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Modeling crop yield response to nitrogen inputs in different crop rotations using data from long-term experiments

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Modeling crop yield response to nitrogen inputs in different crop rotations using data from long-term experiments

Modellering av skördeutbytets beroende av kvävetillförsel i olika växtföljer med data från långliggande fältförsök

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The overarching vision of the programme Mistra Food Futures is to create a science-based platform to enable transformation of the Swedish food system into one that is sustainable (in all three dimensions: environmental, economic and social), resilient and delivers healthy diets. By taking a holistic perspective and addressing issues related to agriculture and food production, as well as processing, consumption and retail, Mistra Food Futures aims to play a key role in initiating an evidence based sustainability (including environmental, economic and social dimensions) and resilience transformation of the Swedish food system. This report is a part of Mistra Food Future's work to identify the next generation's food system sustainability indicators, one of the central activities within Mistra Food Futures.

Mistra Food Futures is a transdisciplinary consortium where key scientific perspectives are combined and integrated, and where the scientific process is developed in close collaboration with non-academic partners from all parts of the food system. Core consortium partners are Swedish University of Agricultural Sciences (SLU), Stockholm Resilience Centre at Stockholm University, RISE Research Institutes of Sweden and The Beijer Institute of Ecological Economics.

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Abstract

Productive and resource-efficient crop production systems are essential to build sustainable food systems. Specific crops and well-designed diverse crop rotations can provide several benefits, including improved food system sustainability. Crop growth models that capture these benefits require detailed and rarely available input data, making them impossible to implement in quantitative research at the scale of national or subnational food systems. Instead, we need simple yet robust cropping system models accounting for the rotated crops that require limited input data and can be employed in food system models. Here, we present a proof-of-concept solution to this challenge. Using data from long-term field experiments in Sweden and Poland, we establish robust relationships between the input of nitrogen and output of crude protein, ruminant metabolizable energy, and harvested dry matter across whole crop rotations with and without leys. These three output metrics capture key aspects of productivity from a food-system perspective. To demonstrate potential applications in food system modeling or life cycle assessment, we calculate carbon and land footprints of outputs. Compared with rotations without leys, crop rotations with leys had higher outputs of crude protein and dry matter, at least at high nitrogen inputs. Productivity of ruminant metabolizable energy did not differ when including leys. This approach provides a promising avenue for further research at the intersection of crop system and food system science, exploiting the wealth of information collected in long-term field experiments thus far.

Keywords: crop rotation, productivity, yield, nitrogen

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1. Introduction

In industrialized agriculture, use of nitrogen (N) is simultaneously a driver of crop productivity and a cause of negative environmental impacts, such as eutrophication, air pollution, and climate change (Sutton et al 2011). Inefficient use of fertilizer N is also a major economic and energetic cost of agriculture. The environmental effects of N pollution are one of the main sustainability challenges of European agriculture and globally. It is widely agreed that agriculture needs to be transformed to reduce the negative environmental impacts, including those related to inefficient N use, while maintaining sufficient yields (Sutton et al 2022, Schulte-Uebbing et al 2022, Einarsson 2024).

Crop yield responses to N inputs and N emissions depend on many factors including pedoclimatic conditions and management practices. Among management practices, changes in fertilization intensity have often been considered (Mueller et al 2012, Lassaletta et al 2014, Billen et al 2021). However, the effect of fertilization depends on the sown crop(s) and their characteristics. Cover crops or winter crops lengthen the fraction of year when the field is covered with a crop, which enhances a variety of soil processes and yields (Garland et al 2021). Increasing plant diversity, e.g., by rotating functionally different crops, can also increase resource capture and use efficiency, through complementarity in root traits and root exudate quality benefitting soil microbial community (Fageria and Baligar 2005), and by reducing weed, pest, and disease damage (Storkey et al 2024). Indeed, higher crop rotational diversity improved cereal yields at a given fertilization rate, and more so at low inputs (Smith et al 2023, MacLaren et al 2022). However, the joint effects of crop rotational diversity and N input on N use efficiency and their large-scale effects remain poorly quantified.

Food system modeling at the subnational or national scale has thus far relied on simplistic relationships between N use and crop productivity, due to lack of data and to limit the number of model parameters. For instance, widely used food system models rely on an assumed fixed relationship between cropland N input and crop yield, either at the level of the whole crop rotation or relative to main crops such as cereals (Lassaletta et al 2016, Billen et al 2021, Schulte-Uebbing et al 2022, Chatzimpiros and Harchaoui 2023). However, these relationships fail to capture variations in outcome depending on specific crop traits and interactions among crops in rotation, which are key aspects of ecological intensification approaches. For example, perennial forage crops such as perennial leys with grass-clover mixtures differ from cereals in their root traits and in the presence of symbiotic N fixation in clover. Several such mechanisms can be simulated using detailed crop growth and cropping-system models, such as DSSAT or APSIM. However, these models rely on detailed input data, which are generally not available for entire countries or regions – the scales of interest for food system modeling. Moreover, these cropping-system models are difficult to validate at these larger scales. There is thus the need to develop simple cropping-system models that capture key differences between crops and crop rotations, such as the different use of biologically fixed N and the interactions between crops in rotation.

Long-Term agricultural field Experiments (LTEs) offer an opportunity to develop and validate simple, but robust, models on how cropping-system productivity depends on N input and the role of the crops included. These experiments run over many decades in many regions and countries, testing long-term effects of various agricultural practices, including crop rotational diversity and fertilization under otherwise consistent management practices (Johnston and Poulton 2018). As such, they provide unique opportunities to explore relationships between yield and fertilization type and level under contrasting cropping practices and a wide range of pedoclimatic conditions. Nevertheless, their potential to provide the relationships needed in food system models has not been explored yet.

The productivity of cropping systems can be quantified as the yields of the different crops, for example cereal grains, oilseeds, and forage. Alternatively, we can use whole rotation outputs from all crops in the rotation taken together. Examples of such aggregated outputs include nutritional contents for human consumption (e.g., calories and macronutrients such as proteins, fats, and carbohydrates) and for livestock feed (e.g., feed energy, crude protein, and/or harvested dry matter). Comparing crop rotation productivity in terms of nutritional content is an attractive option for food system modeling because many food and feed products can be substituted for each other, as long as the human or livestock nutritional needs are met (Lassaletta et al 2016, Billen et al 2021, Gerten et al 2020, Chatzimpiros and Harchaoui 2023). Among the different metrics of nutritional content, ruminant metabolizable energy and crude protein are key components of ruminant nutrition and provide a straightforward way to compare the productivity of crop rotations with a mix of crop products including cereals, grain legumes, oilseeds, as well as forage crops.

The yield of each crop in a rotation is affected by the other crops included in the rotation and how they are managed. A case in point is that, in cereals, only about 40% of assimilated plant N originates in current-year fertilizer, while the rest originates mainly in turnover of soil N and crop residues (Yan et al 2020). A whole rotation perspective is thus needed (Anglade et al 2015, Billen et al 2024). Moreover, N is provided to crops not only by applying inorganic artificial fertilizers or manure on the fields, but also via biological N fixation. If legumes are present in the rotation, the fixation can be substantial, supporting the N requirements of subsequent crops and ultimately reducing the need for organic and inorganic fertilizers. The N use efficiency of an entire rotation is thus best determined considering all the N inputs, including biological fixation.

Using primary data from 8 LTEs in Sweden and Poland, we develop and demonstrate a proof-of-concept model to quantify the effects of total N input and crops in rotation on cropping-system productivity. Specifically, we parameterize simple relationships linking total N input to productivity of ruminant metabolizable energy, crude protein, and harvested dry matter. We explore how the relationships change based on the presence or absence of leys in the rotation. We then demonstrate the usefulness of this model in the context of food system modeling and life cycle assessment by quantifying carbon footprints and land footprints of crop rotations with and without leys.

2. Methods

We developed regression models to explain the yield response to total N inputs in crop rotations with and without leys, using primary data from 8 LTEs. Whole rotations were characterized by total N input, including biological fixation, and outputs in terms of harvested ruminant metabolizable energy, crude protein, and dry matter. We used the resulting regression models in a minimalist life cycle model to estimate the carbon and land footprints of the crop products. The following subsections describe the LTE data, the estimate of inputs and outputs, the statistical modeling, and the footprint calculations.

2.1. Geographical scope

One aim of this study was to generate results applicable to Swedish agriculture, i.e. with reference to typical climatic conditions and crop rotations. We have thus primarily selected data from Swedish LTEs, but also included one site from Poland to obtain a larger dataset and improve statistical inference and robustness, while at the same time focusing on conditions and cropping systems similar to those in Sweden..

2.2. Experimental data and analyses

We used data from 8 LTEs from Sweden and Poland (Table 1). At least two crop rotations of different diversity, i.e., differing in numbers of crop species and/or rotation lengths, were sampled in each site, each including at least one cereal. Each experiment provided a minimum of 10 years of yield data. The median duration was 20 years. All rotated crops were present every growing season and their marketable yields recorded. In some cases, we used a subset of the observations, i.e., those focusing on the longest period with unchanged management practices. In Säby_LTE, we limited the analyses to the diverse rotation and the cereal monocultures with plowed residues, and discarded those with residue burning.

Experimental designs differed among the LTEs and often included treatments beyond rotational diversity, such as tillage and fertilization. These additional treatments were either fully crossed with the rotations, or similarly applied across rotation treatments, e.g., using pesticides equally across all treatments. We did not require that different fertilizations were tested in the experiment, but all sites except one (Osiny) had fertilization treatments crossed with rotational diversity.

We combined treatments not related to species/functional type diversity in the rotation, such as fertilization level, with replicates into a single variable, named ‘experimental group’, which accounts for variability explained by variation in treatments and replicates across and within the LTEs – see Section 2.2.4 below for further explanation.

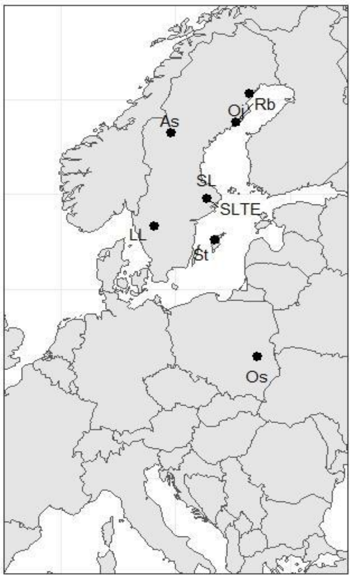

Figure 1: Map of site locations. See Table 1 for code clarification.

The dataset includes 17,383 yield observations from 30 rotations, of which 7 were monocultures, corresponding to 9.8% of the observations. Rotations ranged in complexity from cereal monocultures to rotations including three crop functional types, i.e., cereals plus two among broadleaves (e.g., oil or root crops), legumes and perennial/annual leys. Four rotations included one year of fallow, rendering no yield but potentially providing other benefits including allowing for an early sowing of the subsequent crop.

3.3% of yield data were missing (presumably due to collection errors). A further 1.8% of observations where zero yield was reported without explanation (e.g., frost damage or fallow) were also considered as missing data. Prior to the aggregation as rotation outputs (see below), yields of single crops were visually inspected to check for implausible values. This additional check led to the removal of 8 potato and 4 grass ley yields, which were deemed unrealistically high given the location, based on expert opinion. When possible, we gap-filled the missing and implausible data with the average yield of the same crop, from the same site, year, rotation, and fertilization treatment measured in other plots, in order to still be able to calculate the outcomes for the full rotation. We discarded 12 records of outputs for which such gap filling was impossible for the corresponding rotation, site, year and fertilization treatment.

As the main contrast of interest, we considered the presence or absence in the rotation of perennial leys, i.e., mixtures of perennial grasses and, in some cases, legumes such as clover. An alternative approach would be to consider the number of functional types included in the rotation. However, given the nature of the dataset, the functional richness of 3 most often coincides with leys being included, whereas functional richness 2 corresponds to no ley (Table 1).

Table 1: Site information. Functional richness covered shows levels of rotational functional richness, i.e., the number of crop groups (cereals, annual legumes, broadleaves, and perennial leys) in the rotations. Fertilizer treatment indicates whether the site has subplots with different fertilizer levels. See Smith et al (2023) for more details on the experimental design of each LTE.

Site (code) and country	**Period (number of years)**	**Rotations**	**Functional richness covered**	**Fertilizer levels**	**Reference publication**
Lanna_ley (LL) Sweden	1981-2018 (38)	1. oilseed rape, wheat, oat, barley (undersown ley), grass-clover mix[1], grass-clover mix 2. oilseed rape, wheat, oat, barley (undersown ley), grass ley[2], grass ley 3. oilseed rape, wheat, oat, barley, wheat, fallow	2,3	4	Bergkvist and Öborn (2011)
Osiny (Os) Poland	1996-2019 (24)	1. wheat 2. oilseed rape, wheat, wheat	1,2	1	Martyniuk *et al* (2001)
Röbäcksdalen (Rb) Sweden	1966-2009 (44)	1. barley (undersown ley), grass-clover mix[3], grass-clover mix, rape (fodder), potato, ryegrass 2. barley 3. barley, barley, rape (fodder) 4. barley, barley, potato 5. barley (undersown ley), grass-clover mix[3], grass-clover mix	1,2,3	3	Palmborg (2019)
Säby_ley (SL) Sweden	1981-2016 (36)	as Lanna ley, but with different grass-clover species mixture[4]	2,3	4	Bergkvist and Öborn (2011)
Säby_LTE (SLTE) Sweden	1975-2010 (37)	1. oilseed rape, wheat, oat, barley, wheat, fallow 2. oat 3. barley 4. wheat	1,2	4	Bergkvist and Öborn (2011)
Stenstugu_ley (St) Sweden	1968-2020 (53)	as Lanna Ley, but with different grass-clover species mixture[4]	1,2	4	Bergkvist and Öborn (2011)
Öjebyn (Oj) Sweden	1966-2009 (44)	as Röbäcksdalen	1,2,3	3	Palmborg (2019)
Ås (As) Sweden	1966-2009 (44)	as Röbäcksdalen	1,2,3	3	Palmborg (2019)

1 Mixture of red clover (sown at density of 16 kg/ha) and timothy (sown at density of 8 kg/ha)
2 Mixture of meadow fescue (sown at density of 12 kg/ha) and timothy (sown at density of 12 kg/ha
3 Mixture of red clover (sown at density of 2.5 million seed/ha), timothy (sown at density of 21 million seed/ha) and meadow fescue (sown at density of 3 million seed/ha)
4 Mixture of red clover (sown at density of 8 kg/ha), alfalfa (sown at density of 8 kg/ha) and timothy (sown at density of 8 kg/ha)

2.2.1. Rotational outputs

For each rotation, we quantified the yield in terms of harvested dry matter, ruminant metabolizable energy and crude protein per unit cultivated area rendered by the rotation in each growing season, i.e., the sum of outputs from all the rotated crops for the season. This was possible given that all LTEs had all the rotated crops present each year. Thus, we avoided the confounding effect of the inter-annual variability of growing conditions.

For each crop in the rotation, we obtained crop ruminant metabolizable energy and crude protein outputs by converting crop yields using conversion factors from dry matter to ruminant metabolizable energy or crude protein, obtained from Feedipedia (Table A1). While the composition of sown seeds for leys is known (Table 1), yields were reported as total harvested biomass, with no information of the species-specific contributions. We therefore modeled grass leys as consisting of timothy, and grass-red clover leys as mixtures of red clover and timothy, and we assumed that 20% of the grass-clover ley biomass was clover. This value aligns with typical grass-clover ley composition in Sweden (Einarsson et al 2022), where the sites were located. As a sensitivity analysis for this assumption, we also determined the results assuming 40% clover in the grass-clover ley biomass (see the Appendix).

We calculated the total output of energy, crude protein, or dry matter for each year as the sum of the output from each crops c in the rotation multiplied by the fraction of area under that crop:

$$O_{y,i,j,g} = \sum_{c} M_{c,y,i,j,g} F_{A,c}$$

Here, $O_{y,i,j,g}$ is the sought output and $M_{c,y,i,j,g}$ the i^{th} output (ruminant metabolizable energy, crude protein, or dry matter) produced per unit cultivated area by the crop *c* in year *y* from LTE *j*, in relation to group *g*, i.e., the combination of rotation and "experimental group". The fraction of area under crop *c*, $F_{A,c}$, is 1/rotation length. In other words, the rotation yield is the output equivalent to a one-hectare farm, comprising equally sized plots dedicated to all rotated crops every year.

This aggregation led to 4,736 whole rotation outputs, which are at the basis of all the analyses below.

2.2.2. Rotational N inputs

Total rotational N inputs are the sum of N from inorganic and organic fertilizers, from symbiotic N fixation (annual and perennial legumes), and from atmospheric deposition.

We estimated the symbiotic N fixation using an established model (Lassaletta et al 2014, Anglade et al 2015), multiplying crop yield N content (kgN ha^{-1}) by the percentage of N uptake of the crop derived from N fixation, the ratio of the harvested material to the total above-ground N production, and a multiplicative factor accounting for the total N_2 fixation (including below-ground contributions). Model parameters were taken from Lassaletta et al (2014). Since our data did not include yield N content, we assumed constant N contents for each crop, irrespective of site, rotational diversity and fertilization level. The crop-specific N content was obtained by dividing crude protein content by a factor 6.25 (Table A1; see also Mariotti et al 2008). For grass-red clover leys, we determined the symbiotic N contribution based on the red clover N content and the fraction of yield assumed to be of clover. Similarly to outputs, we assumed clover was 20% of the grass-red clover ley dry matter yield, but we also considered the case of 40%, to test the effect of altering this assumption.

To calculate atmospheric N deposition, we summed wet and dry deposition of atmospheric oxidized and reduced N, obtained from monthly, 0.5° gridded simulation outputs by NCAR Chemistry-Climate Model Initiative (CCMI)[1]. The values refer to the specific year until 2004, but are constant afterwards.

The average share of total N input supplied by biological N fixation was 0% in rotations without leys and 12% in rotations with leys (Figure 2). Note that the latter also include grass leys, which reduces the average contribution of biological N compared with leys with clover. Assuming 40% legumes in ley biomass, the share of biologically fixed N increased to 19% (Figure A1).

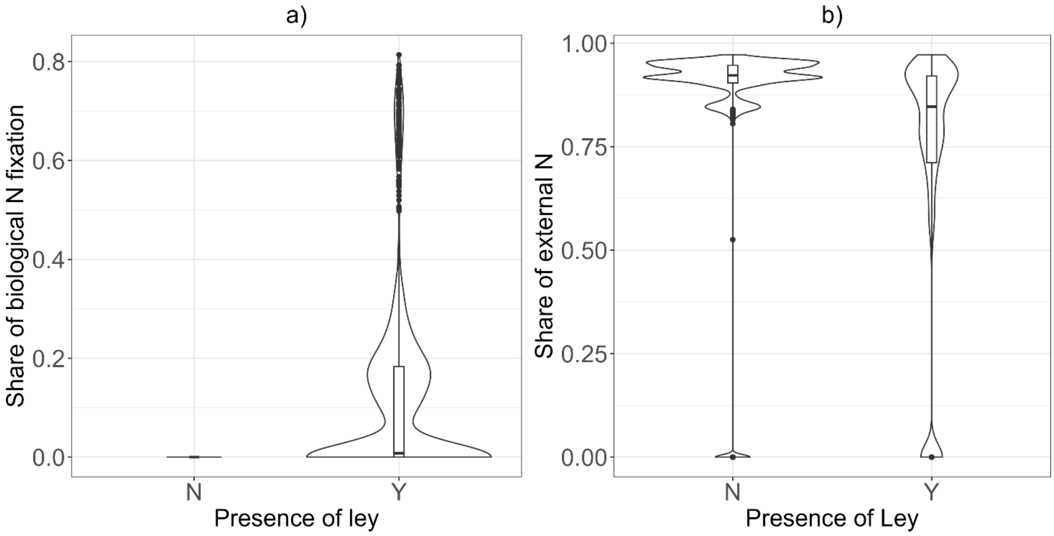

Figure 2: Share of a) biological N fixation, and b) fertilizer N to the total N inputs when perennial leys are absent or present in rotation. Violin plots show the data distribution; horizontal lines indicate the median; upper and lower box limits indicate 3rd and 1st quartiles; upper and lower whiskers extend from the 3rd and 1st quartiles, respectively, to the 1.5 times interquartile range; data outside these limits are shown as individual dots.

2.2.3. N balances of crop rotations

To build further understanding of the N supply and N use in crop rotations, we calculated soil-surface N balances for the LTE data, defined as the difference between total N inputs (the sum of fertilizer N, biological N fixation, and N deposition) and N removal with harvested crop products (Oenema et al 2003, Zhang et al 2020). A positive N balance, i.e., a N surplus, means that more N is supplied to the rotation than removed. This is common, especially in high-input crop rotations, and implies an environmental loss of N from the field (through leaching, volatilization, and denitrification) and/or a net increase in the soil N stocks. Conversely, a negative N balance, i.e., a N deficit, means that crop N removal exceeds total N inputs, which implies a net depletion of soil N stocks, sometimes called “soil mining”. Negative N balances can persist for years or even decades if soil N stocks are large. In the long run, however, sustainable cropping systems

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[1] https://www.isimip.org/gettingstarted/input-data-bias-adjustment/details/24/

should ideally have a small N surplus, given that some environmental N losses are unavoidable (Zhang et al 2020, Einarsson 2024).

2.2.4. Statistical analyses

To obtain a robust fitting, we assumed a linear relationship between rotational output (O) and total N inputs (N_tot). We used linear mixed-effects models to determine how the rotational output changes with total N input N_tot as perennial leys (L) are included or not in the rotations, and over time (t). In other words, t and N_tot are continuous variables, whereas L is a categorical variable (0 for no ley, 1 with ley). The fixed part of the relationship was assumed to be:

$$\mathrm{O} = \beta_0 + \beta_{\mathrm{t}}\mathrm{t} + \beta_{\mathrm{L}}\mathrm{L} + \beta_{\mathrm{N_{tot}}}\mathrm{N_{tot}} + \beta_{\mathrm{Lt}}\mathrm{Lt} + \beta_{\mathrm{LN_{tot}}}\mathrm{LN_{tot}}$$

where β_0 is the intercept, i.e., the output of rotations without perennial leys when t and N_{tot} are set to 0, β_t and $\beta_{N_{\mathrm{tot}}}$ are the linear effects of t and N_{tot}, β_L is the output contribution when leys are present in rotation, and β_{Lt} and $\beta_{LN_{\mathrm{tot}}}$ are the interaction effects between L, and t or N_{tot} respectively.

The random effects of the model accounted for the variation explained by the categorical variables of calendar year (*yr*) and experimental group (g), both nested within sites (s). We also accounted for rotational identity (*rot*), because rotational composition can affect treatments such as fertilization rates, if for example legumes are present. We hence allowed the intercept to vary with *s*:*yr*, *s*:*g*, and *rot*.

To fit the mixed-effect models, we used the 'lme4' package version 1.1-35.5 (Bates et al, 2015), in R version 4.4.1. The model assumptions were checked by visual inspection of the residuals using the 'DHARMa' package in R (Hartig, 2021).

2.3. Calculation of carbon and land footprints

We demonstrated the potential use of the cropping system model in the context of food system modeling or life cycle assessment, by using the results of the statistical analysis to calculate how N fertilizer input (not total N input) affected carbon footprints and land footprints per unit crop output of ruminant metabolizable energy, crude protein, or dry matter. For this proof-of-concept application, we used a life-cycle approach limited to the crop cultivation, with the functional unit being the output, i.e., 1 MJ (ruminant) metabolizable energy, 1 kg crude protein, or 1 kg dry matter contained in the crop harvest.

The carbon footprint is the global warming impact per unit crop output, expressed as carbon dioxide equivalent emissions (CO_2e) using the GWP100 metric, where 1 kg nitrous oxide (N_2O) is equivalent to 273 kg CO_2 (Forster et al 2021). The following greenhouse gas emissions were included:

- CO_2 and N_2O emissions from manufacturing of N fertilizer: 3.3 kg CO2e per kg fertilizer N (Hoxha and Christensen 2018, assuming ammonium nitrate);

- N_2O emissions from fertilizer application to soils, assuming that 1% of fertilizer N is transformed into N_2O (Hergoualc'h et al 2019), i.e., ca 4.3 kg CO2e per kg fertilizer N;
- N_2O emissions from crop residues, assuming N_2O-N emissions equal to 0.2% of harvested N (Einarsson et al 2022); and
- CO_2 emissions from diesel and other fossil energy use in cultivation, assuming emissions of 100 kg CO_2/ha/year, based on energy use in Swedish cultivation (Flysjö et al 2008).

The N fertilizer input was calculated as a fixed share of total N input, based on the average share of fertilizer N input in the LTE datasets (Figure 2). The share of external N in the total N inputs was 88% in the rotations without leys and 72% in the rotations with leys (67% in the sensitivity analysis with 40% legumes in the ley biomass; see Figure A1).

The land footprint is the amount of agricultural land used per unit crop output. It was calculated as the inverse of the per-hectare yield of metabolizable energy, crude protein, or dry matter.

The LTE data contained rotations receiving a total N input of up to about 170 kg N/ha/yr both with and without leys. We therefore calculated the carbon and land footprints for total N inputs in the rotation varying between 50-170 kg N/ha/yr. In the calculation of both footprints, we set the time variable in the regression model to 10 years after the beginning of the experiment. The time dependence is relatively weak (Table 2, A2) and the results are therefore not particularly sensitive to this parameter choice.

3. Results

3.1. Crop rotational output response to total N input

Increasing total N enhanced all crop outputs, but more so with leys in the rotation for crude protein and harvested dry matter (Figure 3, A1; Table 2, A2). All outputs increased with time in the presence of leys, whereas outputs were unaffected by time without leys. For any set total N input, the presence of leys increased crude protein output, assuming a ley composition of 20% legumes, and also tended (at $p < 0.1$) to increase crude protein output at 40% legumes (see Appendix).

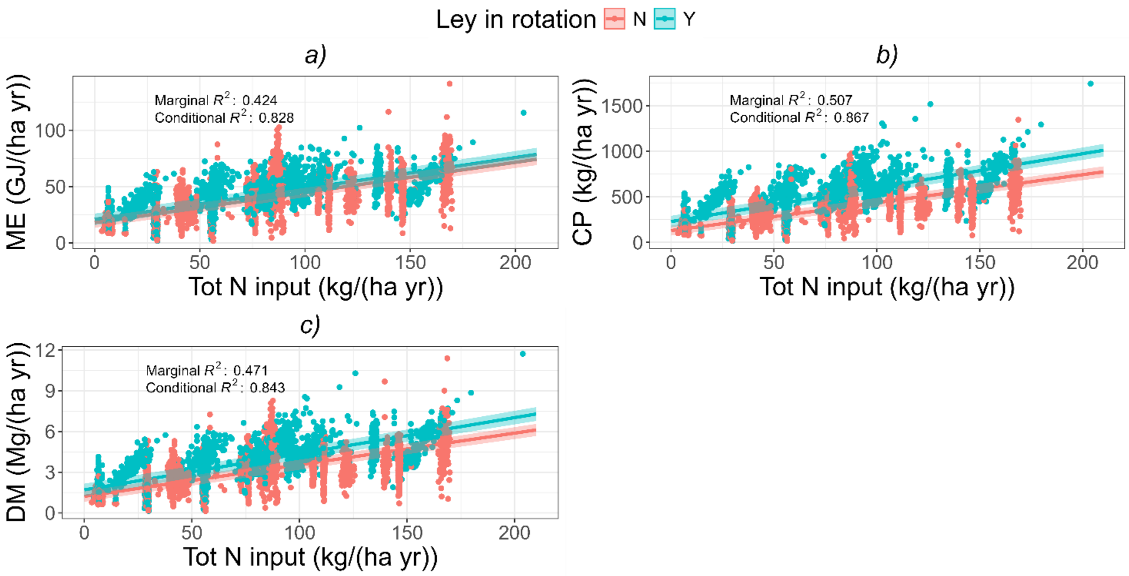

Figure 3. Model predicted (lines) and observed (dots) outputs of a) ruminant metabolizable energy (ME), b) crude protein (CP), and c) harvested dry matter (DM), in response to total N inputs, assuming 20% legume in the grass-clover leys. The predicted response is based on Eq. 2, with fitted parameters (Table 2), and is relative to 10 years after the beginning of the experiment. Red lines and dots refer to rotations without perennial leys; blue lines and dots to rotations with perennial leys. Shaded areas represent 95% confidence intervals.

*Table 2. Summary of the linear mixed effect model (Eq. 2) outputs for a) metabolizable energy, b) crude protein, and c) harvested dry matter assuming 20% legume in the grass-clover leys. Significance: *** p<0.001, ** p<0.01, *<0.05*

a) Ruminant metabolizable energy

Predictor	Coefficient (units)	Estimate	Std Err	Significance
Intercept	β_0 (GJ ha^{-1} yr^{-1})	18.0	2.4	***
N_{tot}	$\beta_{N_{tot}}$ (GJ kgN^{-1})	0.267	0.011	***
L	β_L (GJ ha^{-1} yr^{-1})	2.29	2.96	
t	β_t (GJ ha^{-1} yr^{-2})	-0.00177	0.0354	
N_{tot} x L	$\beta_{LN_{tot}}$ (GJ kgN^{-1})	0.00737	0.00797	
L x t	β_{Lt} (GJ ha^{-1} yr^{-2})	0.0591	0.0206	**

b) Crude protein

Predictor	Coefficient (units)	Estimate	Std Err	Significance
Intercept	β_0 (kg ha^{-1} yr^{-1})	129	29	***
N_{tot}	$\beta_{N_{tot}}$ (kg kgN^{-1})	3.07	0.12	***
L	β_L (kg ha^{-1} yr^{-1})	91.3	36.1	*
t	β_t (kg ha^{-1} yr^{-2})	0.0243	0.368	
N_{tot} x L	$\beta_{LN_{tot}}$ (kg kgN^{-1})	0.654	0.087	***
L x t	β_{Lt} (kg ha^{-1} yr^{-2})	0.794	0.223	***

c) Harvested dry matter

Predictor	Coefficient (units)	Estimate	Std Err	Significance
Intercept	β_0 (Mg ha^{-1} yr^{-1})	1.22	0.21	***
N_{tot}	$\beta_{N_{tot}}$ (Mg kgN^{-1})	0.0233	0.0010	***
L	β_L (Mg ha^{-1} yr^{-1})	0.423	0.260	
t	β_t (Mg ha^{-1} yr^{-2})	-0.000312	0.00287	
N_{tot} x L	$\beta_{LN_{tot}}$ (Mg kgN^{-1})	0.00333	0.00068	***
L x t	β_{Lt} (Mg ha^{-1} yr^{-2})	0.00545	0.00176	**

3.3. N balances of rotations with and without leys

N inputs increased the surplus of N balances irrespective of ley presence. Negative N balances were found in some sites and rotations, in particular at low total N inputs and when leys were included (Figure 4a). Most of the estimated negative N balances were found in a small number of sites (Figure 4b). The soil N deficits were less than 70 kg N ha^{-1} yr^{-1} with the exception of some site, rotation and year combinations, corresponding to particularly high yields (not shown). In the sensitivity analysis, assuming 40% legumes in the grass-clover ley biomass, the N balances in leys were less often negative and more similar to the no-ley N balances (Figure A3).

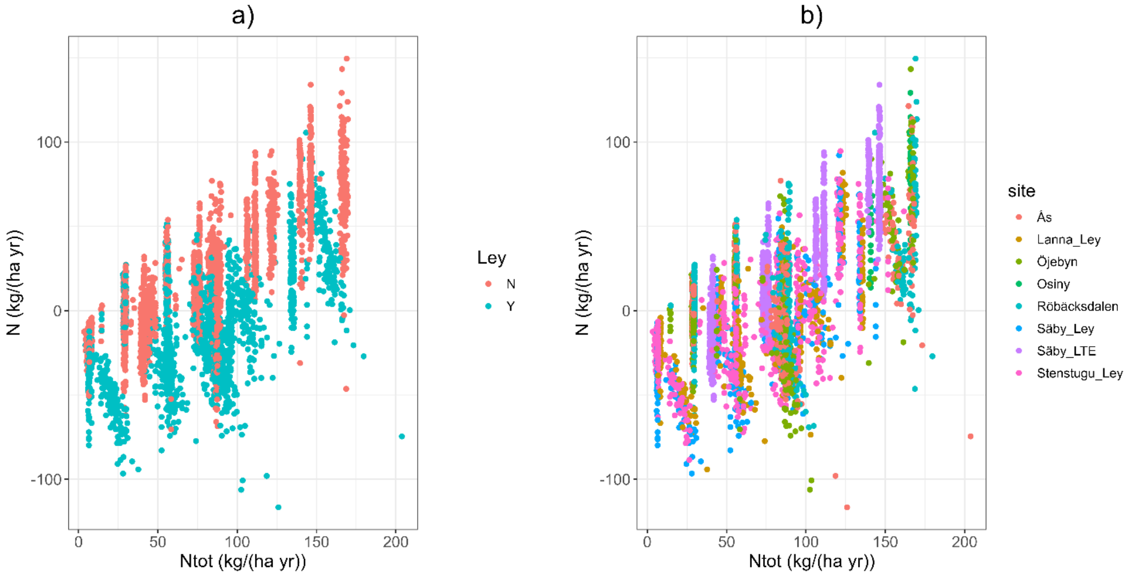

Figure 4. N balances in the rotations at different total N input rates, separated by a) absence (red) or presence (blue) of leys in the rotation and b) site (colors), assuming 20% of grass clover leys is clover.

3.4. Carbon and land footprints

The crop rotations with leys had lower estimated carbon and land footprints than rotations without leys, per unit ruminant metabolizable energy, crude protein, and dry matter produced (Figure 5). The different assumptions about the fraction of legumes in the leys had a very minor effect on the footprints.

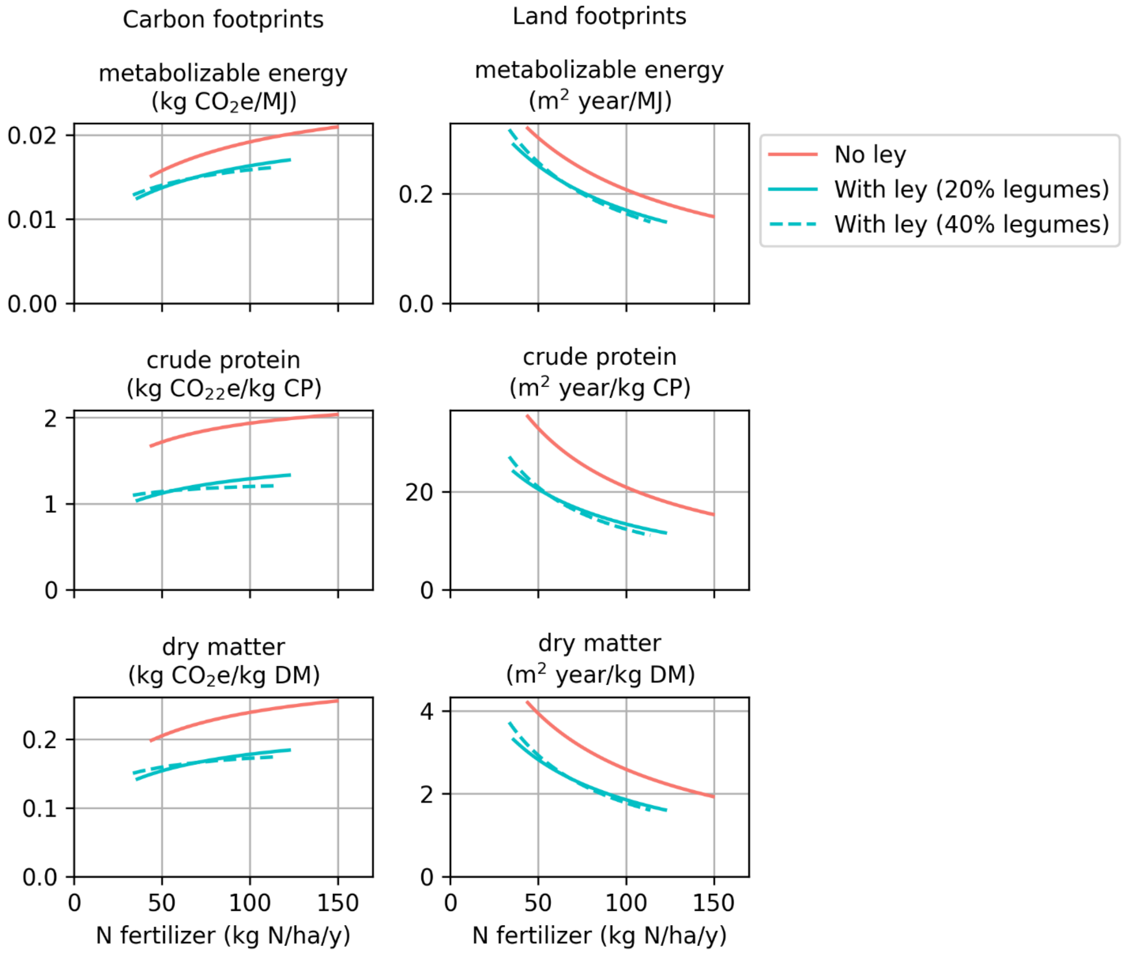

Figure 5. Carbon and land footprints of the crop outputs depending on fertilizer N input. Crop rotations with leys (blue curves) have lower footprints than rotations without leys (red curves) across all three yield metrics (ruminant metabolizable energy, crude protein, and dry matter). The dashed blue lines show results assuming 40% legumes in grass-clover ley biomass.

4. Discussion and conclusions

We demonstrate a pragmatic and useful application of LTE data in support of food system modeling. We parameterized the total N input to output relationships based on primary data from 8 LTEs, located along a gradient of climatic conditions and soil characteristics, from Northern Sweden to Poland. This gradient ensured a robust parameterization of crop rotation effects in general, rather than the results being driven by site-specific factors.

Total N inputs enhanced all crop rotation outputs considered. This is expected, as N is central for plant primary functions (Mu and Chen 2021). Diversifying rotations through including leys increased the return on increasing N inputs. Through complementarity in resource use, root traits, and exudate qualities (Griffiths et al 2022, Bardgett et al 2014), crop diversity in rotation supports a more abundant and diverse soil microbial community, contributing to soil organic matter stabilization and closing the nutrient cycling, ultimately reducing the reliance on external fertilization inputs (Grandy et al 2024, Wang et al 2022, Zhang et al 2021). Diverse crop rotations also break life cycles of weeds, pests, and diseases and promote biodiversity that suppresses them (Storkey et al 2024).

Considering the functional richness of the rotation as an explanatory variable showed that adding one functional type of crop, either broadleaves, legumes or leys, to a cereal only rotation had no effect. In contrast, adding two functional types was beneficial for crude protein and dry matter outputs (not shown). However, in most cases in our data, a shift from two to three functional types in rotation corresponded to adding leys in the rotation (Table 1). We thus conclude that leys offer particular benefits. Leys are mixtures of perennial plants and therefore subject to benefits of extended crop cover for both yields and soil functioning that have been demonstrated in cereal fields across Europe (Garland et al 2021). Another possible mechanism for the particular benefits of leys is that the legumes included in (most) leys contribute biologically fixed N to the subsequent crops at soil depths or periods not covered by synthetic or organic fertilization. Rotations with leys had higher production of crude protein, likely due to leys being functionally different from all other crops in the rotation and in many cases including protein-rich legumes. Indeed, this benefit was more marked when assuming a larger proportion of legumes in the leys. In contrast, metabolizable energy productivity and dry matter were unaffected by leys in rotation at any level of N input. We surmise that the undetectable benefit of leys on these outputs is because they are less affected by the specific advantages conferred by the presence of legumes in the leys.

Rotations with leys gave higher yields in terms of dry matter at high input levels, and of crude protein at all input levels. Leys in rotation also resulted in a higher concentration of crude protein as a share of dry matter. Conversely, the concentration of ruminant metabolizable energy was typically lower in crop rotations with leys (not shown). These results are expected, as the non-ley crops were mainly cereals, which generally have higher energy content than forage crops. The energy concentration is important from the perspective of ruminant nutrition because ruminants can only digest a certain amount of dry matter. Production systems that seek to maximize livestock productivity and feed use efficiency thereby rely on high feed energy concentrations, which require that some cereals or other energy-dense feeds are added to ley forage. In the context of food system modeling, the potential trade-offs and limitations associated with these feed quality metrics could be assessed using an extended model system including livestock metabolism.

We chose a linear dependence of output on N input to obtain a more robust fitting. This is in contrast to more commonly used saturating curves (e.g., van Grinsven et al 2022), which are often formulated with a zero intercept and do not adequately describe the observed outputs at low level input. Moreover, we do not expect or see any clear saturating dependence of outputs on total N inputs in the relatively modest range of total N inputs studied here. Indeed, the fraction of explained variance of the linear model is substantial (marginal R^2: 0.42-0.62; conditional R^2: 0.83-0.90). The fixed effects had a higher explanatory power, i.e., a higher marginal R^2, if considering the linear compared with a two-parameter power law model with zero intercept, whereas the total variance explained, i.e., the conditional R^2, was comparable. Additional research with a wider range of fertilizer treatments will be useful to quantify the saturating dependence of outputs on total N inputs, and how that is approached.

Some crop rotations exhibited negative N balances, always at low total N input and often in rotations with leys. There are several possible reasons for the negative N balances. A main explanation and expectation is simply that at low rates of total N input, net mineralization (“soil mining”) of soil N enables substantial crop growth and net N removal for years or even decades. Negative N balances are expected at low enough rates of total N input. It is possible that some rotations, especially rotations with leys at some sites (Figure 4b), were designed to tend to have negative N balances, to test what happens to the soil processes and cropping system under such conditions. Another contributing factor could be that N inputs are underestimated, or that N output is overestimated in our analyses. This might happen given that N content of crops was not measured in each LTE, but instead estimated using average values from the Feedipedia database, i.e., thereby neglecting site-, rotation-, fertilizer-, and yield-related effects on yield quality (Zörb et al 2018, Hu et al 2021). Bias in the estimates of biological N fixation input can stem from lack of rotation-specific information on legume content in grass-clover leys, requiring the assumption of a fixed legume share. We are also aware of some unreported N fertilization inputs in selected years in one of the sites with the most negative N balance values. We note, however, that the general patterns of results were robust to different assumptions about legume content in leys. Especially the carbon and land footprints (Figure 5) were remarkably insensitive to the assumption about legume content. Nevertheless, refining the dataset with more accurate estimates of N removal and biological N fixation would be useful to improve our understanding of N use efficiency and long-term sustainability of the different crop rotations.

In summary, we used LTE data to estimate the productivity and environmental impacts of crop rotations. The proposed straightforward approach is intended for easy application in food system modeling or life cycle assessment, for which input data availability is often lacking for more detailed crop models. In this proof-of-concept application, we compared the effects of crop rotations with and without leys on carbon and land footprints of produced ruminant metabolizable energy, crude protein, and dry matter. Our approach provides a substantial refinement compared with commonly used food system models that do not account for crops included in different rotations. As such, this approach enables more robust estimates of food system impacts arising from on-farm efforts to improve agricultural sustainability via crop diversification and other farming practices aimed at improving resource use efficiency and capture. This is also an interesting avenue for further data collection for research at the intersection of cropping system and food system science, exploiting the wealth of information collected in LTEs. Further research along these lines could account for a wider range of crop rotations and other farming practices, of environmental impacts, additional productivity metrics and of context controls on productivity, such as pedoclimatic conditions.

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Appendix

Nutritional content of crop products

Table A1 Crude protein (CP) and ruminant metabolizable energy (ME) of the included crops. Feedipedia ID is the chosen nutritional table from Feedipedia (https://feedipedia.org), from where crude protein and ruminant metabolizable energy were obtained.

Crop	**Feedipedia ID**	**CP (kg crude protein/ kg dry matter)**	**ME (MJ/ kg dry matter)**
Barley	Barley grain	0.12	12.40
Oats	Oats	0.11	12.20
Potato	Potato, tuber, raw	0.11	11.90
Rapeseed	Rapeseed	0.21	20.30
Rape(f)	Rape forage, fresh	0.19	10.6
Red clover	Red clover (*Trifolium pratense*), aerial part, fresh	0.20	9.41
Timothy	Timothy (*Phleum pratense*), aerial part, fresh	0.14	9.30
Turnip rape	Turnip rape, for oil[1]	0.21	20.30
Wheat	Wheat grain	0.13	13.10
White clover	White clover (*Trifolium repens*), aerial part, fresh	0.25	11.10

[1] Turnip rape for oil is missing in Feedipedia. Here it is assumed equivalent to rapeseed.

Role of legume content in leys

The following figures and tables show results obtained when assuming 40% legume in the ley biomass. Compared with the results assuming 20% legume, the higher legume content leads to higher estimates of biological N fixation, total N inputs, and N balances in rotations with leys, even though biological N fixation remains low. Table A2 shows the statistical modeling results assuming 40% legume.

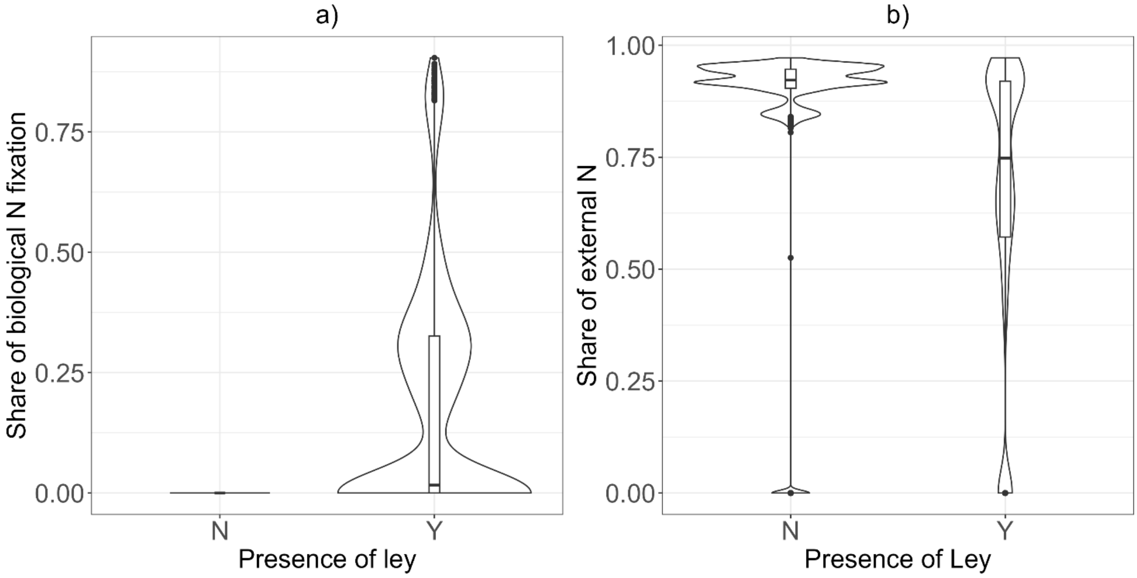

Figure A1. Share of a) biological N fixation, and b) fertilizer N to the total N inputs when perennial leys are absent or present in rotation, assuming 40% legume content in ley biomass. C.f. Figure 2 with results assuming 20% legume.

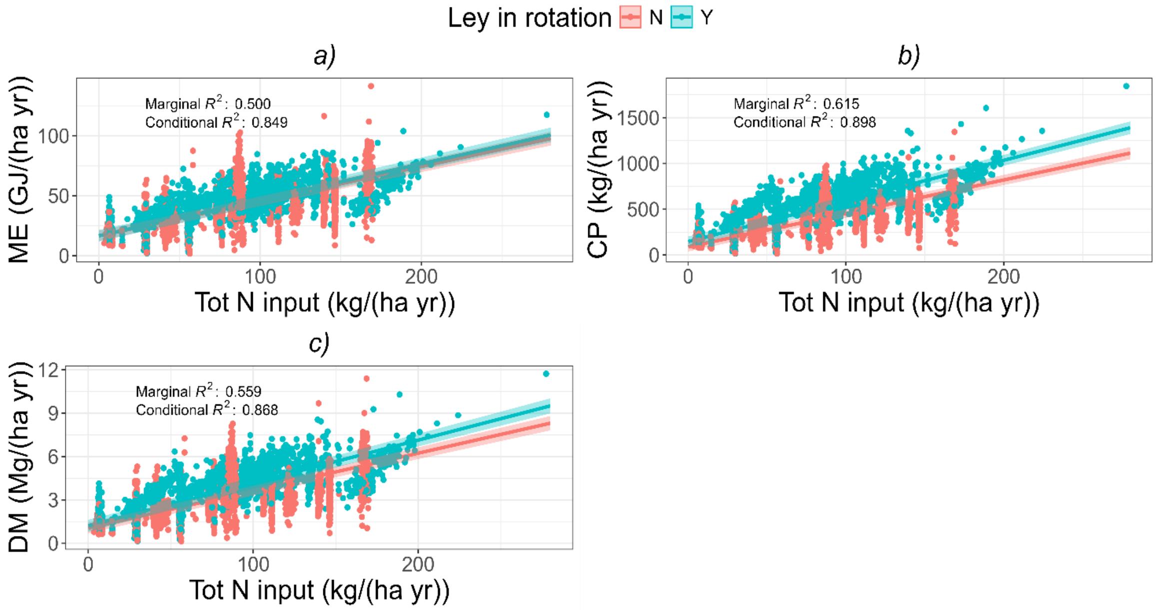

Figure A2. Same as Figure 3 in the main text, but assuming leys contain 40% legume.

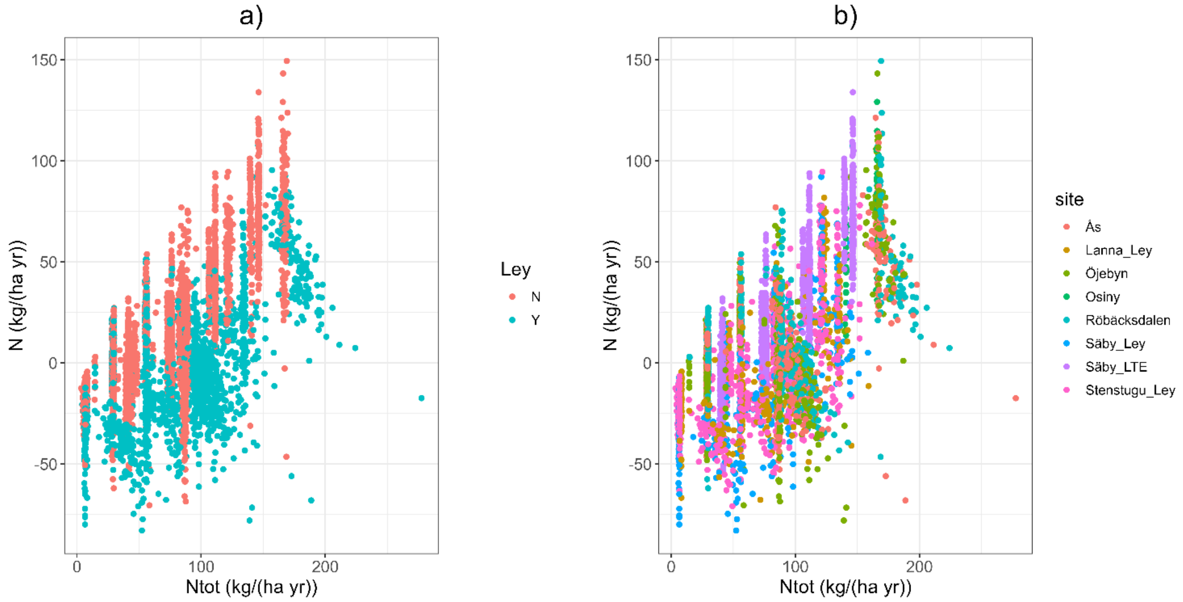

Figure A3. N balance, assuming ley biomass contains 40% legume (c.f. Figure 4 assuming 20% legume).

Table A2. *Same as Table 2 in the main text, but assuming 40% legumes in grass-clover leys. Significance: *** p<0.001, ** p<0.01, *<0.05, .<0.1*

a) Ruminant metabolizable energy

Predictor	Coefficient (units)	Estimate	Std Err	Significance
Intercept	β_0 (GJ ha^{-1} yr^{-1})	16.5	2.3	***
N_{tot}	$\beta_{N_{tot}}$ (GJ kgN^{-1})	0.290	0.011	***
L	β_L (GJ ha^{-1} yr^{-1})	-0.379	2.649	
t	β_t (GJ ha^{-1} yr^{-2})	-0.00335	0.03470	
N_{tot} x L	$\beta_{LN_{tot}}$ (GJ kgN^{-1})	0.0107	0.0077	
L x t	β_{Lt} (GJ ha^{-1} yr^{-2})	0.0486	0.0202	*

b) Crude protein

Predictor	Coefficient (units)	Estimate	Std Err	Significance
Intercept	β_0 (kg ha^{-1} yr^{-1})	89.7	26.4	**
N_{tot}	$\beta_{N_{tot}}$ (kg kgN^{-1})	3.65	0.12	***
L	β_L (kg ha^{-1} yr^{-1})	50.3	28.3	.
t	β_t (kg ha^{-1} yr^{-2})	-0.00474	0.35603	
N_{tot} x L	$\beta_{LN_{tot}}$ (kg kgN^{-1})	0.787	0.082	***
L x t	β_{Lt} (kg ha^{-1} yr^{-2})	0.660	0.216	**

c) Harvested dry matter

Predictor	Coefficient (units)	Estimate	Std Err	Significance
Intercept	β_0 (Mg ha^{-1} yr^{-1})	1.05	0.19	***
N_{tot}	$\beta_{N_{tot}}$ (Mg kgN^{-1})	0.0259	0.0009	***
L	β_L (Mg ha^{-1} yr^{-1})	0.119	0.217	
t	β_t (Mg ha^{-1} yr^{-2})	-0.000503	0.00278	
N_{tot} x L	$\beta_{LN_{tot}}$ (Mg kgN^{-1})	0.00370	0.00065	***
L x t	β_{Lt} (Mg ha^{-1} yr^{-2})	0.00430	0.00171	*

MISTRA
FOOD FUTURES