_{org}/ha	92 kg N_{org}/ha (103 kg N_{org}/ha only fertilized agricultural land)
Mean available N_{org}/ha farm area	farm	68 kg N_{org}/ha	68 kg N_{org}/ha	68 kg N_{org}/ha (80 kg N_{org}/ha only fertilized farm area)
(Available N_{org} – required N_{org}*) / fertilized area	regional	−131 kg N_{org}/ha	−131 kg N_{org}/ha	−89 kg N_{org}/ha
Share of grassland receiving N_{min}	regional	25 %	25 %	24 %
Mean applied N_{org}/ha fertilized grassland	field	116 kg N_{org}/ha	117 kg N_{org}/ha	119 kg N_{org}/ha
Mean applied N_{min}/ha fertilized grassland	field	78 kg N_{min}/ha	76 kg N_{min}/ha	63 kg N_{min}/ha
No. of farms importing/ exporting N_{org}	regional	-	209/384	310/515

* including an increase by application losses (FO 2017) and minimum effectiveness of cattle manure (FOs 2017 and 2020)

4. Discussion

In the following, we will discuss the model results and setup as well as its applicability and potential for further development. Further minor points of discussion are covered in Appendix 8.

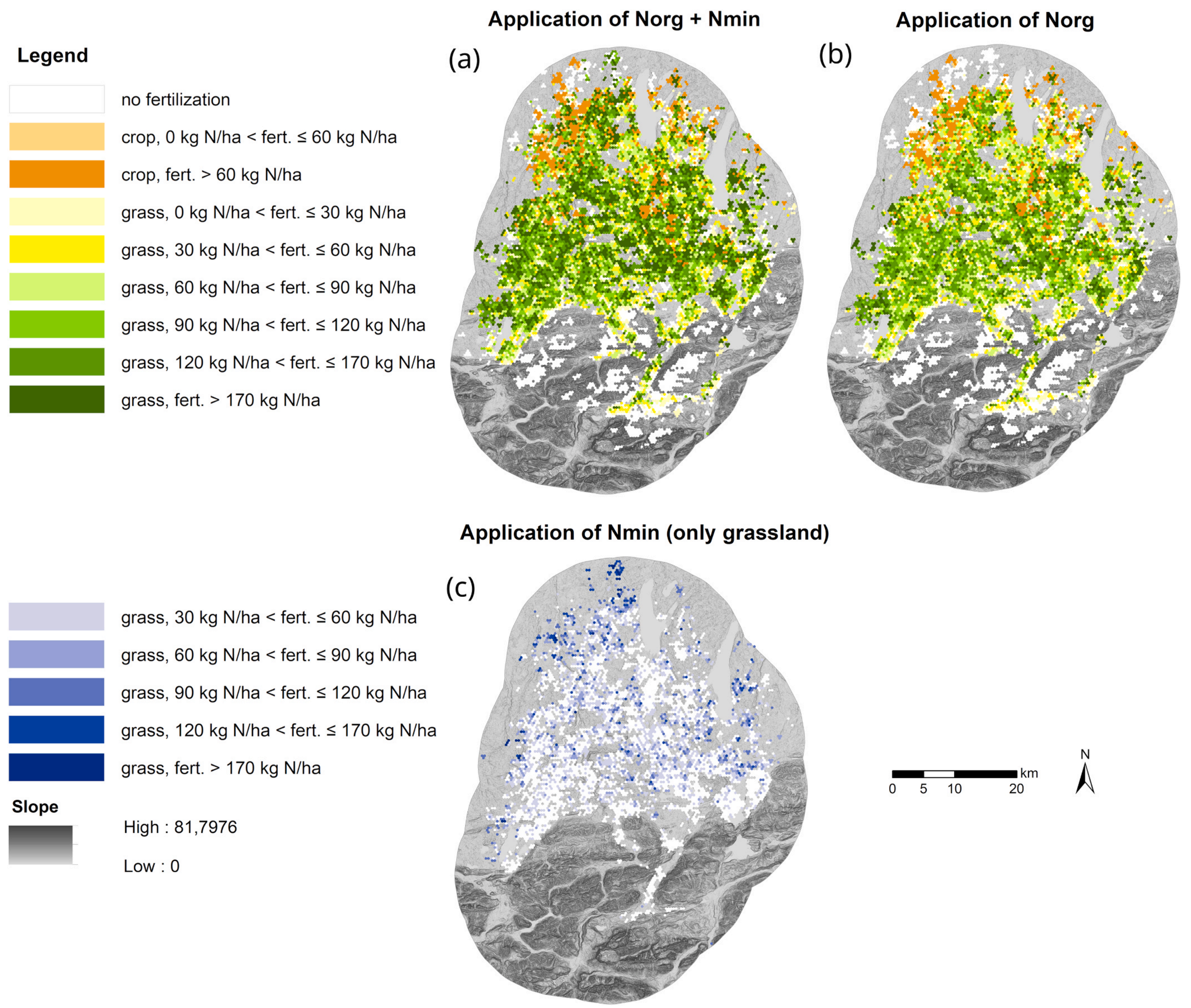

Fig. 4. Spatial distribution of N_{org} and N_{min} (a), N_{org} (b), and N_{min} (only grasslands that receive N_{min}, c) of run (B). Maps exclude non-modelled fields (e.g. fallow land or meadow orchards) and are anonymized by a spatial aggregation of the actual field polygons into a hexagon grid (each hexagon covers an area of 22 ha).

4.1. Modelled fertilizer application rates

In run (C), we applied fertilization ordinance that is effective since 2020 (FO, 2020), to compare its effects on nitrogen application in the study region with the fertilization ordinance that was effective from 2017 to 2020 (FO, 2017), applied in run (A) and (B)). The result that the stricter area requirement for the 170 kg N/ha limit in the revision of the ordinance in 2020 (see Material & Methods) has almost no effect on nitrogen distribution has to be interpreted carefully. First, it assumes a regional perspective. In the entire Ammer region, available organic nitrogen from cattle is not sufficient to fully cover the overall nitrogen requirement. However, at the farm level, the picture can be quite different as there are more farms that, with the stricter rule, have a surplus of farm fertilizer. These farms can trade the excess amount since theoretically, there are enough farms that can take up additional organic fertilizer. In practice, this would lead to transaction costs, which are not considered in the model. If trade is not an option, the farms could, for example, increase their fertilized area (high land competition and prices) or decrease cattle numbers (potential reduction in income). Finally, this result is very specific for the generally less intensively managed study area and must not apply to other, particularly intensively managed, regions. The second major difference in the fertilization ordinances that was considered in run (C) is that application losses are no longer considered. This had the biggest effect on nitrogen management leading to 16 % lower N_{min} applications in the study area (model run (C) compared to (B)). Yet, from a regional perspective, this effect was not big enough to close the gap between available and required N_{org}.

On grassland, the officially defined minimum effectiveness of cattle manure of 50 % (LfL, 2018) assumes that 50 % of the nitrogen becomes available to the plant in the year of application. The other 50 % are assumed to become available in the next year or to be lost through processes such as volatilization or leaching. However, the official scheme for calculating nitrogen requirements accounts for only 10 % of the organic nitrogen applied in the previous year, effectively considering 40 % of the applied nitrogen as lost in the nutrient balance. Starting from February 1, 2025, the defined minimum effectiveness of cattle manure on grassland will be increased by 10 % (i.e. 60 %). This means that less organic fertilizer can be applied since more of the ammonium is assumed to become available to the plants within the year of application. Given the same management and cattle numbers, this will create a similar effect like the no longer assuming application losses and similarly, might not have too strong effects in the Ammer region but probably in more intensively used areas.

The field-specific nitrogen application rates are overall plausible for the study region, as confirmed by the experts at the Office of Food, Agriculture and Forestry (AELF) Weilheim, Germany, responsible for most of the area of the study region. They only disagreed with the above-mentioned few extreme cases of up to 525 N_{org}/ha. The experts argued that at very good locations in a year with a very beneficial climate and under intensive management, these fertilization rates would be possible but are in general unrealistic. An evaluation of the fields in question showed that these fields are indeed rather intensively used meadows and mowing pastures. Particularly the latter make up the largest share. The high nitrogen applications originate from an accordingly high nitrogen requirement. The reason why the model calculated such high values could be that we used simplistic rules to estimate the use intensity of mowing pastures and especially grazing, which can lead to wrong assumptions in some cases. Defining the grazing share of a mowing pasture and identifying grazing intensities is a core issue that needs to be addressed in an updated model version. Nevertheless, Zinnbauer et al. (2023) report that regions with high livestock densities can have extreme values of up to 500 kg N_{org}/ha agricultural land.

The small spatial differences in applied amount of N fertilizer between runs (A)-(C) are not surprising. The net fertilizer requirement, which mainly influences spatial fertilizer distribution, is the same over all runs. Adding nutrient trade in run (B) leads to a better distribution of excess farm fertilizer but the effect in the area is quite low (116 vs. 117 kg N_{org}/ha fertilized grassland) and thus also spatially only hardly visible.

Given the limited research and empirical data on field-level fertilization in the study area, only general trends in the results can be analyzed in comparison to findings from existing literature. In a grassland lysimeter experiment in the Bavarian Alps from 2012 to 2014, Fu et al. (2017) collected organic fertilization rates with cattle manure for different grassland management types. The yearly average application rates of all sites with 2–4 cuts that were only fertilized by cattle manure was 111.25 kg N_{org}/ha, which aligns well with our findings as most of the grassland area in our study region was cut 2–4 times per year. However, they did not consider additional mineral fertilization but calculated with a maximum of six applications per year with 42 ± 10 kg N_{org}/ha each for intensively managed grasslands, i.e. up to 312 kg N_{org}/ha. Most other reports do not differentiate between the fertilization of cropland and grassland. For example, Zinnbauer et al. (2023) report maps of Germany with fertilizer distributions (average of 2014–2016) that show a similar pattern as in Fig. 4 of high application rates of organic and mineral fertilization in the north and lower rates in the south of the Ammer region. In 2019, the German average of organic nitrogen applications was 88 kg N_{org}/ha and 80 kg N_{min}/ha for mineral fertilizer (BMEL, 2024). However, due to the high share of cropland in German agricultural land, these numbers are less informative for grassland-dominated areas such as our study region. Therefore, we prefer comparing them to the county of Lower Saxony, Germany, that also has high grassland shares in several districts. On the county level, the yearly organic fertilization rate was 121 kg N_{org}/ha and the mineral fertilization rate around 99 kg N_{min}/ha in 2018/2019 as well as 118 kg N_{org}/ha and 88 kg N_{min}/ha in 2019/2020. The values of the organic fertilization rates align well with our results of 117 kg N_{org}/ha (run B), 119 kg N_{org}/ha (run C). The mineral fertilization rates are, however, higher than those calculated by FertIG: 76 kg N_{min}/ha (run B) and 63 kg N_{min}/ha (run C). Nevertheless, according to the Bavarian Agricultural Report (StMELF, 2022), mineral fertilization rates were 59.3 kg N_{min}/ha in 2018/2019 but on average 73 kg N_{min}/ha between 2014 and 2018 in Bavaria. These values align well with the mean mineral application rates in our study regions. When comparing the values above, it should also be taken into account that mean mineral and organic application rates in Table 5 are given per ha fertilized grassland whereas the above-mentioned reports state their values per ha agricultural land.

4.2. Model setup

In the following, we discuss different parts of the model setup, i.e. the calculation of available organic nitrogen, consideration of yield uncertainty, calculation of nitrogen requirement, nutrient trade as well as fertilizer distribution.

4.2.1. Available N_{org}

Our ABM FertIG considers only semi-liquid manure of cattle available as organic nitrogen fertilizer (N_{org}). In practice, farms can have a mixture of semi-liquid and solid manure (e.g. if they keep calves or young cattle) or even mainly solid manure. However, according to the stakeholders, about 95 % of the farms in the study area use a semi-liquid manure system for their cattle and solid manure makes up only a small proportion of the entire available manure. Of course, farms can also keep other animals that produce manure such as poultry, sheep or equines, for instance. According to the IACS animal data, cattle produce by far most of the manure in the study area, which is why we focused on cattle manure exclusively. Nevertheless, when coupling FertIG with a model that simulates the effects of organic fertilization on soil, it can make a difference if semi-liquid or solid manure is applied. Additionally, there were 100 active biogas plants for on-site electricity generation in the study region in 2019 (Manske et al., 2022). There is only little difference in nutrient content if manure was used as biogas substrate before applying it to a field as organic fertilizer. However, it is possible that further organic nitrogen was available in the area in terms of residues from these biogas plants if the used energy source was another than cattle manure. This was not considered in the study and could be improved in further model versions, particularly if applied to areas where energy production by fermenting plant-based materials plays an important role and in view of an increasing use of renewable energies. However, due to the high variability in nutrient content of digestate, plant-specific analyses are necessary for reliable data (Wendland and Lichti, 2012). As such data and farm ownership details were unavailable for our study area, we estimated the role of biogas digestate using installed plant capacity. In Appendix 9, we calculate the effective nitrogen from plant-based digestate (after subtracting storage and application losses and considering its minimum effectiveness) to be approximately 274–461 t N_{org}, or 3–5 kg N_{org}/ha of agricultural land. Given the above-mentioned reasons, these figures should be considered rough estimates. Nevertheless, this means that overall, plant-based digestate from biogas plants do play a role in the study region, particularly in the north, where the cultivation of maize is more present. However, the estimated additional N_{org} is rather low on the regional scale meaning that in case of the Ammer region, considering biogas plants in the model would not lead to a significant change in the overall results.

4.2.2. Yield uncertainty

In the application, we only considered grassland yield uncertainty in the sensitivity analysis (Appendix 7) but not in runs (A)-(C). Since field-specific grassland yield data was not available, we used the values given in the LfL guidelines from 2018 (LfL, 2018). These values are based on internal research and field experiments by the LfL. In these experiments, yields and N-concentrations increased with the intensity of land use (Diepolder et al., 2016; Köhler et al., 2013). To represent the Bavarian averages, the monitored yields were modified and adjusted (high uncertainty due to regional differences in soil and climatic conditions). However, farmers were encouraged to use these average yields to estimate the amount of fertilizer requirement and according to the experts at the AELF Weilheim, for most locations the estimated yields are representative. Additionally, (assuming a circular economy) the available amount of N_{org} is in line with the yield assumptions and the corresponding nutrient requirement, leading to overall realistic results for organic and mineral fertilizer applications. Nevertheless, the model also allows for the integration of externally calculated grassland yields, if available.

4.2.3. Nitrogen requirement

When calculating the organic nutrient requirement (i.e. including minimum effectiveness of cattle manure and application losses), the approach assumes the same value for the minimum effectiveness (50 % for grassland and 60 % for cropland) for the entire region. However, the minimum effectiveness of the fertilizer increases with a higher ammonium content and the model does not account for the individual composition of the different farm's organic fertilizers. Additionally, application losses are assumed to be always 17.6 % although this depends on the application technology used about which no data was available. Nevertheless, the applied values are standard values recommended by the LfL guidelines from 2018 (LfL, 2018). Another factor that influences nutrient requirement is the respective field's use intensity. We used valid estimates of cutting events in meadows based on remote sensing data from Reinermann et al. (2023). Even though the overall accuracy of this data is high, it may contain uncertainties i.e. missed cutting events due to cloud cover. For pastures and particularly mowing pastures, the identification of use intensity was very difficult since we knew the number of cattle per farm but did not have any information about stocking densities and grazing frequencies. Therefore, the proposed methodology uses a rather simple approach to derive use intensities of (mowing) pastures, which might cause an over- or underestimation. This could also be an explanation for the unrealistic extreme values in organic fertilizer application (mowing pastures with up to 525 N_{org}/ha field area).

4.2.4. Nutrient trade. We implemented nutrient trade without any economic incentives, which could be improved in future versions considering e.g. costs due to transportation and prices for taking up/selling manure. According to the stakeholders of the study area, distance from field to farm is a much less limiting factor for nutrient trade nowadays since with the high capacities of today's transportation measures, farm fertilizer can be distributed among a farm's fields relatively easy. While calculating transportation costs would be fairly simple to implement, defining rules on whether a farm would pay or earn money for receiving manure requires more thorough research since this depends on the analyzed region. In the Ammer study area, for instance, stakeholders mentioned that in the more intensively used north around Starnberg, farms without cattle would buy manure while farms in the more extensively used south around Garmisch-Partenkirchen would get paid for taking up manure. Additionally, prices for manure depend on market prices of mineral fertilizer, i.e. with increasing prices for mineral fertilizer, trade of farm fertilizer might become more relevant in the future. Another factor that should be considered in this context are transaction costs: In Germany, some of the smaller farms that fulfil certain requirements are excluded from the obligation to determine their fields' fertilizer requirements. As soon as they take up another farm's organic fertilizer, however, they would have to do so, which implies an important bureaucratic obstacle next to the fact that nutrient trade also must be documented by trading farms in general.

4.2.5. Fertilizer distribution. During the growing season in Germany, there are multiple opportunities for the timing of organic fertilizer applications on grasslands whereas on cropland this is mainly possible in spring. Especially maize receives organic fertilizer since it needs more N at a later growing stage and thus the plant can take advantage of the organic fertilizer's mineralization rate. The stakeholders communicated that in the study area, it is very common that the restriction period for nitrogen fertilization on grassland (November, 1st until January, 31st) is postponed by around four weeks towards spring (without exceeding a total of three months). Therefore, at this time of the year, cropland is often the only opportunity for farmers to empty organic fertilizer stocks. For this reason and due to the high share of maize in cropland, the model prefers cropland over grassland when distributing organic fertilizer.

4.3. Applicability and further development

FertIG is currently well-suited for grassland-dominated areas. Unlike most methods mentioned in the Introduction, it is one of the few models capable of calculating field-specific nitrogen rates for grasslands and, to our knowledge, the first agent-based model (ABM) designed for this purpose. The ABM framework uniquely enables the consideration of interactions between agents, such as nutrient trade. This functionality could be further enhanced, for example, by incorporating mechanisms for agents to learn from one another. However, it needs to be taken into account that grazing in pastures and mowing pastures follows very simplistic rules, which should be improved in updated model versions. Additionally, the model is planned to be extended by more sophisticated rules for cropland fertilization. When applying the model to other study areas, the biggest challenge would probably be the collection of input data since field-specific data with a large coverage is rare and often subject to restricted access (e.g. IACS, soil quality). Furthermore, the calculation of nitrogen requirements has to be regionally adapted, i.e. average values for cropland (crop types, soil N_{min} values) and grassland yields (FertIG uses case-study specific standard values for the internal calculation). For the calculation of available farm fertilizer, FertIG only considers semi-liquid manure produced by cattle. It may be necessary to include manure produced by other animals such as pigs, for instance, or extend the model by solid and mixed manure systems. Also, the nitrogen content of cattle manure must be adapted according to milk yield. In terms of nitrogen fertilization in other German regions, restrictions in nitrate-polluted areas might have to be added to the model as these do not apply in our study region and are thus not included in the model code. Furthermore, different countries may have their own restrictions that limit application amounts, which would need to be incorporated into the model. The rules implemented in FertIG are based on Germany's current fertilization ordinance and county-specific agri-environmental schemes. Both may be subject to future changes and would require corresponding updates to maintain the model's accuracy and relevance.

5. Conclusion and outlook

The presented agent-based model, FertIG (Fertilization in Grasslands), provides a powerful tool for simulating spatially explicit nitrogen fertilization at the field scale, capturing both semi-liquid cattle manure and supplementary mineral fertilizer applications on grasslands. This model's strengths lie in its capacity to incorporate legal fertilization restrictions, region-specific grassland yield estimates, and nutrient trading, making it a flexible tool for evaluating fertilization practices. We applied FertIG to the grassland-dominated Ammer region in Germany showing that in the Alpine south, grasslands are mainly managed with low intensity while the management intensity of the region's pre-Alpine part is mixed with fields of low to high use intensity and without any clear spatial pattern. The results also show that the 2020 fertilization ordinance had a noticeable yet limited impact on fertilization management in this region, though these findings are specific to regions with similar agricultural structures and should be generalized cautiously.

FertIG is a valuable tool for analyzing the effects of policy changes on grassland fertilization, such as the modification in the fertilization ordinance and participation in agri-environmental schemes. By adjusting input data, it can also simulate the effects of changes in cattle livestock or use intensities (e.g. frequency of cutting events). The model's outputs can support policy recommendations for sustainable grassland management and assist decision-makers in implementing regionally effective fertilization regulations. Additionally, the fertilization application rates generated by FertIG serve as essential input for other models, such as those focused on biogeochemical processes.

While FertIG can be adapted to other regions in Germany, Europe, and potentially beyond, it requires region-specific adjustments and data preparation. Thus, it should be seen as a foundational framework rather than a plug-and-play tool. Nonetheless, FertIG addresses a significant gap by providing crucial nitrogen fertilization data at the field level, which is often lacking. This data supports process-based models that inform policy actions aimed at protecting essential ecosystem services, thereby contributing to broader environmental and agricultural policy objectives.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors did not use any generative AI or AI-assisted technologies.

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.

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CRediT authorship contribution statement

A. Kaim: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **T.M. Schmitt:** Writing – review & editing, Writing – original draft, Visualization, Validation. **S.H. Annuth:** Writing – review & editing, Writing – original draft, Investigation. **M. Haensel:** Writing – review & editing, Validation. **T. Koellner:** Writing – review & editing, Project administration, Funding acquisition.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.eja.2025.127539.

Data Availability

The data that has been used is confidential. Code and artificial input data are available on https://www.comses.net/codebases/1fef1ba7-ba2b-4fa6-96f9-634b8ad35553/releases/1.0.0/.

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