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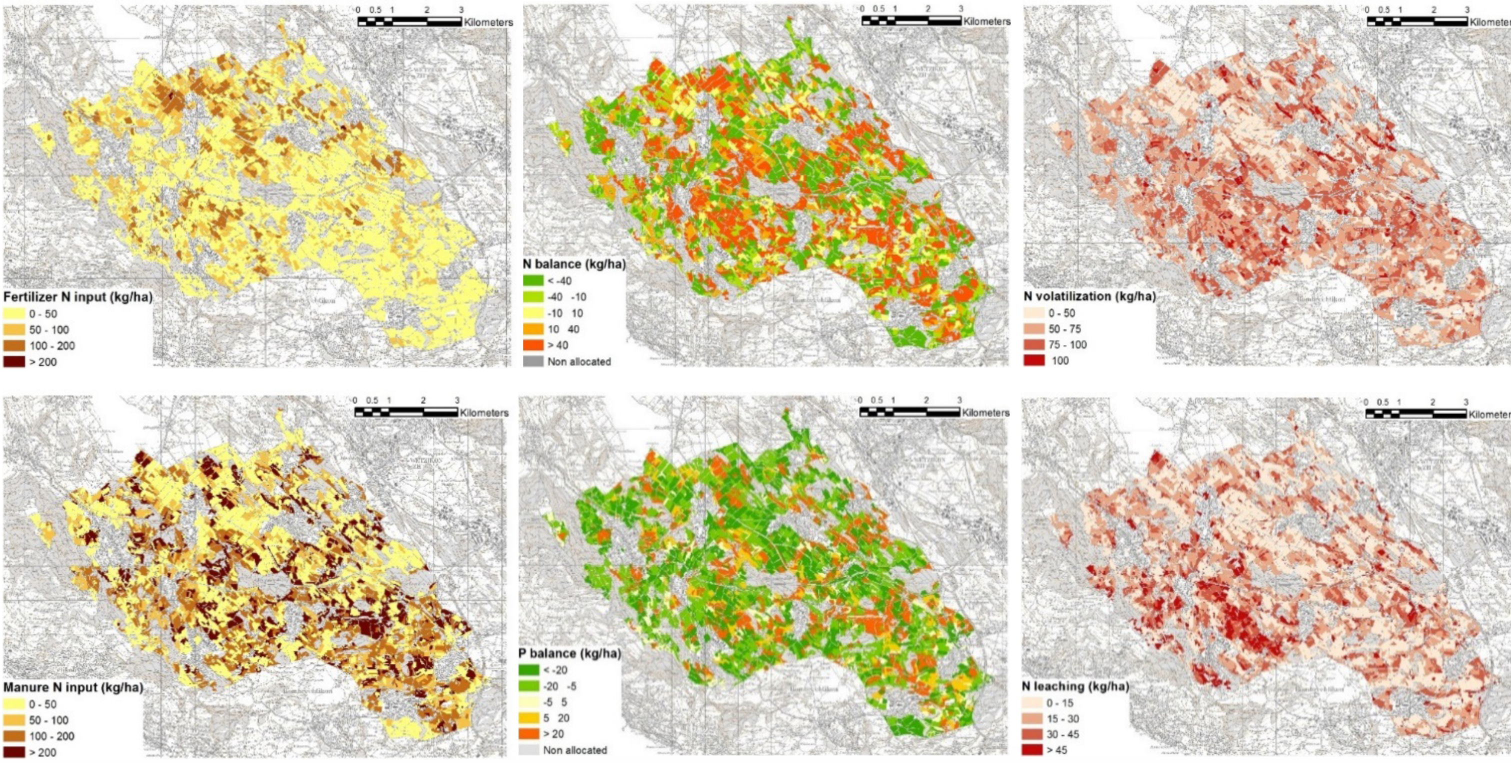

Fluxes of nutrients and trace elements in agricultural soils: A regional-scale model

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Summary

Various quantities of fertilizers and other soil amendments are applied to agricultural soils over time. This can lead to the gradual accumulation of several elements, which can represent a threat for soil quality and for soil functions. We developed a regional modelling tool for assessing element fluxes in agricultural soils and their temporal and spatial patterns. The tool uses georeferenced farm census data, remote sensing images, fertilization guidelines and other data sources. The model provides spatially explicit balances of Nitrogen, Phosphorus, Copper and Zinc. Thus, critical areas with increased risk of element accumulation can be identified. Moreover, the model allows the analysis of simple scenarios, related to economic or policy drivers. Therefore, one of the strengths of the model is the capability of assessing measures towards sustainable agricultural land use through scenario analysis.

Zusammenfassung

Im Laufe der Zeit werden verschiedene Mengen an Düngemitteln und anderen Bodenverbesserungsmitteln auf landwirtschaftliche Böden aufgebracht. Dies kann zu einer allmählichen Anreicherung verschiedener Elemente führen, die eine Gefahr für die Bodenqualität und die Bodenfunktionen darstellen können. Wir haben ein regionales Modellierungsinstrument zur Berechnung der Elementflüsse in landwirtschaftlich genutzten Böden und ihrer zeitlichen und räumlichen Muster entwickelt. Das Modell nutzt georeferenzierte Betriebszählungsdaten, Fernerkundungsbilder, Düngungsrichtlinien und andere Datenquellen. Das Modell liefert räumlich und zeitlich (jährlich) explizite Bilanzen für Stickstoff, Phosphor, Kupfer und Zink. Auf diese Weise können kritische Gebiete mit erhöhtem Risiko einer Elementanreicherung ermittelt werden. Darüber hinaus ermöglicht das Modell die Analyse einfacher Szenarien, die aufgrund wirtschaftlicher oder politischer Faktoren entworfen wurden. Eine der Stärken des Modells ist daher die Fähigkeit, Massnahmen für eine nachhaltige landwirtschaftliche Bodennutzung durch eine Szenarioanalyse zu bewerten.

Riassunto

Varie quantità di fertilizzanti e altri ammendanti vengono applicati ai terreni agricoli in modo continuativo. Ciò può portare all'accumulo graduale di diversi elementi, che possono rappresentare una minaccia per la qualità del suolo e per le sue funzioni. Abbiamo sviluppato uno strumento di modellizzazione regionale per valutare i flussi di elementi nei suoli agricoli e le loro variazioni temporali e spaziali. Il modello utilizza dati geo-referenziati del censimento agricolo, immagini satellitari, linee guida sulla fertilizzazione e altre fonti di dati. Il modello fornisce bilanci di azoto, fosforo, rame e zinco evidenziando le variazioni nello spazio. Pertanto, possono essere identificate aree critiche dove il rischio di accumulo di elementi nel suolo è maggiore. Inoltre, il modello consente l'analisi di semplici scenari, relativi a fattori economici o politici. Pertanto, uno dei punti di forza del modello è la capacità di valutare le misure per l'uso sostenibile dei terreni agricoli attraverso l'analisi di scenari.

Abbreviations

AGIS	Agrarpolitisches Informationssystem - Agricultural Information System (https://www.blw.admin.ch/blw/de/home/politik/datenmanagement/agate/agis.html)
AUI	Agrarumweltindikatoren – Agro-environmental indicators (https://www.blw.admin.ch/blw/de/home/nachhaltige-produktion/umwelt/agrarumweltmonitoring.html)
BLW	Bundesamt für Landwirtshaft – Federal Office for Agriculture
GRUD	Grundlagen für die Düngung landwirtschaftlicher Kulturen in der Schweiz - Principles of fertilisation of agricultural crops in Switzerland (Sinaj and Richner 2017)
LMM	Land Management Model
NABO	Nationale Bodenbeobachtung – Swiss Soil Monitoring Network
ÖLN	Ökologischer Leistungsnachweis – Proof of ecological performance (https://www.blw.admin.ch/blw/de/home/instrumente/direktzahlungen/oekologischer-leistungsnachweis.html)

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List of model parameters

Name	Default	Unit	Description	Section
OBB	6000	m	max distance for manure trading (small farms)	Manure trading (2.6)
OBBgross	50000	m	max distance for manure trading (big farms)	Manure trading (2.6)
mx_K	3	-	max no. of partners (small farms)	Manure trading (2.6)
mx_G	15	-	max no. of partners (big farms)	Manure trading (2.6)
ag	5	ha	max area allocated per iteration	Land allocation (2.8)
dstCoef	20	-	Coefficient for max distance parcel-farm (eq. 35)	Land allocation (2.8)
exp	0.5	-	exponent of the distance function for manure distribution (eq. 52)	Fertilizer and manure distribution to fields (2.10)

List of main model variables

In the following table, X indicates either nitrogen (N) or phosporus (P).

Name	Unit	Description
$X\_need_{i,j,c}$	kg yr^{-1}	Net requirement of element X by crop c at farm j in the year *i*
X_grud_{c}	kg ha^{-1} yr^{-1}	GRUD's recommended annual application rate of element X for crop c
$X\_man\_tot_{i,j,l}$	kg yr^{-1}	Amount of X excreted by livestock *l* at farm *j* in the year *i*
$N\_man\_ava_{i,j,l}$	kg yr^{-1}	Amount of manure N available to plants
$X\_supply_{i,j,c}$	kg yr^{-1}	Desired (planned) supply of X to crop *c* at farm *j* in the year *i*
$X\_rate_{i,j,c}$	kg ha^{-1} yr^{-1}	Application rate of mineral fertilizer X for crop *c*, farm *j* and year *i*
$X\_min_{i,j,c}$	kg yr^{-1}	Amount of X applied via mineral fertilizer for crop *c*, farm *j* and year *i*
$X\_farm\_bal_{i,j}$	kg yr^{-1}	X balance at the farm level, for farm *j* and year *i*
X_input_{k}	kg	Amount of X input to field *k*
X_uptake_{k}	kg ha^{-1}	X uptake at field *k*
$X\_balance_{k}$	kg ha^{-1}	X balance at field *k*

1 Introduction

Agricultural soils receive several types of amendments such as synthetic fertilizers, animal manure, compost, and waste-derived fertilizers. These materials contain macronutrients as well as trace elements. If not correctly managed, amendments can severely affect chemical properties of soils and connected water bodies (Stoate et al. 2001). Nitrogen (N) and phosphorus (P) inputs exceeding crop need increase the risk of losses to water bodies, potentially leading to groundwater contamination and surface water eutrophication (Carpenter et al. 1998, Correll 1998, Akinnawo 2023). Some trace elements are important micronutrients; however, in high concentrations many of them are potentially toxic to soil and water organisms and also to humans if taken up by crops in relevant amounts (Giller et al. 1998, He et al. 2005). Copper (Cu) and zinc (Zn) are used as feed additives and their concentration in animal manures can be significant (Nicholson et al. 1999). Commercial phosphate fertilizers can contain important amounts of cadmium (Cd) and uranium (U) (Kratz et al. 2016). Moreover, P is an essential and irreplaceable element for food production, but phosphate rock reserves from which P fertilizers are obtained are a limited resource, and newly mined deposits are more and more contaminated with undesired elements (Cordell et al. 2009). All above considerations point to the need of an appropriate management of soil amendments to ensure a sustainable agricultural production.

In this respect, Swiss agriculture can be taken as an interesting case study. Nutrient surpluses decreased significantly since the 1970s for N (27%) and P (83%) (Spiess & Liebisch 2020). Particularly the introduction of ecological measures in mid 1990s led to a decline of the N and P surpluses, mainly due to a reduction of mineral fertilizers use (Herzog et al. 2008, Spiess & Liebisch 2020). On the other hand, imported feed has increased dramatically since the mid-1990s. In 2008, farm-gate balances showed average surpluses of 108 kg N ha^{-1} and 5.5 kg P ha^{-1} for Swiss farms. Total amounts of N and P inputs into Swiss agricultural soils (about 1.48 Mio ha) were estimated to 189’469 tons and 25’956 tons, respectively (Bosshard and Richner 2013). The N surplus was quite stable in the last decade around 110’000 tons. The large N inputs into the environment resulting from agricultural production and ways how to reduce these inputs remain a debated issue in Switzerland (e.g. Swiss Confederation 2021; Argento et al. 2022). The current P surplus of 5’000 t is quite close to the reduction goal (4’000 t). Nevertheless, the P surplus of the last three decades (in the order of 200’000 t P) caused the accumulation of P in agricultural soils. The few available regional datasets for soil P measurements show high soil P levels in agricultural soils (Frossard et al. 2004, Keller and van der Zee 2004). These findings are in agreement with the annually published compilation of soil measurements that are mandatory for the farmers in the ecological performance program (Federal Office for Agriculture, BLW 2022). The maps of soil P levels indicate large agricultural regions in central and eastern Switzerland with high soil P levels. Hence, further strategies addressing P cycling, losses and fertilization in Swiss agriculture are required. Regarding trace elements, various studies have shown that despite recent improvements trace metal inputs into Swiss soils are in average still not sustainable (e.g. Herzog et al. 2008, Keller and Schulin 2003, Gross et al. 2021). For instance, management data of 46 agricultural sites of the Swiss Soil Monitoring Network (NABO) showed high net inputs of copper and zinc on intensively managed grassland sites, mainly due to large application rates of animal manure (Gross et al. 2021).

Element balances are widely used as tools to meet environmental targets for nutrient and pollutant management in agriculture (Moolenaar et al. 1998; de Vries et al. 2003; Keller and Schulin 2003; Nicholson et al. 2003; Öborn et al. 2003;; Sheppard et al. 2009). The nutrient management and fertilization strategy adopted by farmers are influenced by several factors such as the farm structure and organization, socio-economic boundary conditions, regulation and incentive policies, and the availability of new types of fertilizers. These factors vary in space and time at different scales, from regional to field level (Seppelt 2000; Rounsevell et al. 2003, Rounsevell et al. 2012; Seppelt and Voinov 2002). Moreover, pollutant export from agricultural land to water bodies is generally characterized by a high spatial variability, with few critical areas contributing the most. In order to capture the spatial and temporal pattern of element inputs into agricultural soils, predict trends under different scenarios, and support the development of measures to reduce element accumulation is soil and their transport to water bodies, tools are required to combine relevant data sources in a spatially explicit way. The development of such tools has been hampered in the past by a lack of spatially explicit land management information at regional scale. For example, several models were developed during the last two decades to simulate land use with respect to an optimisation goal, e.g. economic efficiency of farming systems or environmental goals. A non-exhaustive list includes RAUMIS (Weingarten, 1995), MODAM (Zander, 2001), ProLand (Kuhlmann et al., 2002) and SEAMLESS (van Ittersum et al., 2008). These models do not account for actual farming structures. Thus, they cannot capture the implications of different management strategies.

These limitations can be partially overcome by newly available datasets and recent advancements in remote sensing, geographical information systems (GIS), computational capacity and modelling techniques. Gärtner et al. (2013) proposed a downscaling approach that takes data at farm level and distributes it spatially to the agricultural land. Based on that work, we developed a Land Management Model (LMM), a tool that combines geo-referenced farm census data, land use information generated by remote sensing techniques, data on chemical composition of soil amendments, crop nutrient requirements, typical agricultural practices and fertilizer strategies, and expert knowledge (Della Peruta and Keller 2016). The LMM uses an extensive set of rules implemented in a downscaling algorithm to estimate the application rate of soil amendments and calculate spatially explicit balances of N, P and main trace elements at the field scale. In this report we describe the model and we present results obtained for selected study areas.

2 Model description

2.1 Overview of the model workflow

The aim of the Land Management Model (LMM) is to assess the impact of agricultural management on the chemical quality of agricultural soils, in a spatially explicit way. In particular, the LMM calculates balances of certain elements and substances at the soil surface. Within the LMM, a surface balance is the difference between element input through agricultural operations (mainly fertilization) and output through crop uptake. The surface balances are calculated for each spatial unit and each time step. Spatial and temporal resolutions depend on the data used to run the model. The LMM follows a stepwise approach (Figure 1).

Figure 1: General workflow of the Land Management Model

2.2 Definition of soil surface balance

Typically, agricultural N balances at the soil surface are calculated by accounting for different input and output fluxes:

$$N_{bal} = N_{fert} + N_{man} + N_{was} + N_{dep} + N_{fix} + N_{res} - N_{crop} - N_{vol} \tag{1}$$

where N_{bal} is the N balance, N_{fert} is the input via inorganic (synthetic) fertilizers, N_{man} is the input via animal manure, N_{was} is the input via waste-derived fertilizers such as sewage sludge, urban compost or biogas residues, N_{dep} is the input via atmospheric deposition, N_{fix} is the input via biological N fixation by crops, N_{res} is the input via crop residues left on the field, N_{crop} is the N removed via crop harvest, and N_{vol} is the output via N volatilization.

The balance for P is simpler, since some of the fluxes are irrelevant:

$$P_{bal} = P_{fert} + P_{man} + P_{was} + P_{dep} + P_{res} - P_{crop} \tag{2}$$

The datasets used in this study allowed us to account for all the above fluxes, although sometimes in an indirect way. In particular, the Swiss fertilization guidelines GRUD (Sinaj and Richner, 2017) provide standard values of crop nutrient requirements that are already adjusted to account for input via N fixation (in grasslands and cover crops), incorporation of crop residues in soil, and atmospheric deposition, as well as for N volatilization during manure spreading. Moreover, the guidelines provide simple methods to further adjust the recommended nutrient application if additional information is available. These corrections and methods are based on well documented long-term experiments. Therefore, the model calculates simplified balances where the N and P crop needs account for many of the other fluxes:

$$N_{need} = N_{crop} - N_{dep} - N_{fix} - N_{res} + N_{vol} \tag{3}$$

$$P_{need} = P_{crop} - P_{dep} - P_{res} \tag{4}$$

In other words, N_{need} is the net N requirement by crops after accounting for all other sources and sinks of N (except fertilization). It corresponds to the suggested N fertilization as calculated in GRUD. The same apply for P. In Switzerland, the application of sewage sludge is banned since 2003 (BLW 2004) while other waste-derived fertilizers such as compost and digestate were considered irrelevant within the scope of this work, therefore the terms N_{was} and P_{was} were neglected. The simplified balances can be written:

$$N_{bal} = N_{fert} + N_{man} - N_{need} \tag{5}$$

$$P_{bal} = P_{fert} + P_{man} - P_{need} \tag{6}$$

2.3 Farm structure: nutrient stocks and needs

The model performs an assessment of the farms structure, and calculates nutrient stocks and needs at the farm level, by using two datasets. The first dataset is the farm census AGIS (Agricultural information system, BLW 2018a), conducted annually on all farms, providing crop areas by species as well as livestock headcount by species. The second dataset was derived from the GRUD manual (Sinaj and Richner, 2017) and provides average N and P requirements for each crop type, as well as average N and P excretion rates for each livestock type. The Annex lists all types of crop and livestock that the model can currently handle.

Firstly, the model uses the above data to calculate annual N and P requirements by crops (including meadows and pastures):

$$N\_need_{i,j,c} = N\_grud_c * area_{i,j,c} \tag{7}$$

$$P\_need_{i,j,c} = P\_grud_c * area_{i,j,c} \tag{8}$$

where $N\_need_{i,j,c}$ (kg) is the amount of N required by crop *c* at farm *j* in the year *i*, N_grud_c (kg ha^{-1} yr^{-1}) is the GRUD's recommended annual application rate for crop *c*, and $area_{i,j,c}$ (ha) is the area of crop *c* at farm *j* in the year *i* (similar notation is used for P).

The GRUD authors estimated N_grud_c and P_grud_c based on average crop yields and nutrient crop concentrations in Switzerland. Values of N_grud_c are already corrected for N inputs via deposition and fixation. The authors distinguished nutrient concentrations in grain and straw; therefore, it is possible to account for nutrients that re-enter the soil via the incorporation of crop residues. They also suggest how to correct yield predictions based on performance goals. In the case of arable crops, yield is supposed to grow linearly with increased N applications, until a maximum is reached. In the case of meadows and pastures (collectively termed grassland in this paper), different yield levels are proposed based on the intensity of use (i.e. fertilization, number of cuts per year, grazing time) and on the altitude. Moreover, the authors provide methods to correct estimated N needs based on soil characteristics, climate, and the legacy of previous crops (e.g. cover crops) and previous fertilizations. In our model, we apply correction factors on crop yields to account for performance goals (see fertilization strategy below). The effect of altitude on grassland yields is also accounted for by using a digital elevation model (SwissTopo 2018). For this study, it was not possible to map grassland based on the intensity of use. However, we accounted for the intensity levels recorded in AGIS. We neglected other types of corrections, for the following reasons: (i) we assumed that most farms apply the average recommended values, because it is cumbersome to compute the corrections; (ii) we faced a lack of data, especially for soil nutrient status; and (iii) we wanted to avoid excessive model complexity and source of uncertainty. For most farms, there will be a risk of nutrient surplus from not taking into account the N released from manure applied in previous years. We believe this model feature correctly captures farmers' behaviour in the study area.

Secondly, the model calculates annual N and P excretions by livestock. In order to come up with realistic N budgets, the model takes into account the losses of N occurring while the animal manure is stored, by applying a correction factor specific to each livestock type:

$$N\_man\_tot_{i,j,l} = N\_excr_l * nh_{i,j,l} * \alpha_l \tag{9}$$

where $N\_man\_tot_{i,j,l}$ (kg yr^{-1}) is the amount of N excreted by livestock *l* at farm *j* in the year *i*, N_excr_l (kg head^{-1} yr^{-1}) is the N excretion rate for livestock *l*, $nh_{i,j,l}$ is the number of head of livestock *l* at farm *j* in the year *i*, and α_l is the fraction of N lost during storage of manure from livestock *l*.

The model also accounts for N availability to plants. According to GRUD, N availability ranges between 10 and 85% of total N. Our model assumes that only 60% of manure N is available to grass species. If arable crop species are grown, availability is further decreased based on the fraction of arable land over total land, using the following equation:

$$N\_man\_ava_{i,j,l} = N\_man\_tot_{i,j,l} * \beta_{i,j} \tag{10}$$

where $\beta_{i,j}$ is the availability factor for farm *j* and year *i*, calculated as follows:

$$\beta_{i,j} = 0.6 - 0.15 * \frac{Aa_{i,j}}{At_{i,j}} \tag{11}$$

where $Aa_{i,j}$ (ha) is the area of arable land and $At_{i,j}$ (ha) is the total area, both for farm *j* and year *i*. Consequently, N availability ranges between 45% and 60%.

We underline that our model computes both types of manure N: total N is useful to assess environmental N balances (including the residual N susceptible to accumulation and losses via leaching, denitrification, etc.), while available N is useful to compute agronomic balances.

Concerning P, the model assumes that P budget in manure does not undergo storage losses and is fully available to crops:

$$P\_man_{i,j,l} = P\_excr_l * nh_{i,j,l} \tag{12}$$

where $P\_man_{i,j,l}$ (kg) is the amount of P excreted by livestock *l* at farm *j* in the year *i*, P_excr_l (kg head^{-1} yr^{-1}) is the P excretion rate for livestock *l*, and $nh_{i,j,l}$ is the number of head of livestock *l* at farm *j* in the year *i*. The Annex lists all crop needs and livestock excretion rates of N and P used in the model.

2.4 Fertilization strategy

The LMM simulates the fertilization strategy of each farm, trying to reconstruct the farmer's decisions concerning nutrient management and fertilization plans. A proper estimation of fertilization strategies is crucial for obtaining reliable field-scale element balances. This includes trading of farm manure with neighbouring farms, the amount and location of manure application, and purchase and application of synthetic fertilizers. The targeted crop yield and milk production levels drive the management intensity and consequently the fertilization intensity. However, each crop has specific needs in terms of type of fertilizer (mineral or organic) most appropriate to cover its requirements at different stages of crop growth. Moreover, other considerations influence the farmers' decisions such as regulations, incentives etc. The LMM reconstruct as far as possible the fertilization strategy farm by farm following a set of rules and assumptions based on: (i) existing fertilization datasets, (ii) regulations and laws constraining farmer's options for land management, such as fertilization guidelines and legislative boundary conditions, (iii) guidelines reflecting best management practices, and (iv) expert knowledge (agricultural advisors, fertilization specialists and farmers). We used empirical regressions based on the AUI dataset (BLW 2018b), consisting of data collected at more than 300 farms located all over Switzerland, from which we selected subsets representative of the study area.

2.4.1 Overall fertilization intensity

Firstly, the model estimates the management intensity of the farm, i.e. how much the nutrient inputs diverge from the average values suggested in the GRUD guidelines. This estimation is based on farm livestock density (livestock units per hectare):

$$LD_{i,j} = \frac{LU_{i,j}}{At_{i,j}} \tag{13}$$

where $LD_{i,j}$ (LU ha-^{1}) is the livestock density at farm *j* in the year *i*, $LU_{i,j}$ are the livestock units at farm *j* in the year *i*, and $At_{i,j}$ (ha) is the total area of farm *j* in the year *i*. Livestock units are calculated using conversion factors specific for each livestock type:

$$LU_{i,j,l} = nh_{i,j,l} * \gamma_l \tag{14}$$

where $nh_{i,j,l}$ are the number of heads of livestock *l* at farm *j* in the year *i*, and γ_l is the conversion factor for livestock *l*.

We assume a direct linear relationship between livestock density and intensity, as exemplified in Figure 2. This assumption is based on the consideration that higher livestock densities imply (i) the necessity of reaching higher crop productivity to meet the need of fodder, and (ii) the necessity to spread more manure on the farmland.

Intensity factors were calculated through linear regression functions derived from the AUI database. We derived one factor for each crop, because of differences in the feasibility of manure application and in the use of the crop as fodder. The regression model was:

$$INT_c = m_c * LD + q_c \tag{15}$$

where INT_c is the intensity factor for crop *c*, m_c is the coefficient for crop *c*, LD is the livestock density, and q_c is the constant for crop *c*. The regression coefficients m_c and q_c derived from the AUI dataset are used in the LMM to estimate the intensity factors:

$$INT_{i,j,c} = m_c * LD_{i,j} + q_c \tag{16}$$

where $INT_{i,j,c}$ is the intensity factor for crop *c*, farm *j* and year *i*, and $LD_{i,j}$ is the livestock density at farm *j* in the year *i*.

All intensity factors are constrained within plausible ranges based on GRUD indications. The intensity factors are used to correct GRUD's fertilization amounts, obtaining the desired (planned) supply of nutrients:

$$N\_supply_{i,j,c} = N\_need_{i,j,c} * INT_{i,j,c} \tag{17}$$

$$P\_supply_{i,j,c} = P\_need_{i,j,c} * INT_{i,j,c} \tag{18}$$

where $N\_supply_{i,j,c}$ (kg yr^{-1}) is the desired (planned) supply of N to crop c, at farm j in the year i. Same applies for P. For example, a factor of 1.2 determines an increase of 20% in nutrient applications, while a factor of 0.7 determines a decrease of 30%.

In Switzerland, farms receive direct payments, but only if they demonstrate that they comply with given rules. One of the most important rules is that nutrient inputs cannot exceed 110% of crop needs. Since this limit applies at the farm level, inputs to specific crops may be in excess of plant needs, but overall the limit should be respected:

$$\frac{\sum_c P\_supply_{i,j,c}}{\sum_c P\_need_{i,j,c}} \leq 1.1 \tag{19}$$

The model can use eq. 19 to check whether the farm is respecting the rule, and it can constrain the crop-specific intensities in order to verify the equation. However, the degree to which farms really fulfill this rule is uncertain. We assume that the AUI database, used here for estimating fertilization intensity, is representative of the actual farmers' behavior, meaning that the rule may not be always respected at every farm. Therefore, in default mode, the model does not constrain the intensities according to eq. 19.
It is important to remark that the nutrient amounts calculated above are just planned amounts; real application amounts depend on the success of manure trading, and are calculated in a following step.

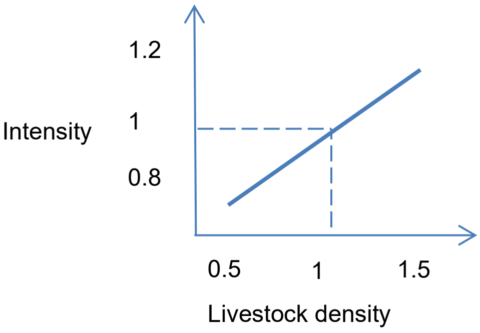


Figure 2: Relationship between livestock density and fertilization intensity

2.4.2 Mineral fertilizers supplied to arable crops

In a second step, the model determines the amount of N and P supplied as mineral (commercial) fertilizer to arable crops. The amount of mineral fertilizer applied to permanent grassland (if any) will be determined later, after manure trading takes place (section 2.5). This is because typically farmers will try to fulfill grassland needs with manure available at the farm. If grassland needs are not fully met after manure trading, then mineral fertilizer will be used. The method used for grassland is the same explained here.

Application rates for each crop type are estimated using regression functions derived from the AUI dataset. The predictor is the index AR, which is the ratio between arable land and total land (specific for each farm and year):

$$AR_{i,j} = \frac{Aa_{i,j}}{At_{i,j}} \quad (20)$$

The rationale for this method is that arable farms use higher commercial fertilization rates compared to mixed farms (BLW, 2018b). The likely reason is that arable farms produce only small amounts of manure (if any at all). Purchasing and transporting manure from other farms can be difficult and expensive; therefore, arable farms have to rely on commercial fertilizers. On the contrary, mixed farms have to use the self-produced animal manure in the most efficient way. Figure 3 exemplifies the direct linear relationship between AR and fertilizer-N application rate.

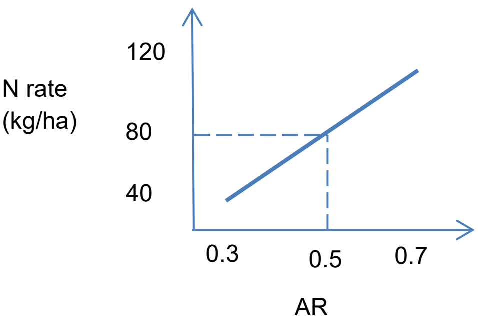


Figure 3: Relationship between arable land index (AR) and fertilizer N application rate

The LMM uses the regression coefficients obtained from the AUI dataset to estimate the application rate of N and P via mineral fertilizer (annually for each farm):

$$N\_rate_{i,j,c} = r_{N,c} * AR_{i,j} + s_{N,c} \quad (21)$$

$$P\_rate_{i,j,c} = r_{P,c} * AR_{i,j} + s_{P,c} \quad (22)$$

where $N\_rate_{i,j,c}$ (kg ha^{-1} yr^{-1}) is the application rate of mineral fertilizer N for crop *c*, farm *j* and year *i*, while $r_{N,c}$ and $s_{N,c}$ are slope and intercept of the regression line for crop *c*, respectively. A similar equation is used for P.
The obtained rates are constrained within plausible ranges, defined for each crop according to reliable sources (expert knowledge, manuals provided by fertilizer companies). Finally, total application amounts are calculated:

$$N\_min_{i,j,c} = N\_rate_{i,j,c} * area_{i,j,c} \quad (23)$$

$$P\_min_{i,j,c} = P\_rate_{i,j,c} * area_{i,j,c} \quad (24)$$

where $N\_min_{i,j,c}$ (kg yr^{-1}) is the amount of N applied via mineral fertilizer for crop *c*, farm *j* and year *i*. A similar equation is used for P.

No mineral fertilizers are allowed in farms which officially adopt the organic farming methods ("bio" farms). Temporary grassland (artificial meadow) is not accounted as arable land when calculating the AR index.

2.5 Nutrient balances at farm scale

In this step, the model uses all the results from the previous steps to estimate element balances at farm level. Manure N amounts are summed up across all livestock types, while the mineral N amounts as well as the planned N supplies are summed up across all crop types:

$$N\_farm\_bal_{i,j} = \sum_{l} N\_man\_ava_{i,j,l} + \sum_{c} N\_min_{i,j,c} - \sum_{c} N\_supply_{i,j,c} \quad (25)$$

where $N\_farm\_bal_{i,j}$ (kg yr^{-1}) is the farm N balance for farm *j* and year *i*. Note that the N balance at farm level is calculated on the available N fraction. Similarly, for P:

$$P\_farm\_bal_{i,j} = \sum_{l} P\_man_{i,j,l} + \sum_{c} P\_min_{i,j,c} - \sum_{c} P\_supply_{i,j,c} \quad (26)$$

A positive balance indicates a surplus of N (or P). A negative balance indicates a deficit of N (or P).

2.6 Manure trading

If the farm nutrient balance is positive (i.e. there is a surplus of either N or P or both), then the farm has to get rid of the excess manure, by exporting it to other farms able to accept it. On the other hand, only farms that have a deficit for both N and P can accept manure. All calculations are done using available N as the target element.

When a farm has a nutrient surplus, the amount of manure that must be exported is calculated according to the rule that both N balance and P balance must become zero or negative. Therefore, the amount of N that must be exported is calculated as the maximum between two values:

$$N\_exp_{i,j} = max\left(N\_diff_{i,j}, \frac{P\_diff_{i,j}}{P\_N_{i,j}}\right) \quad (27)$$

where $N\_exp_{i,j}$ is the amount of N that should be exported via manure exchange by farm *j* in the year *i*, and $P\_N_{i,j}$ is the ratio P:N in manure for farm *j* and year *i*, calculated as:

$$P\_N_{i,j} = \frac{\sum_{l} P\_man_{i,j,l}}{\sum_{l} N\_man\_ava_{i,j,l}} \quad (28)$$

Note that the P:N ratio in manure is specific to each different farm and year, due to different composition of the livestock. Also note that a deficit of P may be created in order to balance N, and vice versa.

Similarly, when a farm has a nutrient deficit, the amount of manure that can be accepted is limited by the rule that neither N balance nor P balance can become positive. In other words, the amount of manure that can be accepted to fill N deficit is limited by the amount of P that is imported with that manure, and vice versa. Therefore, the amount of N that can be imported is calculated as the minimum between two values:

$$N\_imp_{i,j} = min\left(\left|N\_diff_{i,j}\right| , \left|\frac{P\_diff_{i,j}}{P\_N_{i,j}}\right|\right) \tag{29}$$

where $N\_imp_{i,j}$ is the maximum amount of N that can be imported via manure exchange by farm *j* in the year *i*. In Eq. 29, $N\_diff_{i,j}$ and $P\_diff_{i,j}$ are negative since they represent deficits. In order to change sign, absolute values are taken.

Two restrictions are implemented in the model: (i) the manure cannot be transported for more than a given distance, and (ii) it cannot be exported to more than a given number of importers. Derogations are in place for big livestock farms with high nutrient surplus, for which both the maximum distance and the maximum number of importers can be increased. By varying these model parameters, different scenarios can be evaluated. These and other model parameters are listed in section 2.14.

Manure trading is simulated as follows. Firstly, the model calculates the distance between each farm and the surrounding farms (up to the maximum distance discussed above). Secondly, the model simulates trading between "big" exporters and importers. For each exporter, the nearest importer is chosen as trading partner. The model can optionally adopt an alternative approach: all reachable importers are identified, and the difference between nutrient offer and demand is calculated for each potential importer; the importer whose demand is closest to the offer (minimum difference) is chosen as partner. The rationale behind the latter option is that for a farm it is easier to trade with a partner who can accept (or provide) approximately the amount of manure that the farm must export (or import). In this way, the number of partners can be minimized, and as a consequence the number of trips needed to transport the manure (and the related paperwork) is also minimized. However, the current default behavior is to choose the nearest importer.
The transaction between the exporter farm *x* and the importer farm *m* is accounted in the following way:

$$N\_ex_{i,x,m} = min(N\_exp_{i,x} , N\_imp_{i,m}) \tag{30}$$

where $N\_ex_{i,x,m}$ is the amount of manure N moved from farm *x* to farm *m* in the year *i*.
The amount of P exchanged is calculated on the basis of the P:N ratio in the manure of the exporter farm:

$$P\_ex_{i,x,m} = N\_ex_{i,x,m} * P\_N_{i,x} \tag{31}$$

Moreover, total N exchanged is calculated based on the ratio available N / total N:

$$N\_tot\_ex_{i,x,m} = \frac{N\_ex_{i,x,m}}{Na\_Nt_{i,x}} \tag{32}$$

where $Na\_Nt_{i,x}$ is the ratio available N : total N in the manure of the exporter farm *x* in the year *i*:

$$Na\_Nt_{i,x} = \frac{\sum_l N\_man\_ava_{i,x,l}}{\sum_l N\_man_{i,x,l}} \tag{33}$$

Each time this cycle is run, only one transaction is finalized (at most). The cycle is run for a maximum of N times, where N is the maximum number of partners. The cycle is stopped when any one of these conditions is met:

1. All small exporters have gotten rid of their nutrient surplus;
2. All potential importers have received the nutrient they needed;
3. The maximum number of partners has been reached.

After this cycle is over, a similar cycle is run for the "small" exporters (with different constraints).
Finally, the amount of N (both available and total) and P exchanged via manure trading is added to (or subtracted from) the total amount for each farm. For example, the available N in the manure of an exporter farm will decrease as follows:

$$N\_man\_ava'_{i,a} = N\_man\_ava_{i,a} - \sum_{b} N\_ex_{i,a,b} \tag{34}$$

where $N\_man\_ava'_{i,a}$ (kg) is the amount of available N in manure at farm *a* after manure trading, $N\_man\_ava_{i,a}$ is the amount of available N in manure before manure trading, and $N_ex_{i,a,b}$is the available N exported from farm a to farms b, with b = 1:n where n is the number of partners dealing with farm *a*. It is important to point out that due to the restrictions, LMM simulations may result in cases where some farms cannot get rid of their nutrient surplus, therefore not complying with regulations. We believe that this situation is plausible, given the characteristics of the studied system.

2.7 Mineral fertilizers to permanent grassland

If grassland nutrient needs are not fully met after manure trading, then mineral fertilizer can be used. The method to estimate application rates is the same used for arable crops (section 2.4.2). Our analysis of the AUI dataset supports this choice: application of mineral fertilizers to permanent grassland is not uncommon at intensively managed farms.

2.8 Land allocation

The LMM is a spatially explicit model. A land allocation procedure is required because only the main farm building is georeferenced in the farm census, while the farm land is not. In other words, the location of the fields is unknown. The land allocation routine is based on the downscaling approach developed by Gärtner et al. (2013). It combines the farm census data with a map of agricultural land. This map must differentiate grassland from arable land. Each farm receives an area of grassland and arable land corresponding to that recorded in the farm census. A given farm receives the nearest available land. In order to avoid that the farm receives all the nearest land, not leaving enough land to the nearby farms, allocation occurs in several iterations: only a limited surface is allocated per iteration, set by a model parameter (see list of model parameters at the beginning of this document). However, this “competition” for land could result in implausible land fragmentation and excessive distances between a farm and its fields. Therefore, the model limits the distance between the farm building and its land to a threshold, proportional to the total area of the farmland:

$$mdist_{i,j} = \sqrt{\frac{At_{i,j}}{\pi}} * dstCoef \tag{35}$$

where $mdist_{i,j}$ is the maximum distance for farm *j* and year *i*, $At_{i,j}$ is the total farm area and *dstCoef* is a model parameter (Annex 3). In Eq. 35, the radical term is the radius of a circle with the same area of the farm; the parameter *dstCoef* accounts for elongated shapes of the farmland.

This part of the model was specifically designed to make use of different remote sensing (RS) data and methods. Classification of the agricultural land in two classes, i.e. permanent grassland and arable land, improves the accuracy of land allocation (Gómez Giménez et al. 2016; Stumpf et al. 2018). The land allocation module can deal with both vectorial and raster data. The advantage of vectorial data, and specifically of RS image segmentation, is that it can delineate basic land units (fields or group of fields), making the resulting maps more realistic. The use of raster data usually does not allow for field delineation, therefore resulting maps cannot depict the agricultural land pattern as precisely as vectorial data; however, simulation with raster data usually requires less computational time.
However, land use classification introduces a problem: the total area of each land use (as identified by RS) might not be consistent with the census data. In this case, there is not enough area of a certain land use, and too much area of the other land use. Because of this mismatch, some parcels are not allocated to any farm. We used the term "non-allocated land" to identify these parcels. The amount of non-allocated land must be minimized and ideally should be zero. However, in order to still be able to calculate spatially explicit balances in presence of a mismatch, two rescaling factors were introduced (one per land use). The factors were calculated for each farm separately, based on the difference between the area stated in the census and the area effectively assigned by the land allocation procedure:

$$\delta a_{i,j} = \frac{Aa'_{i,j}}{Aa_{i,j}} \tag{36}$$

$$\delta g_{i,j} = \frac{Ag'_{i,j}}{Ag_{i,j}} \tag{37}$$

where $\delta a_{i,j}$ is the rescaling factor for arable land, $Aa'_{i,j}$ (ha) is the area of arable land allocated by the model, and $Aa_{i,j}$ is the area of arable land according to the census, all for farm *j* and year *i*. Same notation is used for the equation for grassland area. Both factors range from 0 to 1. The maximum value of 1is reached only in case of perfect match. In all other cases, when the farm cannot receive all the needed land, farm nutrient budgets, as well as planned nutrient inputs and outputs, are rescaled multiplying them by the factors. For example, the N supply to a given crop is rescaled as follows:

$$N\_supply'_{i,j,c} = N\_supply_{i,j,c} * \delta a_{i,j} \tag{38}$$

where $N\_supply'_{i,j,c}$ is the planned supply of N to crop *c* after rescaling. For grassland, the factor $\delta g_{i,j}$ is used instead.

2.9 Manure management

At this stage of the modelling process, the total nutrient supply decided in the fertilization plan, as well as the corresponding amount of mineral fertilizer and manure to be applied in order to meet the fertilization goals, have been calculated for each farm. The model assumes that all required mineral fertilizer is available at the farm. In contrast, the amount of manure available at the farm may not match the requirements, due to a not fully successful manure exchange. Consequently, there may be a deficit or a surplus of N and/or P.
Available N is the target variable for the following model steps. This is because N is the most important nutrient for crop production, and farmers manage the available manure trying to optimize N inputs. Therefore, manure P inputs will be determined by manure N inputs, and calculated based on the N:P ratio in manure. This ratio is specific for each farm and year, given the annual changes in livestock composition at each farm.

When it comes to manure application, the model gives priority to maize (for silage) and grassland (both temporary and permanent). On these cultivations, manure can be spread more easily over a longer period of the growing season, compared to other crops. Moreover, they are the main fodder crops used to feed the livestock. When the needs of maize and grassland are covered, the rest of manure (if any) is spread on the other crops.

We translated this conceptual model to a mathematical model. In the following equations, all terms are referred to a particular year *i* and a particular farm *j*. We will omit the indices *i* and *j* for sake of readability. First of all, the gap between mineral fertilizer N and planned N supply is calculated for each crop:

$$N\_gap_c = N\_supply_c - N\_min_c \tag{39}$$

where N_gap_c is the part of N required by crop *c* that is not covered by mineral fertilizer, and should therefore be covered by the manure available at the farm after manure trading.
Crops are divided in two groups: the first one consists of the priority crops maize and grassland, while the second group contains all other crops. The gaps to be covered are pooled together for the two groups:

$$N\_gap\_priority = \sum_p N\_gap_p \tag{40}$$

$$N\_gap\_other = \sum_o N\_gap_o \tag{41}$$

where *p* are the indices of the priority crops, and *o* are the indices of the other crops.

The allocation of manure N to the different crops is done iteratively. Firstly, the model tests if the manure available at the farm is enough to cover the gaps of the priority group. If so, it allocates the exact quantity needed to fill the gaps; otherwise (if the manure is not sufficient) the available manure is shared between crops proportionally to the planned supply. For example, for maize:

$$N\_man_{maize} = \begin{cases} N\_gap_{maize} & N\_man\_ava' > N\_gap\_priority \\ N\_man\_ava' * \gamma_{maize} & N\_man\_ava' \leq N\_gap\_priority \end{cases} \tag{42}$$

where N_man_{maize} is the amount of manure N allocated to maize, $N\_gap\_gr_{maize}$ is the amount of N needed to reach the planned supply for maize, N_man_ava' is the manure N available at the farm, and γ_{maize} is a factor that determines how to share the scarce manure between the priority crops:

$$\gamma_{maize} = \frac{N\_supply_{maize}}{\sum_p N\_supply_p} \tag{43}$$

where $\sum_p N\_supply_p$ is the planned N supply for all priority crops.

The same approach is used for grassland. The model handles 4 types of grasslands: one temporary grassland, and 3 levels of intensity for permanent grassland. For sake of simplicity, the following equations refer to just one type of grassland:

$$N\_man_{grass} = \begin{cases} N\_gap_{\,grass} & N\_man\_ava' > N\_gap\_priority \\ N\_man\_ava' * \gamma_{grass} & N\_man\_ava' \leq N\_gap\_priority \end{cases} \tag{44}$$

$$\gamma_{grass} = \frac{N\_supply_{grass}}{\sum_p N\_supply_p} \tag{45}$$

After taking care of priority crops, the model checks if there is any manure left:

$$N\_man\_ava'' = N\_man\_ava' - N\_man_{maize} - N\_man_{grass} \tag{46}$$

where N_man_ava'' (if positive) is manure N available after allocation to priority crops. This manure is then available for the other crops (the second group), and it is allocated using the same approach explained before. For example, for wheat:

$$N\_man_{wheat} = \begin{cases} N\_gap_{\,wheat} & N\_man\_ava'' > N\_gap\_other \\ N\_man\_ava'' * \gamma_{wheat} & N\_man\_ava'' \leq N\_gap\_other \end{cases} \tag{47}$$

$$\gamma_{wheat} = \frac{N\_supply_{wheat}}{\sum_o N\_supply_o} \tag{48}$$

where $\sum_o N\_supply_o$ is the planned N supply for all crops of the second group.
The same is done for all other crops.

After this first iteration, all crops received some manure, according to the quantity available at the farm, up to an amount sufficient to cover the planned supply. Since planned supply may differ from needs as recommended by GRUD, after this step there may be some surpluses with regard to GRUD standards.

The second iteration can start now. This iteration is performed only if there is still some manure left:

$$N\_man\_ava''' = N\_man\_ava' - \sum_c N\_man_c \tag{49}$$

where N_man_ava''' is surplus manure N (with respect to the planned supply of all crops).

This surplus is firstly allocated to priority crops, using the same mechanism described by eqs. 42 to 45, where the quantity N_man_ava' is replaced by N_man_ava'''. The resulting quantities are added to the amount allocated to each crop.

Subsequently, in case some manure is still available, it is quantified as:

$$N\_man\_ava'''' = N\_man\_ava''' - N\_man_{maize} - N\_man_{grass} \tag{50}$$

and allocated to the other crops, using eqs. 47 and 48, where the quantity N_man_ava'' is replaced by N_man_ava''''.

2.10 Fertilizer and manure distribution to fields

In this module, nutrients contained in manure and mineral fertilizers are distributed to the fields, farm by farm. In the case of arable land, nutrients are pooled together for all crops and then evenly shared between the arable fields belonging to the farm, so that the application rate is the same for all fields. The reason for this procedure is that the information on crop types is not spatially explicit. However, given that crop rotation is a common practice in Switzerland, simulated application will approximate real application in the medium term (3-5 years). For example, for N:

$$N\_input_k = \left(\sum\nolimits_c N\_min_c + N\_man_c\right) * \frac{A_k}{\sum A} \tag{51}$$

where N_input_k (kg) is the amount of N input to field *k*, A_k (ha) is the area of field *k*, and $\sum A$ (ha) is the total arable area of the considered farm.
For grassland, however, the distance from the farm is taken into account. Fields closer to the farm get more nutrients, while fields far from the farm get less, according to weights calculated with the following equation:

$$w_k = \left(\frac{d_{max} - d_k + 1}{d_{max}}\right)^{exp} \tag{52}$$

where w_k is the weight for field *k*, d_{max} (m) is the distance of the farthest field, d_k (m) is the distance of field *k*, and *exp* is a model parameter. By setting exp = 1, weights are linearly proportional to the distance; by setting *exp* = 0, distance has no effect. To avoid excessive fertilization rates near the farm, the recommended maximum value is exp = 0.2. Weights are normalized to the field area:

$$w'_k = w_k \frac{A_k}{\sum A} \tag{53}$$

where A_k is the area of field *k*. Finally, weights are rescaled to sum up to 1:

$$w''_k = \frac{w'_k}{\sum w} \tag{54}$$

Nitrogen input to grassland field *k* is therefore calculated as:

$$N\_input_k = \left(\sum\nolimits_g N\_min_g + N\_man_g\right) * w''_k \tag{55}$$

where *g* is the index of grassland types (i.e. 3 levels of intensity). Since current land use maps do not distinguish between grassland intensities, these levels are pooled together when it comes to nutrient distribution to fields.
Note that when land use map is a raster layer, each pixel represents a “field”, therefore area A_k is the same for all fields (e.g. 30 m * 30 m = 0.09 ha for products derived from Landsat images).
Finally, similar equations are used for P.

2.11 Nutrient uptake by crops (field scale)

Nutrient uptake for each field is based on GRUD (Sinaj and Richner 2017) average values for the crops grown in that field. However, the model adjusts uptake values according to N inputs at the specific field, assuming a linear correlation between input and yields (and therefore between input and uptake). The correlation coefficients are derived from regressions calculated on the AUI datasets:

$$yield_{c,k} = yield_c + b * \Delta N\_input_{c,k} \tag{56}$$

where $yield_{c,k}$ (t) is yield of crop *c* at field *k*, $yield_c$ (t) is the average yield of crop *c* given optimal N input, and ΔN_input_k (kg ha^{-1}) is the difference between GRUD’s optimal (recommended) input and the actual input at field *k*.
N uptake is then calculated using the ratio between actual yield and expected yield:

$$N\_uptake_{c,k} = N\_crop_c * \frac{yield_{c,k}}{yield_c} \tag{57}$$

where $N\_uptake_{c,k}$ (kg ha^{-1}) is the N uptake by crop *c* at field *k* and N_crop_c (kg ha^{-1}) is the average N uptake according to GRUD. Uptake values are constrained within plausible ranges using the concept of minimum and maximum yields as described in Richner et al. (2010).
Since the model does not know what particular crop is grown on any given field *k*, uptake is averaged out across all possible crops grown at the farm, weighted for the relative area occupied by each crop:

$$N\_uptake_k = \sum\nolimits_c N\_uptake_{c,k} * \frac{A_c}{\sum A} \quad (58)$$

where N_uptake_k (kg ha^{-1}) is N uptake at field *k*, and A_c (ha) is the area occupied by crop c at the farm.
Phosphorus uptake is estimated using equations similar to eqs. 57 and 58.

2.12 Nutrient balances at field scale

In the final step, the model calculates surface balances at field level:

$$N\_balance_k = N\_input_k - N\_uptake_k \quad (59)$$

$$P\_balance_k = P\_input_k - P\_uptake_k \quad (60)$$

where $N\_balance_k$ and $P\_balance_k$ (kg ha^{-1}) are N and P balances at field *k*.
Regarding nitrogen, two kinds of balances are calculated, differing for the N input: available N or total N. The first one (available N) is an “agronomic balance”, showing how well the fertilization plan was designed and implemented. The second one (total N) is an “environmental balance”, showing surplus N that is potentially lost to water bodies or the atmosphere.

2.13 Trace element fluxes

In the current version of the model, fluxes of trace elements Copper (Cu), Zinc (Zn) and Cadmium (Cd) are estimated using a simplified approach.
Concentrations of Cu, Zn and Cd in plants are calculated based on crop P requirements and fixed ratios Cu:P, Zn:P and Cd:P in crops. For example, for Cu:

$$Cu\_crop_{i,j,c} = P\_crop_{i,j,c} * Cu\_P_c \quad (61)$$

where $Cu\_crop_{i,j,c}$ is the content of Cu in crop *c*, and Cu_P_c is the ratio Cu:P in crop *c*.

Amounts of Cu and Zn excreted by livestock are calculated based on P excretion and fixed ratios Cu:P and Zn:P in manure:

$$Cu\_man_{i,j,l} = P\_man_{i,j,l} * Cu\_P_l \quad (62)$$

$$Zn\_man_{i,j,l} = P\_man_{i,j,l} * Zn\_P_l \quad (63)$$

where $Cu\_man_{i,j,l}$ is the amount of Cu excreted by livestock *l* at farm *j* in the year *i*, and Cu_P_l is the ratio Cu:P in the manure of livestock *l*. Similar notation is used for Zn. Ratios Cu:P and Zn:P were derived from measurements of element concentration in manures done in the year 2006 at 14 farms monitored by the Swiss Soil Monitoring Network (NABO).

The input of Cd caused by the application of mineral fertilizers is calculated based on a fixed ratio Cd:P (in the current version of the model, a generic average value is used):

$$Cd\_rate_{i,j,c} = P\_rate_{i,j,c} * Cd\_P \quad (64)$$

where Cd_P is the ratio Cd:P.

The amount of Cu and Zn imported or exported via manure trading is calculated on the basis of the Cu:P and Zn:P ratios:

$$Cu\_ex = P\_ex * Cu\_P \quad (65)$$

$$Zn\_ex = P\_ex * Zn\_P \quad (66)$$

where Cu_ex is the amount of Cu exported, and P_ex is the amount of P exported. The ratios depend on the specific composition of the traded manure.

The amount of total N, P, Cu and Zn supplied through manure application are calculated using the Na:Nt, P:N, Cu:P and Zn:P ratios, respectively. For example, the amount of manure P applied to crop c is calculated as:

$$P\_man_c = N\_man_c * P\_N_{i,j} \tag{67}$$

where P_man_c is the amount of manure P applied to crop c.

Trace element inputs to fields are calculated using equations similar to eqs. 51 to 55 (Section 2.10). Finally, uptake of trace elements by crops are calculated with equations similar to eqs. 57 and 58 (Section 2.11).

2.14 Model parameters

The model has a limited number of parameters (Table 1). This characteristic allows an easy interpretation of the effect that each parameter has on the model output. Details on each parameter are given in the corresponding section.

Table 1: Model parameters

Name	Default	Unit	Description	Section
OBB	6000	m	max distance for manure trading (small farms)	Manure trading (2.6)
OBBgross	50000	m	max distance for manure trading (big farms)	Manure trading (2.6)
mx_K	3	-	max no. of partners (small farms)	Manure trading (2.6)
mx_G	15	-	max no. of partners (big farms)	Manure trading (2.6)
ag	5	ha	max area allocated per iteration	Land allocation (2.8)
dstCoef	20	-	Coefficient for max distance parcel-farm (eq. 35)	Land allocation (2.8)
exp	0.5	-	exponent of the distance function for manure distribution (eq. 52)	Fertilizer and manure distribution to fields (2.10)

3 Data acquisition and model testing / validation

3.1 Data acquisition and pre-processing

Dealing with regional modelling at the interface between soil, climate, agricultural management, and socio-economic issues requires the compilation of various information sources. This involves a comprehensive data survey and several pre-processing steps to harmonize the data for each specific study area (Table 2).
Inconsistent and heterogeneous data sources have been harmonized effectively. For instance, the AGIS data set (BLW 2018a) showed temporal inconsistencies with regard to livestock categories and codes as well as crop type codes. Therefore, we developed automatic harmonisation routines for the AGIS data 1999-2014. Moreover, some required data sets were confidential and therefore difficult to compile. Thus, responsible authorities have been involved in the elaboration of project objectives, leading to contractual agreements on restricted use of the particular data set. Confidential data was obtained from the relevant cantonal soil agencies, cantonal agricultural agencies, and the federal agricultural agency.

Table 2: Main data sources

Source	Data	Spatial resolution	Temporal resolution	Used to	References
Agricultural census AGIS	Farm location, crops, livestock	All farms (~60'000) across Switzerland	Annually 1999-2014	Calculate farm element budgets	BLW 2018a
Fertilization guidelines GRUD	N & P crop requirements; excretion rates	Switzerland	4 issues (1987-2017)	Calculate farm element budgets	Sinaj and Richner 2017
Agro-environmental monitoring AUI	Management operations (>65'000 records)	Nearly 300 farms across Switzerland	Annually 2009-2014	Calibrate / Simulate fertilization strategy	BLW 2018b
Manure trading HODUFLU	Manure N & P transported between farms	Pilot study area plus surrounding communities	2014	Calibrate manure trading	BLW 2019
Zurich cantonal soil monitoring	Soil P from archived soil samples	40 sites in pilot study area	5-15 years since 1995	Validate soil surface balance	Kanton Zürich 2019
Proof of ecological performance ÖLN	Soil P status	Aggregated at municipality level	2011-2013	Scenario analysis (reduced P inputs)	BLW 2018c
Processed Landsat images	Land use classes	30x30 m, Switzerland	Multi-temporal analysis from 1990s	Downscale farm data (land allocation)	Gómez Giménez et al. 2016, Stumpf et al. 2018
Topographic survey SwissTopo	Digital Elevation Model	2x2 m Switzerland	Status 2014	Correct yields for altitude	SwissTopo 2018

3.2 Pilot study area

The study area is located in the canton of Zurich, Switzerland. The total area is 71 km^2 of which 41 km^2 of utilized agricultural area (UAA). The average altitude is 556 m asl. The average precipitation rate is 1134 mm per year, while the annual average temperature is 9.3 °C (MeteoSwiss, 2015). The study area comprises approximately 250 farms, of which the majority run dairy farms or a mixed system that includes arable crops production. Nearly 60% of the UAA is covered by permanent grassland, while the rest is mainly arable land. Perennial crops cover less than 1% of the surface. The main crops grown in the arable land are maize (both for silage and corn), winter wheat, triticale and winter barley. The average livestock density is 1.1 LU ha^{-1}.

Our analyses focused on nutrients nitrogen (N) and phosphorus (P). We carried out simulations for the period 2010-2014. Our reference year for farm-scale results is 2012. When showing results at the field scale, we always consider the average over the period 2010-2014 (five years) in order to take into account the effect of crop rotation.

3.3 Model calibration and verification

In order to test the reliability of the LMM as a tool for predicting future trends and supporting the adoption of proper measures to increase the sustainability of agricultural management, LMM retrospective predictions for the case study were verified at each step of the workflow.

The accuracy of land allocation was assessed quantitatively by comparing the land allocation maps with a property layer provided by the Zurich cantonal agency (AVZH). This layer shows which parcels of land belong to the same property. We performed this analysis for a subset of the farms located in the study area. For each AGIS farm, we found the corresponding farm in the AVZH dataset, and we overlaid the respective areas in the GIS software ArcGIS. We then calculated the amount of area perfectly overlapping. We summed up all overlapping area, and divided it by the total area of AVZH farms that was used for the analysis, obtaining an index of agreement *IA*:

$$IA = \frac{A_{over}}{A_{tot}} \tag{68}$$

where A_{over} is the overlapping area among the two dataset and A_{tot} is the area of the AVZH that was considered in this analysis. To reach the value of 1, this index requires perfect overlapping for all the farms. Further details can be found in Gómez Giménez et al. (2016). An additional analysis was performed for all farms, farm by farm, to test the average distance between the farmland allocated by the LMM and the “real” farmland as recorded in the AVZH layer (technically, the distance was measured between the centroids of the land parcels). This average distance can be considered as the mean error of land allocation. In our study area, small farms have typically 20 ha or less. If we assume that the farmland has a round shape, this results in a maximum distance farm-field of 250 m. Therefore, we considered the validation successful if the mean error was less than 250 m.

The manure trading between farms was verified by comparing the LMM predictions to the HODUFLU database of canton Zurich (BLW 2019). This database, released under confidentiality terms, records all transports of manure between farms and it is available only from the year 2014 onwards. As terms of comparison, we considered the annual import and export of manure to/from the study region.

The fertilization strategy (i.e. the indices of fertilization intensity) was validated using a subset of the AUI dataset. In fact, part of the AUI dataset was used to derive the regression functions, while the remaining part was used to validate them.

Finally, the overall accuracy of the model in estimating the nutrient balances at field level was tested qualitatively by using information provided by the cantonal soil monitoring network of canton Zurich (Kanton Zürich 2019). The cantonal agency provided topsoil samples (0-20 cm) collected from 13 sites within the study area. At each site, samples were collected at least twice during the period 1996-2013. For this study, samples were analysed for P and some trace metals using the ammonium acetate – EDTA extraction method. We calculated average annual concentration changes during the observation period, and determined the overall trend: either accumulation (positive change) or depletion (negative change). These trends where then compared to the balances estimated by the LMM at the same sites (more precisely, for the fields containing the surveyed sites). In case of positive balance, we assumed an accumulation trend, while for negative balance we assumed a depletion trend. Finally we checked the concordance between soil measurements and LMM estimates, in terms of overall trends.

3.4 Coupling the LMM to a bio-physical model: soil system balance

In contrast to the surface balance computed by the LMM, a soil system balance accounts for additional element fluxes through the soil profile, over the soil surface and to the atmosphere (runoff, erosion, leaching, volatilization), and usually includes N transformations (nitrification/denitrification). In order to test the feasibility of computing a regional soil system balance, we implemented a loose coupling between the LMM and the EPIC model.

EPIC is a widely used mechanistic agro-environmental model. It simulates, among other processes, crop growth, soil nutrient dynamics, and management operations at field-scale (Williams et al 2006). The model has been widely applied to study environmental impacts of agricultural soil use, including soil nutrient cycling and losses. We used version 0509, setting the model parameters according to the results we obtained in previous calibration studies (Della Peruta et al., 2014; Della Peruta et al 2016).

In order to run the EPIC model, we had to collect and prepare additional information for both study areas. Soil data on soil texture, pH, organic matter content, and rock fragments content were provided by the PMSoil project (Nussbaum et al. 2018) on a regular grid and for five soil layers. Weather data was derived from the MeteoSwiss (2018) gridded data, a dataset containing daily values of air temperature (mean, max and min), precipitation, and global radiation on a 2 km resolution grid. Topographical data, in particular slope, was derived from the Swiss digital elevation model (2 m resolution; SwissTopo 2018). The N soil system balance at field scale was computed as:

$$\begin{aligned} Soil\ N\ balance &= fertilizer + manure + deposition + fixation \\ &- crop\ uptake - volatilization - erosion - runoff - leaching \end{aligned} \tag{69}$$

3.5 Scenario analysis

The LMM model can be used to assess scenarios, based for example on socio-economic trends, policy implementation, management strategies. As a proof of concept, we run LMM simulations under two different scenarios. The first one was elaborated by using the agent-based model SWISSland (Möhring et al. 2016), which predicts farm structural changes under changing socio-economic conditions. We chose a scenario of free trade agreement with the EU, leading to a decrease of farms' income by 32% and a decrease of the total number of farms by about one fourth in the period 2013-2025. In the second scenario, nutrient management is constrained by soil P status: P inputs were reduced down to 80% of GRUD's values where soil P concentration exceed 60 mg P / kg soil (ammonium acetate – EDTA extract). Data on soil P status were derived from the ÖLN database (Ecological performance, BLW 2018c), aggregated at community level.

4 Results and discussion

4.1 Manure trading

In the model simulations, most of the manure trading happened inside the study area, with more than 28 t N exchanged during the year 2012. In contrast, exchange with other communities outside the study area were quite limited. These values are quite different from those recorded in the HODUFLU program for the year 2014. However, the resulting net import of 2.2 t N yr^{-1} was very similar to HODUFLU value (Table 3). The pattern of P trading is probably closely correlated to that of N.

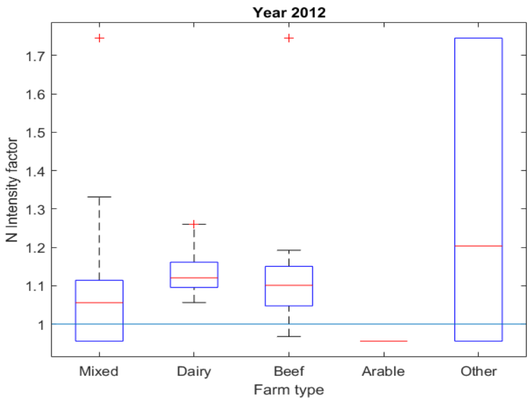
According to the LMM, much of the nutrient needs could be satisfied by agreements among local farms (internal trading). Instead, HODUFLU records show that manure travels into / out from the study area much more than predicted by the LMM. This discrepancy could depend on the fact that in reality manure is transported by companies that must optimize their logistic. They collect manure only from farms that can provide big amounts, and deliver to farms that require big amounts. Big farms are relatively rare in Switzerland and presumably rather far from each other. In the model, this situation can be simulated by imposing a minimum threshold to the manure exchanged between farms. Della Peruta et al. (2019) showed that manure redistribution in Switzerland, such that would allow to meet ecological performance goals for nutrient balance, could be obtained by direct agreements among farms within an average distance of 10 km, where each farm would have to make agreements with 5 other farms on average, if small amounts of manure are allowed to be transported. In order to work, this approach must rely on companies willing to transport small amounts of manure for short distances. Another option is to have farmers transporting manure themselves, but this option may be unrealistic unless subsidized, because it would add to their workload.

Table 3: Manure trading: HODUFLU records (year 2014) vs. LMM simulations (year 2012).

	HODUFLU	LMM	
	N (t yr^{-1})	N (t yr^{-1})	P (t yr^{-1})
Internal trading	4.2	28.4	7.0
Imported to the study area	7.1	2.7	0.7
Exported from the study area	5.1	0.5	0.2
Net import	2.0	2.2	0.5

4.2 Fertilization strategy

In general, the overall N fertilization intensity was higher than GRUD's recommendations (GRUD has intensity 1 by definition). The intensity factor was above 1 for almost all farms, with dairy farms showing the highest intensity (apart from the class "other" which includes special crop farms, and represent a very small fraction of the agricultural area). On the contrary, the overall P fertilization intensity was always lower than GRUD's recommendations, with arable farms showing the lowest intensity (Figure 4).



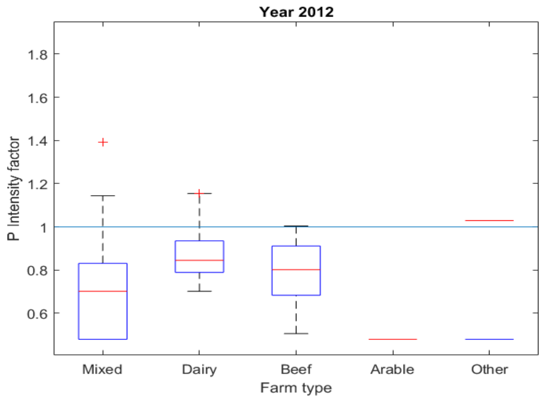


Figure 4: Estimated N and P fertilization intensity by farm type

4.3 Land allocation

The combination of satellite images acquired during the vegetative period generated a land use thematic map of arable land and permanent grassland. The overall accuracies of each land cover classification achieved ca. 98%. High classification accuracies ensured consistency between the farm census and the land use dataset, which minimized the amount of non-allocated land (2.2%). When comparing the land allocation results to the AVZH property map, the index of agreement was 0.51 (51% accuracy). In other words, half of the fields could be located with extreme precision. These results should be seen as preliminary until a proper validation dataset can be obtained. Nonetheless, they indicate a substantial positive influence of remotely sensed inputs on the land allocation performance. Further details can be found in Gómez Giménez et al. (2016).

4.4 Nutrient balances

4.4.1 Regional scale balances

Overall, the study area received an N surplus of nearly 64 tons during the year 2012, corresponding to an average surplus of 15 kg ha^{-1} yr^{-1}. P balance was negative, around -37 tons, corresponding to an average deficit of -9 kg ha^{-1} yr^{-1} (Table 3). Around 30% of the area received N surplus of more than 50 kg ha^{-1}. There was a P surplus on 28% of the area.

Table 4: Nutrient fluxes and balances in the study area, year 2012

	N (t yr^{-1})	**P (t yr^{-1})**
Mineral fertilizer input	128.5	15.1
Manure input	417.6	81.8
Harvest removal	482.4	133.8
Balance	63.7	-36.9

4.4.2 Farm scale balances

For most mixed farms the N balance ranged between -50 and +30 kg ha^{-1}, showing a great heterogeneity. On the contrary, the N balance was positive (indicating a surplus) for most dairy farms. All arable farms had N surplus. However, the P balance was negative for most farms, irrespective of the type (Figure 5).

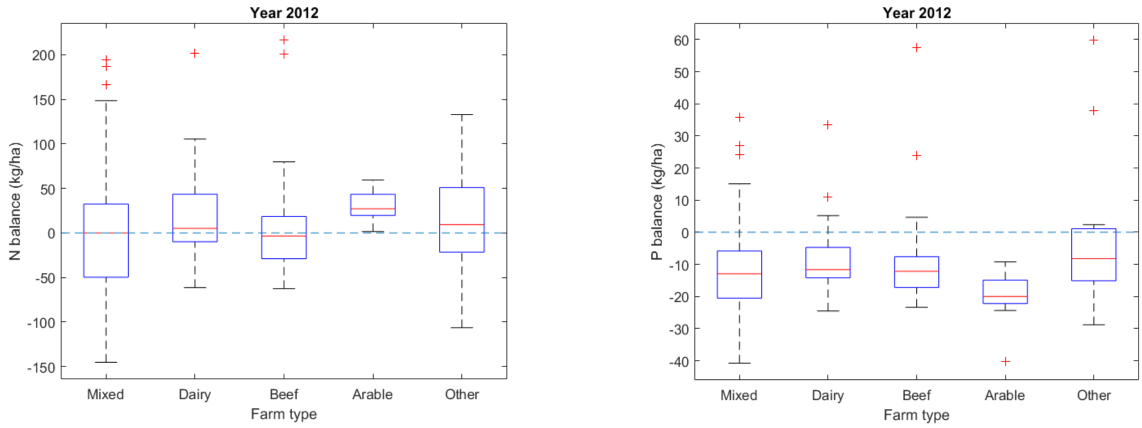


Figure 5: N and P balances at farm level, by farm type

4.4.3 Field scale balances

During the period 2010-2014, the N balance at field level showed a great heterogeneity, with some fields having a significant surplus while other showing a clear deficit. However, the median of N balance was positive only for fields managed by arable farms. When grouping the results by land use, a clear pattern is evident, with home pasture fields (i.e. pasture near the barns) having a surplus of approx. 150 kg ha^{-1} yr^{-1}, while arable fields show a deficit. Grassland fields have a more complex pattern, showing that the model depicted the presence of intensive and extensive grasslands. Organic (bio) farms clearly apply less N to arable fields, compared to conventional farms (Figure 6).

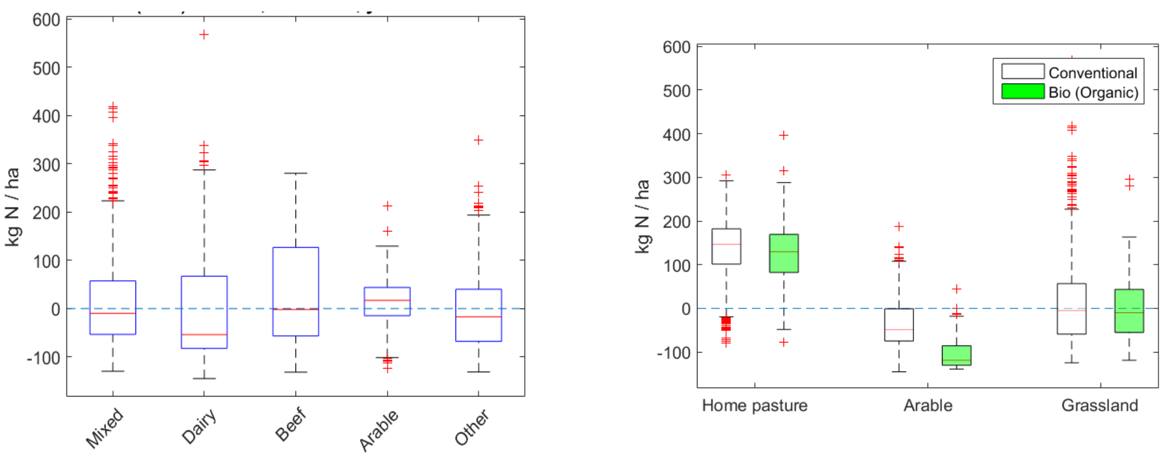


Figure 6: N balance at field level, by farm type and by land use

In contrast to N balances, P balances were negative for most fields. However, some fields had P surpluses up to 50 kg ha^{-1} yr^{-1}, and even higher. When grouped by land use, the pattern of P balances was similar to that of N, with clear surplus for home pasture. Although grassland had mostly negative balances, some grassland fields received P surplus up to 25 kg ha^{-1} yr^{-1}, or even higher. Organic arable fields revived less P than conventional ones (Figure 7).

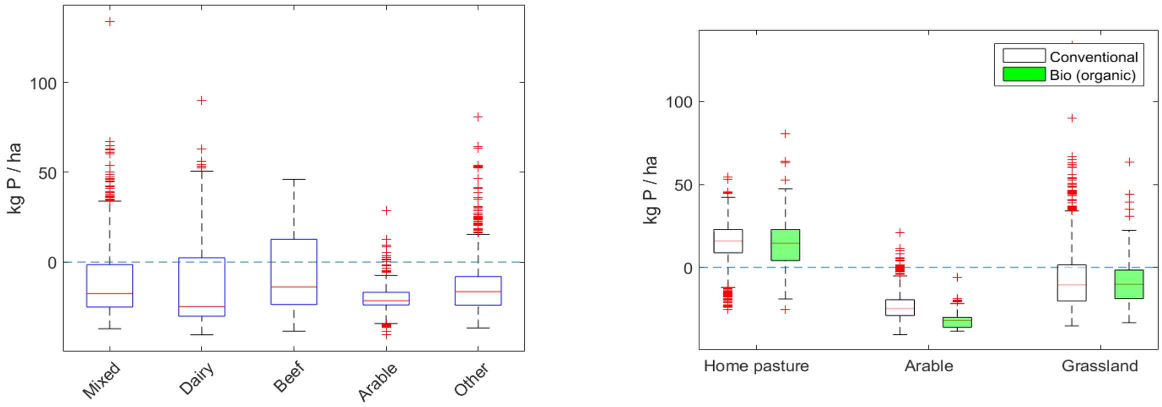


Figure 7: P balance at field level, by farm type and by land use

4.4.4 Spatial pattern of nutrient inputs

During the reference period 2010-2014, nutrient inputs were mainly as manure N and P, especially in grassland areas (Figures 8 and 9). Areas of higher inputs are clearly recognizable.

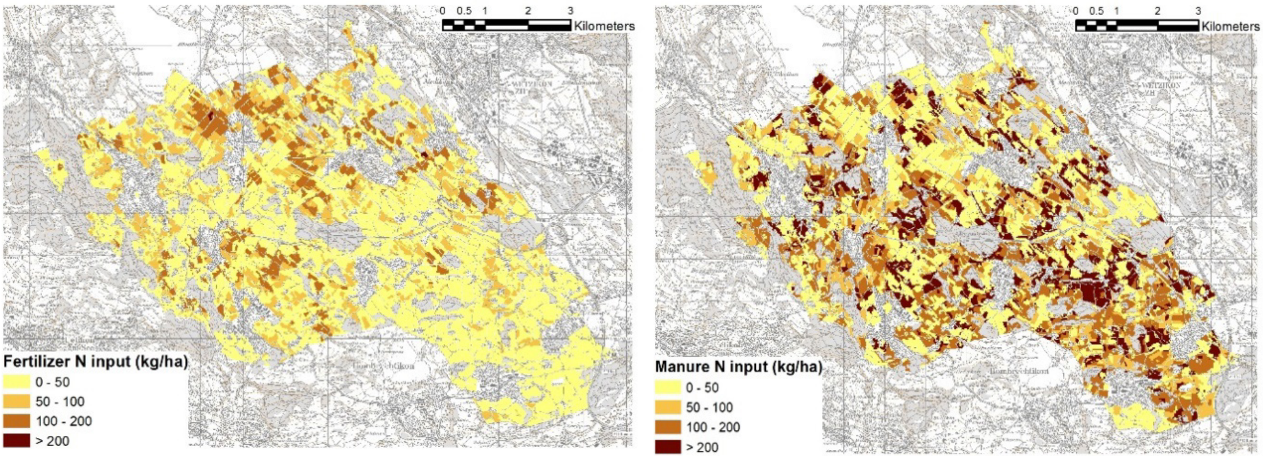


Figure 8: Maps of fertilizer and manure N inputs

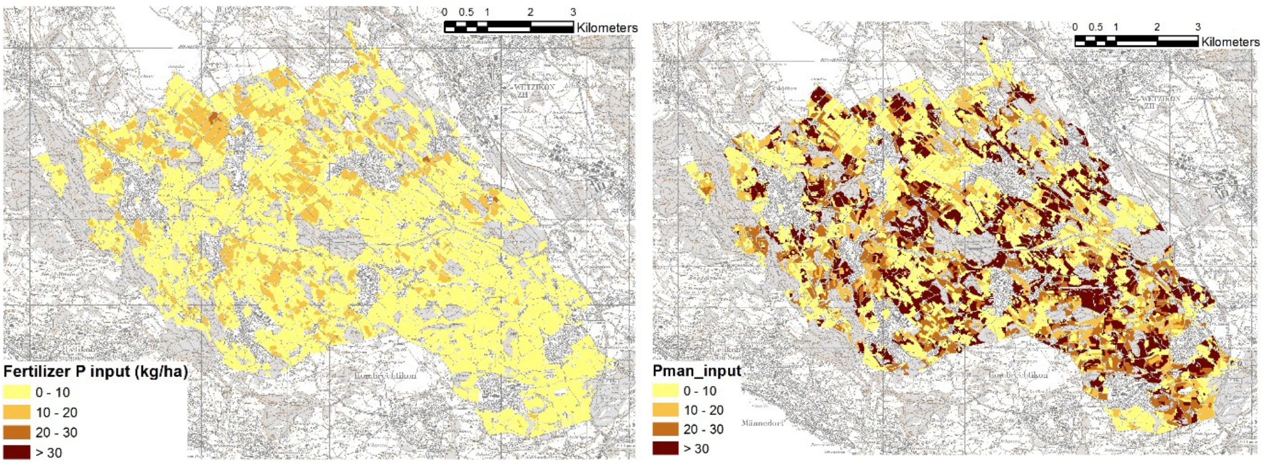


Figure 9: Maps of fertilizer and manure P inputs

4.4.5 Spatial pattern of nutrient balances

The spatial distribution of N balance is quites heterogeneous, with areas of high surplus ("hotspots"). The spatial pattern of P balance is similar to that of N balance (Figure 10). This was expected, since most nutrient inputs take place via manure application. However, P deficit is much more common than N deficit (green areas in both maps). The identified hotspots are at risk of soil nutrient accumulation and related environmental impacts such as groundwater infiltration (N), surface water eutrophication (P) and trace element effects on soil biota.

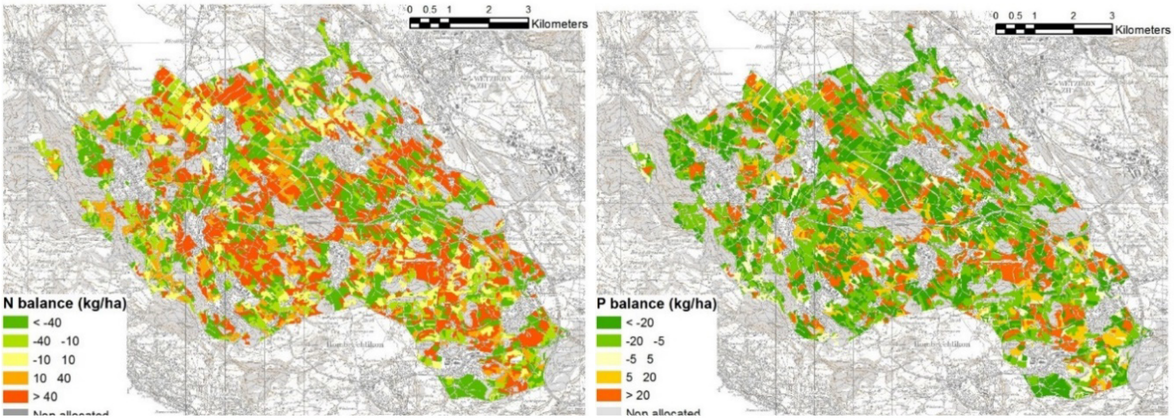


Figure 10: Maps of N and P balances

4.4.6 Comparison with measured temporal changes in soil

As a first attempt to assess the overall model accuracy, we compared the modelled P balance to measured soil P changes in time. The measurements were done on samples provided by the cantonal soil monitoring network (KABO), taken at 13 sites within the study area. The sites were sampled at least twice during the last decade. We used a qualitative approach, with the assumption that a positive balance (surplus) would lead to P accumulation in soil, while a negative balance (deficit) would lead to P depletion. Therefore, we compared the trends measured at the KABO sites with the trends expected at the same locations given the modelled P balance. We found agreement in 10 sites out of 13, representing an overall accuracy of 78%. The model overestimated the balance in 2 cases and underestimated it in 1 case. However, we are aware of the low statistical significance of these results, given the small amount of sampling points. Future projects should aim to collect more validation data for further calibration and validation of the model.

4.4.7 Soil system balance

The bio-physical model EPIC was coupled to the LMM and run for the reference year 2012. While nutrient inputs where the same, nutrient removal by harvested crops differed slightly because of differences in estimated crop yields between LMM and EPIC (mean absolute difference of 8% for permanent grassland, 16% for temporary grassland, and around 16-19% for the arable crops).

Among the element fluxes calculated by EPIC, the most significant ones where N volatilization, N leaching (Figure 11) and N fixation. The spatial pattern of these fluxes, especially leaching, was strongly influenced by soil properties. Areas of severe N leaching are critical for the risk of groundwater pollution by nitrates. The soil system balance is therefore promising for addressing such problems and designing mitigation measures.

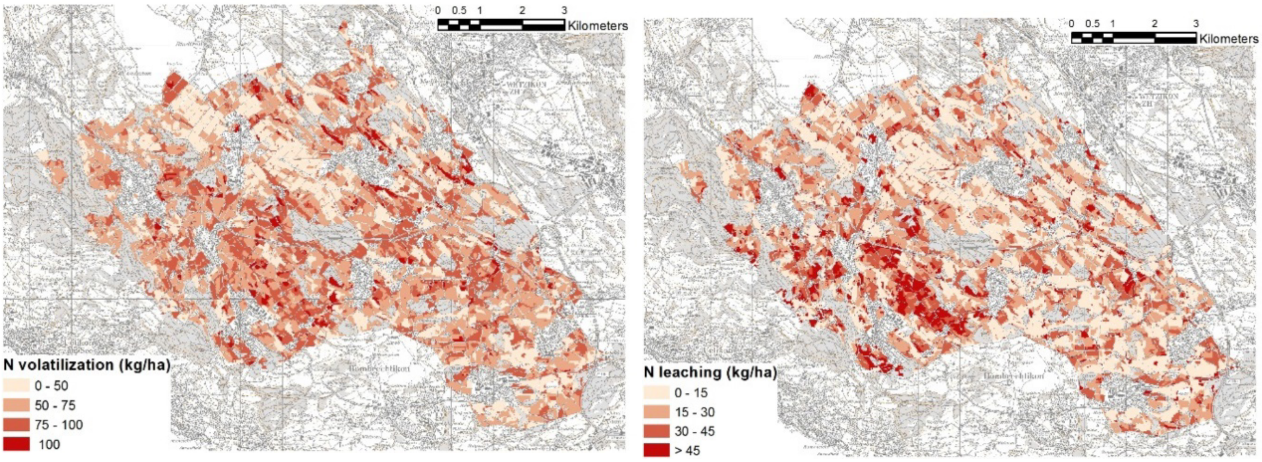


Figure 11: Maps of N volatilization and N leaching

4.4.8 Scenario analysis

The first scenario, elaborated with the model SWISSland (Möhring et al. 2016), simulated a free trade agreement with the EU, leading to a decrease of farms' income by 32% and a decrease of the total number of farms by about one fourth in the period 2013-2025. Under this scenario we found a difference in the spatial pattern of nutrient balances (Figure 12). The results suggest that a free market agreement would favor a concentration of agricultural activity in specific zones of the study area, leading to an intensification, while other zones would be managed more extensively.

In the second scenario, nutrient management was constrained by soil P status: P inputs were reduced down to 80% of GRUD's values where soil P concentration exceed 60 mg P / kg soil. Under this scenario we found a significant reduction of P surplus in specific areas (Figure 12), as expected.

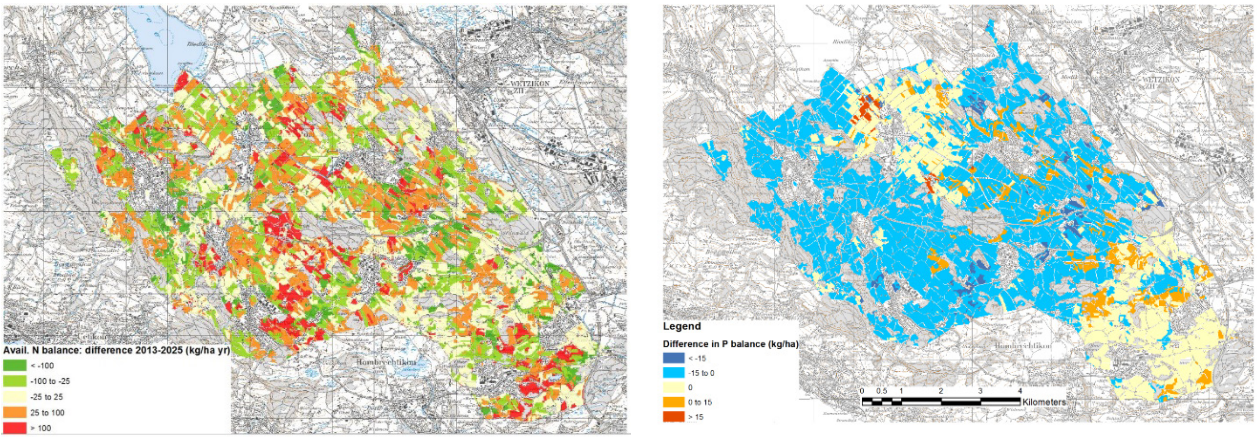


Figure 12: Balance changes under the "free trade" (left) and "reduced P input" (right) scenarios

The share of agricultural area with P surplus decreased from 50% to 24% when implementing the "reduced P input" scenario. The model reached this goal by reducing mineral P inputs, and by increasing the manure export from the study area while decreasing the manure import (Figure 13). These findings can help in designing effective measures to reduce nutrient surpluses in critical areas.

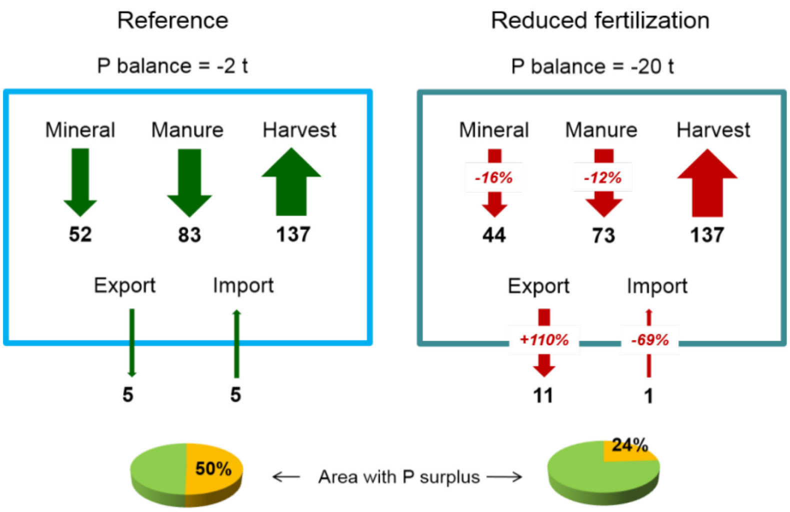


Figure 13: Changes in nutrient management and P surplus under the reduced fertilization scenario

5 Conclusions and outlook

The LMM model proved to be capable of assessing the nutrient fluxes in agricultural soils, depicting the spatial pattern of accumulation hotspots, as well as to evaluate changes under different scenarios.
This tool can operate at different scales, and its spatial and temporal resolutions depend on the input data provided by the user.

The model is parsimonious in that the number of parameters is small. Users can easily variate the parameters and analyze their effects on the model results.
All input data is easily editable, enabling the evaluation of any kind of scenarios. As soon as new data becomes available, it can be used in the model, thus decreasing the level of uncertainty.
The LMM model can be loosely coupled with the bio-physical model EPIC in order to compute soil-system balances. Although this introduces further uncertainty, it allows the assessment of nutrient losses to other environmental compartments (air, water). When more precise data becomes available, simulations of these fluxes should become more reliable.

In particular, the uncertainty would decrease by providing precise amounts of soil amendments applied to the soil, the type of amendment, and the time and mode of application. This data is generally only availabe at specific location and not at regional scale. The LMM tries to overcome this limitation by implementing a fertilization strategy. At the moment, the strategy is based on regressions made on the AUI dataset. This mechanism can be improved by using other datasets, and by adding information on the mode and time of application, that at the moment are standardized for each crop type. Time and mode of application are supposed to have a great impact on nutrient fluxes such as percolation, volatilization, and others.

Moreover, better soil property maps would increase the accuracy of EPIC in estimating the mentioned fluxes. The availability of soil information is heterogeneous and differ for each canton. The ongoing attempt to harmonize soil information in Switzerland will certainly help in this regard.

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Appendix: Nutrients in crops and farm manure

The following tables show N and P requirements of crops, as well as N and P livestock excretion rates, currently used in the LMM model. All values are taken from the fertilization guidelines GRUD (Sinaj and Richner 2017).

Nitrogen and Phosphorus requirements of arable crops.

Crop	Recommended N input (kg ha^{-1} yr^{-1})	Recommended P input (kg ha^{-1} yr^{-1})
Winter wheat	140	27
Maize (silage)	110	43
Maize (grain)	110	42
Temporary ley	140	39
Winter barley	110	28
Triticale	110	24
Sugarbeet	100	37
Potato	120	36
Oilseed rape	140	28

Nitrogen and Phosphorus requirements of grasslands.

Management intensity	Altitude (m)	Recommended N input (kg ha^{-1} yr^{-1})	Recommended P input (kg ha^{-1} yr^{-1})
Low	-	15	7
Middle	< 700	105	17
	700-1000	80	13
	1000-1500	55	9
	> 1500	40	7
High	< 700	140	39
	700-1000	115	35
	1000-1500	85	28
	> 1500	60	20

Nitrogen and Phosphorus excretion rates of livestock.

Livestock	N excretion rate (kg yr^{-1})	P excretion rate (kg yr^{-1})
Milking cow	115	18
Mother cow	80	13
Calf	34	3.5
Cattle (< 4 months)	13	2
Cattle (4 mo-1 yr)	25	3
Cattle (1-2 yrs)	40	6
Cattle (> 2 yrs)	55	9
Bull (< 2 yrs)	40	6
Bull (> 2 yrs)	50	8
Fattening calf	13	2
Nurse sow	42	10
Sow	35	8
Piglet	4.6	1
Fattening pig	13	2.5
Sheep	12	2
Milking sheep	21	4
Goat	16	2
Nurse mare	52	13.5
Foal (< 3 yrs)	42	8
Horse (> 3 yrs)	44	10
Mule	33.5	6.4
Hen	0.8	0.2
Young hen	0.34	0.09
Fattening chicken	0.45	0.07
Turkey	1.4	0.3