Legume Futures

Legume-supported cropping systems for Europe

Legume Futures Report 1.4

Agronomic analysis of cropping strategies

Compiled by:

M. Reckling, J.-M. Hecker, N. Schläfke, J. Bachinger & P. Zander, ZALF;

G. Bergkvist, SLU;

R. Walker, J. Maire, V. Eory, K. Topp & B. Rees, SRUC;

I. Toncea, NARDI;

A. Pristeri, UDM; and

F.L. Stoddard, University of Helsinki

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INTRODUCTION

Legume crops have a number of environmental effects in rotations (Legume Futures report 1.6), but farmers and agronomists need assistance with understanding the possibilities for incorporating them into arable and forage rotations and assessing the financial risks and benefits of doing so. Hence, Report 4.2 focused on the generation of rotations for five case regions across the Legume Futures network, and this report focuses on the deeper evaluation of the agronomy of those rotations and the feasibility of their application, as assessed by one of the senior agronomists at each of the five relevant partner institutions.

Materials and Methods

Generation of crop rotations

Crop rotations in general and those including legumes are rarely found in European farming practice. In order to explore legume cropping systems in different test cases beyond the current farming practice, crop rotations needed to be derived from other sources. The approach described here is a rule-based crop rotation generator that is able to produce a large set of agronomic suitable rotations for single regions and sites across Europe. In contrast to other approaches for the generation of rotations e.g. ROTOR (Bachinger & Zander 2007), ROTAD (Dogliotti et al 2003) and CropRota (Schönhart et al. 2011), this method was more flexible to be applied under various site conditions.

The generator has been developed in Python (www.python.org, 2013). Input data and output data were stored in a PostgreSQL database as backend and an export to a MS Access database was used to (i) support discussions – e.g. with stakeholders – about input data, rules, results, and restrictions and (ii) as interface to allow further processing of the results e.g. the agronomic and economic evaluation. The structure of the input data is shown in Figure 1.

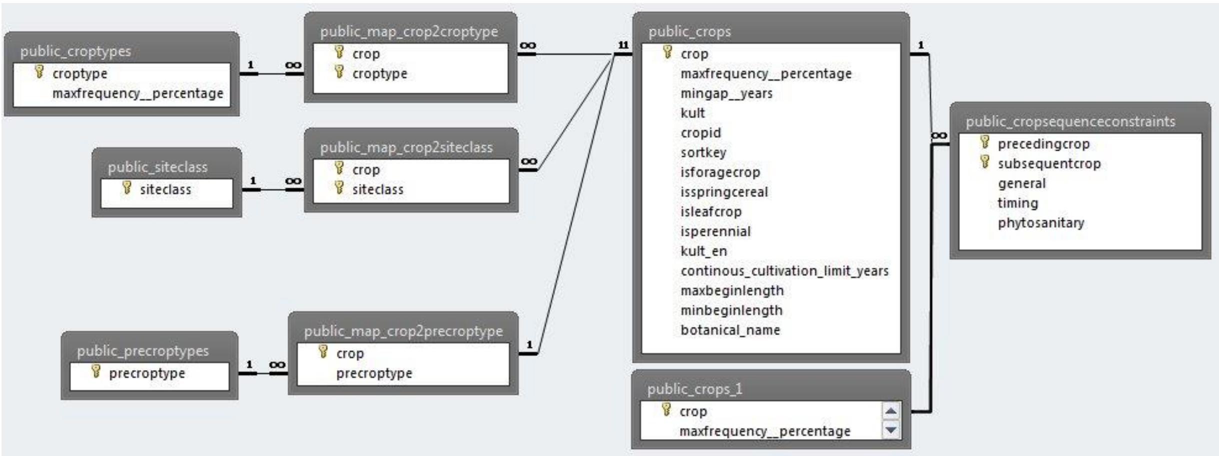

Figure 1: Database of crop rotation generator - entity relationship diagram

Region-specific crop rotation rules were the basis for generating crop rotations of 3 6 years for each of the test cases and their site classes. Rules captured characteristics of single crops, crop types, and crop-pairs (sequences) within a crop rotation. Details on the input data are reported in Deliverable 4.2.

The parameters were used to describe restrictions and rules. To control soil-borne pests and diseases the minimum cultivation break (years), the maximum share of crops (%) and the crop sequence constraints (score) are relevant. Crop type frequency constraints (%) help to control soil-borne pests and diseases that are relevant for crops of the same type e.g., cereal nematodes. Timing restrictions (score) ensure that the cropping periods of subsequent crops do not overlap and allow sufficient time for seedbed preparation. In order to produce no rotations that are at risk of failing due to risky combination (e.g. timing or phytosanitary constraints), only sequences without limitations were considered.

Methods of the agronomic, economic and environmental assessment

Generated crop rotations are evaluated with the following indicators: i) gross margin ii) N-leaching, iii) N-efficiency (Neff), iv) N balance index (NBI) and v) N_2O emissions. Rotations generated were evaluated by calculating average values per ha per year for all assessment criteria. The average values can be used for relative comparisons between different rotations, e.g., comparing rotations with and without legumes.

Economic assessment

Gross margin is the main indicator for economic evaluation for both arable and forage crops. Equation (1) shows the calculation of the gross margin (GM) without labour costs and subsidies:

(1) $GM = R_{CPA} – C_{VAR}$

where R_{CPA} are the revenues calculated with equation (2) and C_{VAR} the total variable costs calculated with equation (3):

(2) $R_{CPA} = Y_{MP}P_{MP} + Y_{BP}P_{BP}$

(3) $C_{VAR} = C_{seed} + C_{fert} + C_{pest} + C_{irrig} + C_{MA} + C_{S}$

where Y_{MP} is the fresh matter yield (t/ha), P_{MP} the product price (€/t), Y_{BP} is the fresh matter yield of the by-product (t/ha), P_{BP} the price of the by-product (€/t). C_{seed} is the cost of seed (€/ha), C_{fert} the total cost of fertilisers (€/ha), C_{pest} the total costs of pesticides (€/ha) and C_{irrig} the costs of irrigation (€/ha), C_{MA} the variable costs of machinery (€/ha), C_{S} costs of other services (€/ha). Prices for forage crops were not available, since such crops are often used on-farm and economic assessments of forage crops require a farm-level analysis. Therefore, gross margins of the forage crops themselves were not taken into account in the rotational gross margins of forage rotations. Hence gross margins of arable rotations should not be directly compared with those of forage rotations, but comparisons within either of these classes is legitimate.

Assessment of nitrogen leaching, efficiency and balance

A modelling approach was developed for the N assessment based on ROTOR, a static and rule-based tool for evaluating crop rotations (Bachinger and Zander 2007). The functions in the N assessment module from ROTOR have been modified in order to assess conventional legume and non-legume supported farming systems. The algorithms of N mineralization, N fixation, Nitrate leaching and N balance have been modified to consider the effect of mineral and organic N fertiliser applications. The required input data for the nitrogen assessment is reported in Deliverable 4.2.

N-balance calculation: The N balance allows for the assessment of N removal, N_2 - fixation, and N losses through nitrate leaching, according to site characteristics and preceding crop category. According to Hege (1995), the sum of the atmospheric deposition and the non-symbiotic N_2 - fixation can be assumed to equal the denitrification losses and can therefore be excluded here. The annual N balance of each crop production activity (CPA) is calculated as:

(1) $$N_{balance} = (N_{fix} + N_m + N_s + N_{fert}) - (N_{remov} + N_{lea})$$

where $N_{balance}$ is the CPA-specific N balance (kg/ha of N), N_{fix} the N_2 - fixation of grain legumes as sole or intercrops and forage crops as sole crop calculated with equation (2) and of legume-grass mixtures calculated with equation (6), N_m the N in manure, N_s the N in seeds, N_{fert} the N in mineral fertiliser, N_{remov} the N removal of harvested products, N_{lea} the NO_3 -leaching calculated with equation (7).

N_2 - fixation calculation: N_2 - fixation is calculated specifically per crop, and varies depending on preceding crop, yield, the soil content of mineralised N from preceding crop residues in spring, and inputs from organic, plant-available N from manure and mineral fertiliser. Equation (2) is applied for sole-cropped grain and forage legumes and cereal-legume mixtures and equation (6) for legume-grass mixtures.

N_2 - fixation for sole crops and cereal-legume mixtures is calculated as (adapted from Hülsbergen and Biermann 1997):

(2) $$N_{fix} = Y_{CPA} * N_C * R_{NR} * R_{Nfix} * R_L$$

where Y_{CPA} is the CPA specific yield (t/ha), N_C indicates the N content of the harvested grain dry matter (%), R_{NR} the crop specific ratio of N in grain yield to N in crop and root residues, R_{Nfix} the ratio of symbiotically fixed N to total N, and R_L is the legume portion in the dry matter yield (in cereal-legume mixtures). R_{Nfix} depends on the soil content of mineralised N from preceding crop residues in spring, and on inputs from organic, plant-available N in manure and mineral fertiliser. We assumed that R_{Nfix} is a linear function of plant-available N in the soil (N_{soil}) which is defined by two related values:

(3) $R_{NfixMin} \rightarrow N_{soil} \geq 150$ kg N/ha

(4) $R_{NfixMax} \rightarrow N_{soil} < 30$ kg N/ha

R_{Nfix} for any given N_{soil} value between 30 and 150 kg is calculated by the function equation:

(5) $R_{Nfix} = R_{NfixMax} (a * N_{soil} + b)$

Where 'a' is the slope and 'b' the intercept of the linear function (Table 1).

Table 1: Maximum and minimum Ndfa (R_{Nfix}) values for selected crops (adapted from Peoples et al. 2009 and Palmason et al. 1992) and resulting slopes and intercepts of the linear equation.

Crop	$R_{NfixMax}$	$R_{NfixMin}$	a	b
Faba bean	0.92	0.60	-0.0029	1.0870
Common bean	0.68	0.38	-0.0047	1.1103
Pea	0.99	0.50	-0.0041	1.1237
Lupins	0.98	0.86	-0.0010	1.0306
Soy bean	0.95	0.60	-0.0031	1.0921
Pea/oat mixture	0.99	0.60	-0.0033	1.0985
Vetch/rye mixture	0.99	0.80	-0.0016	1.0480
Clover	0.95	0.70	-0.0022	1.0658
Alfalfa	0.95	0.70	-0.0022	1.0658

N_2 - fixation of legume-grass mixtures can be computed for different percentages of legumes in the dry matter of the gross yield according to Schmidt (1997) and Schmitt and Dewes (1997) as follows:

(6) $N_{fix} = (Y_{tot}\ R_L\ N_L\ R_{Nres}\ R_L N_{fix} + Y_{tot}\ (1 - R_{Lb})\ N_G\ R_{Gnfix})\ 10$

where Y_{tot} is the total dry matter yield without harvest losses at 5 cm cutting height (t/ha) (calculated as $Y_{tot} = Y_{CPA} R^{-1}_{Hloss}$ where R_{Hloss} is the ratio of harvest losses set to 0.65 for hay and 0.85 for silage crop). R_L is the legume portion in the dry matter yield, N_L the N content in legume dry matter [%], R_{Nres} the ratio of N in legume yield to N in stubble and root residues, R_{LNfix} the ratio of symbiotically fixed N to total N in legumes, N_G is the N content in grass yield, and R_{GNfix} is the ratio of fixed N transferred to grass ($R_{GNfix} = 0.25*R_L$).

Nitrate leaching calculation: NO_3 leaching is calculated as a function (adopted from Gäth and Wohlrab, 1992) of the soil leaching probability and N surplus:

(7) $N_{lea} = N_{surp}\ L_P$

where N_{surp} is the N surplus [kg/ha], calculated with equation (8), L_P the leaching probability during the winter months (mean winter precipitation divided by water holding capacity at rooting depth; LP values > 1 were set to 1):

(8) $N_{surp} = N_m + N_{fert} + N_{min} - N_{remov}$

where N_{min} is the cropping activity specific N mineralisation [kg/ha], calculated with equation (9).

As proposed by Bachinger and Zander (2007), mean nitrogen mineralisation was assumed to be a function of the total organic nitrogen content (N_{org}) modified by the pre-crop specific N supply level. The site-specific organic carbon content is assumed to be stable in agronomically suitable crop rotations with a well-balanced N supply:

(9) $N_{min} = N_{org}\ R_{mina}\ R_{minNL}\ R_{minC}$

where N_{org} is the organic N content [kg/ha] in the ploughing horizon (Ap) calculated with equation (10), R_{mina} the mean annual soil N mineralisation rate of N_{org}, R_{minNL} the coefficient of the preceding crop specific residual N level (coefficients taken from ROTOR), and R_{minC} is a coefficient to modify N_{min} depending on the crop and the associated soil tillage and irrigation intensity (i.e. 1.1 for grain legumes, 1 for all other crops and 1.5 for irrigated crops in Calabria).

(10) $N_{org} = R_{Corg}\ R^{-1}_{CN}\ BD\ D_{Ap}\ 10^5$

where R_{Corg} is the content of organic carbon in topsoil [%], R_{CN} the C/N ratio, BD is the bulk density, D_{Ap} the depth of ploughing horizon [cm].

This static assessment does not distinguish different pools of soil organic matter from which N is mineralized or between organic and inorganic N residues (Bachinger and Zander 2007). However, the coefficient R_{minNL} takes the different N pools indirectly into account for the different residual N levels.

N assessment at rotational level: To ensure a sufficient N supply on the level of crop rotations, the contribution of each cropping activity to the overall N balance of a full rotation was assessed.

The N balance in relation to the total N input (NBI) of full rotations was calculated as:

(11) $NBI = sumN_{balance} / sum(N_{fix} + N_m + N_s + N_{fert})$

The nitrogen utilization rate is used as an indicator for the N efficiency (Neff) of the N output in relation to the N input of organic and mineral N fertiliser and N in seed was calculated as:

(12) $Neff = sumN_{remov} / sum(N_m + N_s + N_{fert})$

Assessment of nitrous oxide emissions

The soil-based N_2O emissions from crop cultivation are calculated with the IPCC 2006 Tier 1 methodology (Paustian et al. 2006). They include direct and indirect N_2O emissions from synthetic N applied, manure N applied and N from crop residues, and do not include emissions from manure deposited during grazing, emissions from N mineralization or organic soils. Consistent with the IPCC 2006 guidelines, the N_2O emission from biological N-fixation is assumed to be zero. Standard IPCC 2006 emission factors have been used. The average annual N_2O emission of each rotation is calculated as the mean of the annual emissions from each year of the rotation.

The total of the N_2O emissions of the rotation is calculated according to IPCC guideline 2006, chapter 11:

$$N20\ total_{emission_{rotation}} = N20\ indirect_{emission_{rotation}} + N20\ direct_{emission_{rotation}}$$

The direct $N_2 0$ emissions were calculated by the following equation:

$$N20\ direct_{emission_{rotation}} = \sum_{i=0}^{ncrop} \left(\left(Fsn_{crop} + Fon_{crop} + Fcr_{crop} \right) \times 0.01 \right) \times \left(\frac{44}{28} \right)$$

Where

Fsn = annual amount of synthetic fertiliser N applied to soils, $kg.N.yr^{-1}$

Fon = annual amount of animal manure N additions applied to soils $kg.N.yr^{-1}$

Fcr = annual amount of N in crop residues (above-ground and below-ground), including N-fixing crops, and from forage/pasture renewal, returned to soils, $kg.N.yr^{-1}$

$$Fcr = \sum (crop * Cf \times Fracrenew * (Rag - Nag \times (1 - Fracremove) + (Rbg * Nbg)))$$

Crop = harvested annual dry matter yield for crop, kg/ha

Cf = combustion factor

Fracrenew = fraction of total area under crop that is renewed annually

Rag = ratio of above-ground residues dry matter (AGDM) to harvested yield for crop (Crop), kg/kg

Nag= N content of above-ground residues for crop, kg/kg

FracRemove = fraction of above-ground N residues of crop removed annually for purposes such as feed, bedding and construction, kg/kg

Rbg = ratio of below-ground residues to harvested yield for crop, kg/kg

Nbg = N content of below-ground residues for crop, kg/kg

Indirect $N_2 0$ emissions were calculated according to the following formula:

$$\mathrm{N20\ indirect}_{emission_{rotation}} = \sum_{i=0}^{ncrop} \mathrm{N20adt}_{crop_i} + N20L_{crop_i}$$

Where

$N_2 0$adt from atmospheric deposition of N volatilised from managed soils

$N_2 0_{(ATD)}$–N = annual amount of N_2O –N produced from atmospheric deposition of N volatilised from managed soils, kg/yr

$$\mathrm{N20adt}_{crop} = \left((Fsn * 0.1 + Fon * 0.2) * 0.01\right) * \left(\frac{44}{28}\right)$$

$N_2 0$L from N leaching/runoff from managed soils in regions where leaching/runoff occurs

$N_2O_{(L)}$–N = annual amount of N_2O –N produced from leaching and runoff of N additions to managed soils in regions where leaching/runoff occurs, kg/yr

$$\mathrm{N20L}_{crop} = \left((Fsn + Fon) * 0.3\right) * 0.0075 * \left(\frac{44}{28}\right)$$

Application of the assessment in five test cases across Europe

Test cases

The test cases were well distributed across the agro-climatic zones in Europe (Table 2) with contrasting bio-physical and socio-economic conditions. In each test case, one research institution was involved to provide in depth knowledge and data and give insights into practical limitations of legume cultivation.

Table 2: Stratification of selected test cases across Europe

Agro-climatic zone	Country, region	NUTS code	Research institute	No. of site classes	Area covered
Nemoral	Sweden, Västra Götaland	SE23	SLU	1	50%
Atlantic	Scotland, Eastern	UKM2	SRUC	4	66%
Continental North	Germany, Brandenburg	DE41, DE42	ZALF	5	99%
Continental South	Romania, Sud-Muntenia	RO31	NARDI	1	42%
Mediterranean	Italy, Calabria	ITF6	UDM	3	58%

Within each case study region, 1 to 5 site classes were identified to capture the heterogeneity of bio-physical and socio-economic conditions within the regions as explained in more detail in Deliverable 4.2. For this report the following site classes were selected as examples (Table 3).

Table 3: Selected site classes within the test cases across Europe (for this report)

Country, region	Site class	Soil type	% of total region
Germany, Brandenburg	LBG3 and LBG4[1]	Sandy clay loam and sandy loam	63
Italy, Calabria	rainfed	Loam	36
Romania, Sud-Muntenia	Chernozem	Chernozem	42
Scotland, Eastern	Grade 3	Cauldside/Whitsome/Darvel/Hobkirk	40
Sweden, Västra Götaland	clay soil	Silty clay loam	50

[1] LBG3 for arable and LBG4 for forage rotations

Data source

In each of the five test cases a structured survey was conducted in the years 2012-2013 to obtain crop production data on pre-crop and site specific crop management and crop rotation rules. The data was collected for all common non-legume crops and agronomical suitable legumes. Statistical data from official statistics was the basis of information and has been complemented by expert knowledge. Two-four experts were consulted in each region and each one had >5 years of experience in applied agronomy with special competence in legume cropping systems and crop rotations.

A special emphasis of the survey was on the pre-crop effects of all crops that affect the management activity of the subsequent crop. Considered pre-crop effects were the effect on yield, fertilisation and the effect on agro-chemical applications. Such information was not available from official statistics and therefore derived from other sources that included primary data from long-term field experiments (including unpublished data), scientific literature and expert knowledge.

The limited available information on legume crop management and pre-crop effects was the greatest challenge for the data collection and presents some uncertainty of this data. However, this information is extremely important in assessing the multiple ecological and economic services of legume crops. Therefore, the collected information was checked for plausibility against available scientific literature.

Guidance for agronomists

The rotations generated in this way were compiled into spreadsheets. Graphs were plotted showing N leaching potential, N_2O emission potential, N balance index, and N efficiency against gross margin, separately for arable and forage emissions. They were then asked the following list of questions, with some explanations of what we sought.

- What is the rotation giving the best Gross Margin?
- Does it resemble the most common (or a common) rotation used in the test region?
- If there are several (up to 5) contenders for "best", you can discuss them as well.
- What are the top legume-containing rotations? (up to 5)
- How much of a sacrifice in Gross Margin is required for them?
- Are they otherwise feasible?
- Do you see any particular strengths or weaknesses or peculiarities in them?
- How much benefit of N leaching potential is achieved by making the step from the highest gross margin non-legume rotation to a suitable (in your eyes as an agronomist) high-gross-margin legume-containing rotation?
- Are there any benefits to N leaching potential from choosing rotations (either non-legume or legume-containing) with just slightly lower N leaching potential?
- Can you put a monetary value on the reduction in N leaching potential, on-farm or beyond the farm gate?
- How do our best –legume and +legume rotations look?
- Which aspects of NBI are most relevant in your region?
- Does this alter the choice of the "best" legume-containing rotation, and if so, how?
- What rotations make particularly good use of N inputs by having high Neff figures?
- Does this alter the choice of the "best" legume-containing rotation, and if so, how?
- What are the benefits to N_2O potential of having a legume-containing rotation instead of a non-legume rotation (keeping in mind that we are necessarily looking at the best of the gross margins)?
- Are there any cases where a tiny sacrifice in gross margin would make a major difference in N_2O potential?
- Is there a rotation that captures most or all of the potential benefits?
- Please summarize the results so far, and attempt to balance them if different rotations offer different benefits.

- Are the potential N savings from using a legume crop large enough to be significant for the farmer? for the environment?
- What else limits legume use, beside gross margin? Is it market opportunities?
- Lack of germplasm sufficiently well adapted to the climate or growing conditions?
- (Lack of) local knowledge about how to grow them?
- What are the known risks or uncertainties involved in the legume crops that figure in your rotations?
- What else is needed to get the legume-supported rotations into use? Is support required for protein production as well as nitrogen mitigation?
- Do you think that the rotation generator has generated all the possible rotations for your region? Are there any obviously missing rotations? Do you see the top-valued rotations as agronomically feasible?
- Please rank the rotations in terms of practicality, relevance and feasibility, based on the overall analysis, and comment on these aspects.

The agronomists returned their evaluations to the task coordinator.

Results and Discussion

The rotation generator produced up to 24000 possible arable rotations for each site, and comparable numbers of possible forage rotations. Gross margins of arable rotations ranged from 130 €/ha in Brandenburg (soil class LBG2) to 890 €/ha in Scotland. The gross margins of the forage rotations were calculated on a different basis from those of the arable rotations, so the reader should not compare between forage and arable rotations. The agronomists' own reports are in Appendices 1-5, and an overview is presented below.

Gross margins

In Romania, adding common bean to the rotation had a huge effect on annual gross margins, adding 400€/ha over the comparable non-legume rotation, because of the high value of this food crop (Table 4). The best soya rotation also added 86€ over the best non-legume, and the best pea rotation about 20€ more. In Scotland, replacing one cereal with faba bean added 45€/ha to the best non-legume rotation with tubers and root crops, and 57€/ha to the best non-legume rotation without tubers or root crops. In Calabria, adding white lupin to the irrigated highland rotation added 160€/ha to the 540€/ha of the non-legume rotation, but adding faba bean to the rainfed arable rotation reduced the gross margin by 34€/ha.

Table 4. Optimum arable rotations for the 5 test sites across Europe (see Table 3) according to gross margin, their N leaching potential and nitrous oxide emission potential.

Region	Non-legume Rotation	Gross margin (€)	N leaching (kg/ha)	N_2O (kg/ha)	Legume rotation	Gross margin change	Leaching change	N_2O change
Romania	W rape maize w wheat	432	13	3.5	Bean maize w wheat w rape	+418	-2	-0.7
Romania	W rape maize w wheat	432	13	3.5	Soya bean maize w wheat w rape	+86	+1	-0.7
Scotland "best"	Potato w wheat w oat swede s barley w oat	844	41	5.3	Potato w wheat w oat swede s wheat faba bean	+45	0	-0.1
Scotland "likely" without tubers or roots	W rape w barley w oat s barley w barley	490	46	5.2	W rape w barley w oat faba bean w barley	+57	-10	-0.6
Italy irrigated highland	Potato w rape w wheat w rape w wheat	549	61	2.4	Potato lupin w rape lupin w wheat	+160	+20	-0.3
Italy rainfed	W rape w wheat w rape w wheat	267	12	2.0	W rape w wheat w rape w wheat faba bean	-34	+2	-0.4
Sweden	W rape w wheat linseed w wheat s barley	644	34	3.7	W rape w wheat faba bean w wheat s barley	-51	0	-1.3
Germany	W rape w wheat s barley	130	28	4.7	W rape w wheat w rye w rye pea	-19	-8	-1.2

s = spring-sown crop, w = winter (autumn-sown) crop.

In Sweden, however, the best arable legume-supported rotation, with faba bean, lost 51€/ha from the equivalent non-legume rotation (644 €/ha). Similarly, in Brandenburg, the arable rotation lost value when a legume was added (19€/ha from 130€/ha).

Substituting grass-clover for grass in Scotland added only 5€/ha to the gross margin of 563€/ha (Table 5). Using oat-vetch as a forage instead of winter barley in Calabria added over 1000 €/ha to the 335 €/ha of the non-legume rotation, thus a 4-fold improvement in value. This valuation needs to be checked. The best forage rotation in Sweden, with grass-clover instead of grass, added 34€/ha to the basis 860€/ha and the best in Germany added 60€/ha to the very low return of 90€/ha.

Thus, in all four forage rotations, legumes added to the gross margin, but the same applied in only 5 of the 8 arable systems.

Table 5. Optimum forage rotations for the 4 test sites across Europe (see Table 3) according to gross margin, their N leaching potential and nitrous oxide emission potential. Forage rotations were not generated for Romania.

Region	Non-legume Rotation	Gross margin (€)	N leaching (kg/ha)	N_2O (kg/ha)	Legume rotation	Gross margin change	Leaching change	N_2O change
Scotland	Grass grass grass w oat s oat	563	33	9.2	grass-clover grass-clover grass-clover w oat s oat	+5	-5	-2.0
Germany	w rape w rye sil maize sil maize s barley	22	39	5.4	grass-clover grass-clover w rye s barley w rape w rye	+120	-17	-2.6
Italy rainfed	W rape w barley w rape w barley	335	7	1.7	W rape oat-vetch w rape oat-vetch	+1008	-7	+1.8
Sweden	Pea-oat grass grass grass w rape w wheat	860	15	6.4	Pea-oat grass-clover grass-clover grass-clover w rape w wheat	+34	0	-0.9

sil = silage, s = spring-sown crop, w = winter (autumn-sown) crop

N leaching potential

Nitrogen leaching potentials varied widely between sites, not surprisingly, and the effects of legumes were relatively small but generally towards reduced leaching. In Romania, there was little effect of legumes, and the potential was generally 9-12 kg/ha. In Scotland, adding a legume had little effect on N leaching from the best arable legume rotation including potato, but reduced the N leaching potential by nearly a quarter in the potato-free rotation. Similarly, the best legume-supported forage rotation leached about 5 kg less than the non-legume rotation. In Calabrian irrigated highlands, there was a positive correlation of gross margin with N leaching potential, and adding legumes added to leaching potential in each cluster of similar rotations. In the rainfed lowlands of Calabria, however, the best gross margin was found together with the lowest leaching potential in the legume-supported rotation. In Sweden, adding legumes to both arable and forage rotations reduced N leaching potential by about 5%. In Brandenburg, adding the legume to the arable rotation reduced leaching since it replaced high-leaching oilseed rape, and adding the legume to the forage rotation reduced leaching potential by about half.

Thus, in several cases, legumes added environmental benefits by reducing N leaching potential, and this was associated with an increase in gross margin. In Romania, there was no consistent effect on leaching and in Calabrian highlands, legumes led to increased leaching potential. In the Brandenburg arable rotation, the effect on N leaching potential was countered by the large loss in gross margin.

Nitrous oxide emission potential

In all of the arable rotations and all but one of the forage rotations, the inclusion of a legume resulted in a slight reduction in the N_2O emission potential, and even within legume-supported rotations there were interesting patterns. In Romania, the common bean rotation with the highest gross margin had the lowest N_2O emission potential. The same applied in the soya bean rotations. Only the low-value rotations showed no difference plus or minus legume. The agronomist noted that sunflower rotations, important in the region, had about 0.5 kg/ha less N_2O emission potential with legumes than without. In Scotland, there was a slight reduction in N_2O potential with legumes in the arable rotations and a clear reduction in the forage rotations. In Calabrian irrigated highlands, the lowest N_2O emission potential was in the best arable legume rotation, and in the rainfed lowlands, a slight reduction in gross margin was necessary to lower N_2O emissions. In the arable rotations of Brandenburg, there was a general positive correlation of N_2O emissions with gross margin, but a considerable spread, so the top legume rotation by gross margin had 1 kg less N_2O emission potential than the top non-legume rotation. In the forage rotations, legumes led to a marginal decrease in N_2O emissions. In Sweden, legumes reduced N_2O emission potential by 0.5 kg/ha in arable rotations and 1.0 kg/ha in forage rotations.

Other measures of environmental impact

The nitrogen balance index and nitrogen efficiency were generally improved in the legume-supported rotations over the values found in the non-legume rotations.

Other aspects of the expert evaluation of rotations

Although the experts themselves provided the "rules" for the rotation generator, such as inappropriate crop sequences, and although they had some weeks to examine the outputs, it was only when they had to write something that they noticed some peculiarities. The agronomists also demonstrated valuable insights in other ways, such as by noting that a rotation below the most profitable might be more acceptable for one reason or another.

The Scottish agronomist found it unreasonable that all of the generated rotations contained potato. They were all 6-year rotations, the rotation interval for this high-value crop, but it was seen unrealistic that all farms would grow potato. Hence a second round of rotation generation was necessary, and for this to succeed, another rule had to be relaxed, that the maximum use of cereals could be 80% instead of the previous 75% in a 5-year rotation. His expertise led him to question following grass with oilseed rape, and the frequency of oat in several of the high-value rotations. He found that the 10th best arable legume rotation, in gross margin terms, was potentially more reliable than the nine better ones by avoiding risky sequences such as winter oilseed rape after winter wheat (at a cost of 36 €/ha), and was still more profitable than the best non-legume rotation.

Similarly, the Romanian agronomist questioned the suitability of grain maize before winter wheat or winter barley, a feature of the highest gross-margin non-legume rotations, since maize can still be ripening at the time when the winter cereal should be sown. The current importance of sunflower in his region caused him to watch for the continued presence of that crop in the rotations, and he found that it was often outside the top 10 gross-margin rotations.

In both Calabria and Brandenburg, the non-legume rotations with the highest gross margins were considered by the experts to be the same as the most widespread rotations in the regions.

Conclusions

The exercise of generating rotations has turned out to be valuable. Opportunities to include legumes in rotations have been highlighted and their environmental and economic impacts have been assessed and are, in general, positive. The exercise has, furthermore, demonstrated that a mechanical assessment of the generated rotations is not enough: the eye of the expert is necessary to determine what is reasonable and what is not, and to feed back possibilities for further refinement of the guidelines for generating rotations.

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ANNEX 1. Eastern Scotland

Gross Margin (GM) comparisons

Non-legume rotations

The non-legume arable orientated rotation generated by the model that provided the greatest average GM (Euro 843.72 / ha) across the rotation was found to be potato > wheat > woat > swedes > sbarley > woat. This rotation would be very unusual for the region, where most arable cropping tends to be cereal dominated with sbarley the main crop with some wbarley, wwheat or wosr as a break crop. Potatoes are usually grown on a relatively small area by specialist growers, particularly on land Class 3 used as the default in the model. Swedes are also a relatively minor crop, usually grown for livestock feed, although some are grown for human consumption. However, the generator has also been used to provide rotations that do not include potatoes which is more representative of for the majority of the region.

The non-legume arable orientated rotation generated by the model with the second highest average GM (Euro 824.73 / ha) is perhaps a little more representative of some of the key arable areas within the region, given earlier caveats about the potatoes. This rotation consisted of potato > wwheat > wbarley > wbarley > wbarley > wosr. There may be a few concerns about a high value crop such as potatoes following wosr especially in terms of soilborne plant pathogens, but it has some potential.

The non-legume forage orientated rotation generated by the model that provided the greatest average GM (Euro 562.60 / ha) across the rotation was found to be grass > grass > grass > woat > soat. This rotation would be quite unusual for the region as oats are a fairly minor crop, but it certainly has potential. The next four rotations with the highest GM were as follows:

GM placing	Crop 1	Crop 2	Crop 3	Crop 4	Crop 5	Average GM (€ / ha)
2	grass	grass	grass	wrape	swheat	541.00
3	grass	grass	grass	wrape	soat	522.90
4	grass	grass	grass	woat	sbarley	496.00
5	grass	grass	grass	wrape	sbarley	492.50

All of these rotations are plausible, although it would be fairly unusual in the region to grow wosr after grass. Swheat is a minor crop and oats are also relatively minor crops, especially the winter sown type.

Legume rotations

The legume-containing arable orientated rotation that contained potatoes generated by the model that provided the greatest average GM (Euro 888.76 / ha) across the rotation was found to be potato > wwheat > woat > swedes > swheat > fababean. This is approximately Euro 45 (5.3%) more than the best average GM from the non-legume arable orientated rotation that contained potatoes. However, as with the non-legume arable orientated rotation, this legume containing one includes a number of crops that are either specialist, and therefore grown on relatively small areas (e.g. potatoes), or the rotational shifts are possible in good seasons (e.g. wosr after wwheat), but may create problems with timing in poor ones and therefore in reality tend to be avoided to reduce the risk. The highest GM (Euro 547.48 / ha) for a non-potato legume-containing orientated rotation that was generated by the model was wrape > wbarley > woat > faba bean > wbarley. This is perhaps more representative of the type of rotation that might be grown in the area, although there are still some caveats. For example, as previously noted, woat is still a relatively minor crop, as is faba bean, although one aim of this project is to highlight the potential for more legume / home grown protein inclusion in rotations for the region. This rotation generated around Euro 300 / ha less than the rotations containing potatoes, with the difference in GM primarily being related to the exclusion of potato crops. Spring barley is by far the most common cereal in the region, as it has some flexibility in sowing, particularly when ground conditions and weather are unfavourable to drilling, or overwintering, an autumn sown cereal crop. These points provide some evidence of the risk averse nature of many farmers. There are also potential premiums for malting barley which can be sold relatively close to where it is produced, and this may also influence the decision making on which cereal crop to grow.

The legume-containing forage orientated rotation generated by the model that provided the greatest average GM (Euro 567.60 / ha) across the rotation was found to be grassclover > grassclover > grassclover > woat > soat. This is only Euro 5 (0.9%) more than the highest average GM non-legume forage orientated rotation generated by the model. As with the non-legume forage orientated rotation, the cereals allocated would be quite unusual for the region as oats are a fairly minor crop, especially the winter type, but it certainly has potential.

It is interesting to note that in many cases, the higher GMs actually belong to the legume based rotations for both arable and forage orientated rotations generated by the model. Those rotations including potatoes, swedes or oats (winter or spring) also tend to be towards the upper end of the GM scale, irrespective of the inclusion of legumes in the rotation or not. As highlighted previously, both potatoes and swedes are specialist crops and tend to be grown on relatively small areas due to the economic risk associated with them, either through seasonal weather or price fluctuation, and may be a reason why rotations with a lower GM may be more common in this region.

Environmental indicators compared with GM

N Leaching

The N-leaching potential across the model generated rotations for arable orientated rotations with and without legumes is compared against the GM data in Fig 1.

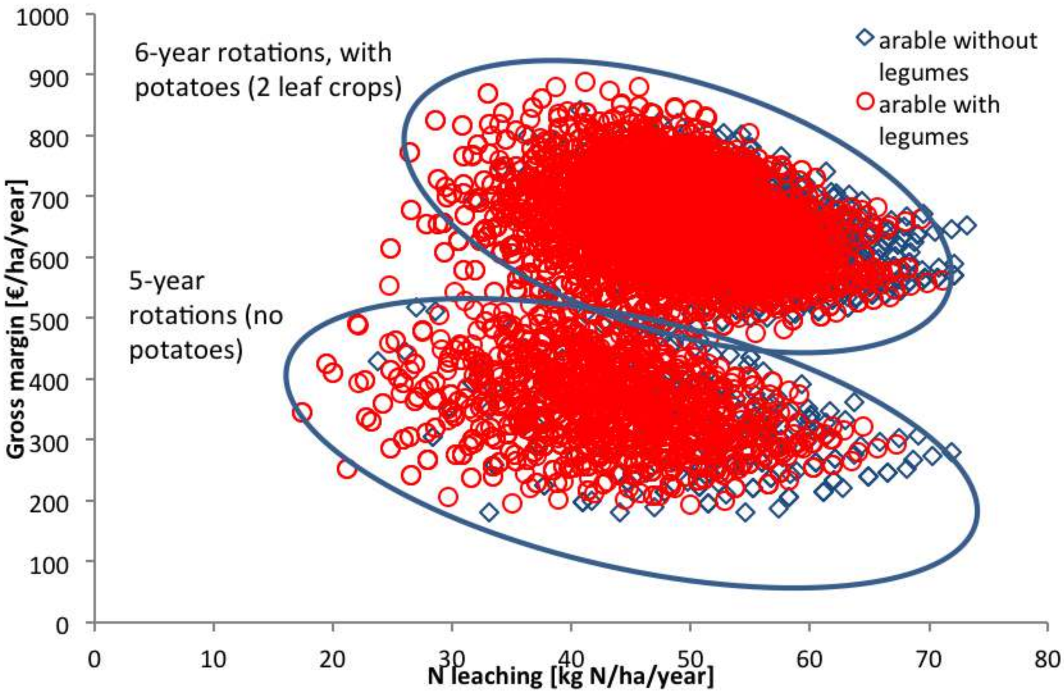


Figure 1: N leaching potential across the model generated rotations against GM calculated for arable orientated rotations with (red circles) and without (blue diamonds) legumes.

There is a tendency for the model generated arable orientated legume-containing rotations to have both lower N leaching potential and in the majority of cases a lower GM than their non-legume counterparts. The highest GM arable orientated non-legume rotation generated by the model produced a rotational average of 40.75 kg leachable N / ha for Euro 843.7 / ha. This compares to a rotational average of 41.12 kg leachable N / ha for Euro 888.7 / ha for the highest GM legume-containing arable orientated rotation. In this comparison, the legume-containing rotation produced an average of 0.37 kg more leachable N / ha for an economic gain of Euro 45 / ha. If potatoes are excluded from the rotations, the highest GM for a legume containing rotation is Euro 547 / ha, but producing only around 35 kg leachable N / ha, and for a non-legume containing rotation (swedes > sbarley > wbarley > wbarley > woat), the GM is Euro 512.5 / ha with 28.6 kg leachable N / ha.

When considering some of the slightly more likely rotations for the region generated by the model, the second highest GM from the non-legume arable orientated rotation produced 47.4 kg leachable N / ha for Euro 824.7 / ha compared to 44.19 kg leachable N / ha for Euro 852.37 / ha for the legume-containing counterpart (10th best GM in this case). In this comparison, the legume-containing rotation produced an average of 3.21 kg less leachable N / ha for an economic gain of Euro 27.67 / ha.

The N-leaching potential across the model generated rotations for forage orientated rotations with and without legumes is compared against the GM data in Fig 2.

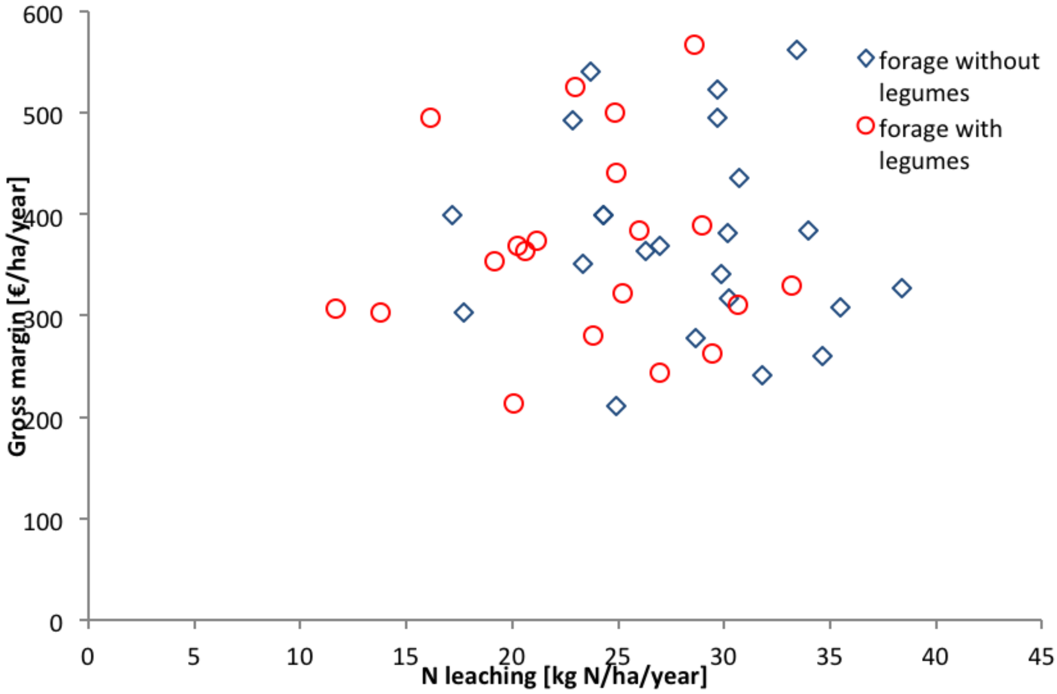


Figure 2: N leaching potential across the model generated rotations against GM calculated for forage orientated rotations with (red circles) and without (blue diamonds) legumes.

There is a tendency for the model generated forage orientated legume-containing rotations to have lower N leaching potential but a very slightly reduced average rotational GM to their non-legume counterparts. The highest GM forage orientated non-legume rotation generated by the model produced a rotational average of 33.43 kg leachable N / ha for Euro 562.60 / ha. This compares to a rotational average of 28.59 kg leachable N / ha for Euro 567.60 / ha for the highest GM legume-containing forage orientated rotation. In this comparison, the legume-containing rotation produced an average of 4.84 kg less leachable N / ha for an economic gain of Euro 5 / ha.

When looking at the average leachable N compared to their GMs for the top five rotational scenarios generated by the model, the non-legume forage orientated rotations produced 29.13 kg leachable N / ha for Euro 530.63 / ha compared to 23.15 kg leachable N / ha for Euro 522.25 / ha for the legume containing forage orientated rotations which equates to

5.98 kg less leachable N / ha at a loss of Euro 8.38 / ha across the legume containing rotation compared to the non-legume one.

N Balance Index (NBI)

The NBI measures (inputs – outputs) / inputs, and if the value is outside the range of + / - 0.1, the system is considered out of balance. The NBI data across the model generated rotations for arable orientated rotations with and without legumes is compared against the GM data in Fig 3.

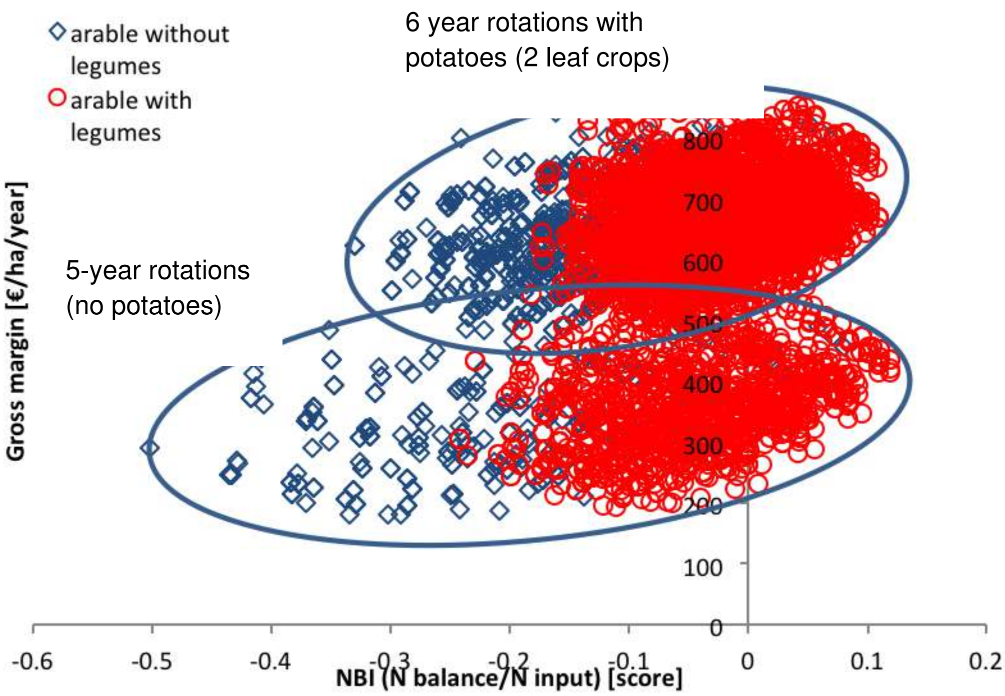


Figure 3: NBI estimated across the model generated rotations against GM calculated for arable orientated rotations with (red circles) and without (blue diamonds) legumes.

The model generated arable orientated rotations without legumes appear to have a greater proportion of NBI’s below -0.1 than their legume-containing counterparts suggesting that soil organic matter is being exported from the system. However, there are still plenty of arable orientated rotations that contain legumes that also show a tendency to lose soil organic matter, and the GM from these rotations is arguably lower than the non-legume arable orientated rotations with similar NBI balances. Overall, the legume-containing arable orientated rotations are probably more in balance than those arable rotations not containing legumes and very few of the model generated arable orientated rotations, both with and without legumes, show a positive NBI in excess of +0.1 where soil organic matter is increasing.

The highest GM arable orientated non-legume rotation generated by the model produced a rotational average NBI of -0.161 for Euro 843.7 / ha. This compares to a rotational average NBI of -0.028 for Euro 888.7 / ha for the highest GM legume-containing arable orientated rotation. In this comparison, the legume-containing rotation was in balance, whereas the non-legume containing rotation was losing soil organic matter.

When considering some of the slightly more likely rotations for the region generated by the model, the second highest GM from the non-legume arable orientated rotation produced an NBI of +0.052 for Euro 824.7 / ha compared to an NBI of +0.041 for Euro 852.37 / ha for the legume-containing counterpart (10th best GM in this case). These can both be regarded as in balance, although both rotations have the potential to provide a very slight increase in soil organic matter.

The NBI estimated across the model generated rotations for forage orientated rotations with and without legumes is compared against the GM data in Fig 4.

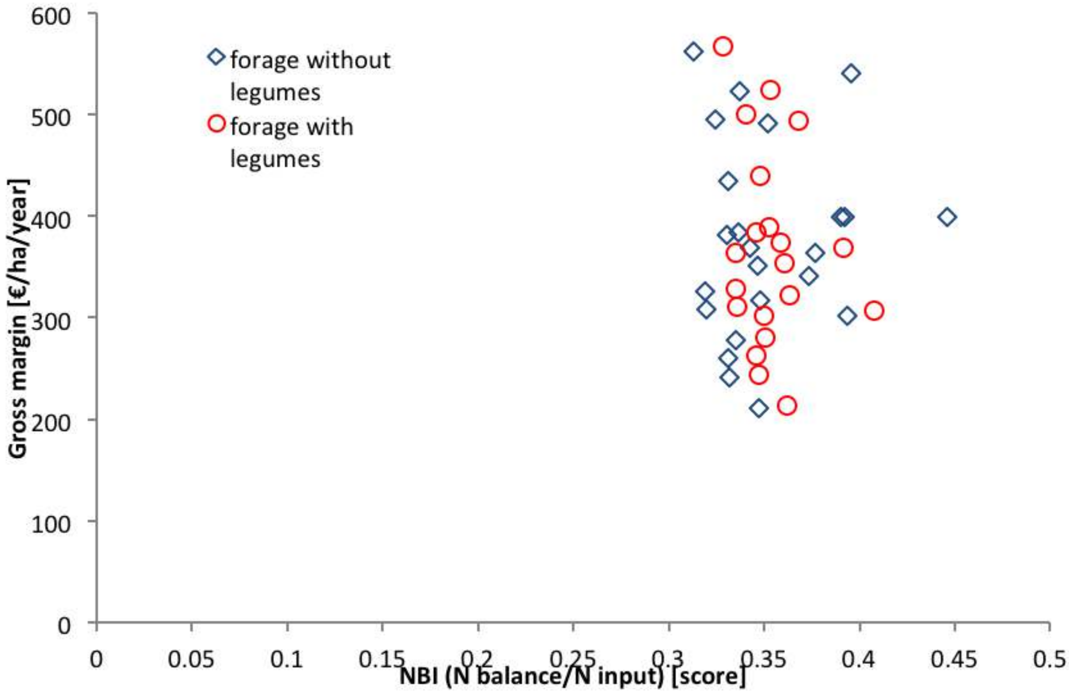


Figure 4: NBI estimated across the model generated rotations against GM calculated for forage orientated rotations with (red circles) and without (blue diamonds) legumes.

All of the forage orientated rotations, with and without legumes, had strong positive NBI scores, which mirrored convention. There appeared to be no clear differences showing when comparing these to their GM values. Arguably, the rotations which were legume based had marginally greater NBI scores overall than the non-legume rotations.

Coefficient of N Performance (Neff)

Neff is the ratio of N output to N input, and a high Neff score indicates that a rotation is making good use of the N that is being applied (e.g. mineral N fertiliser, bulky organic manures such as FYM, or seed). The Neff data from the model generated rotations for arable orientated rotations with and without legumes is compared against the GM data in Fig 5.

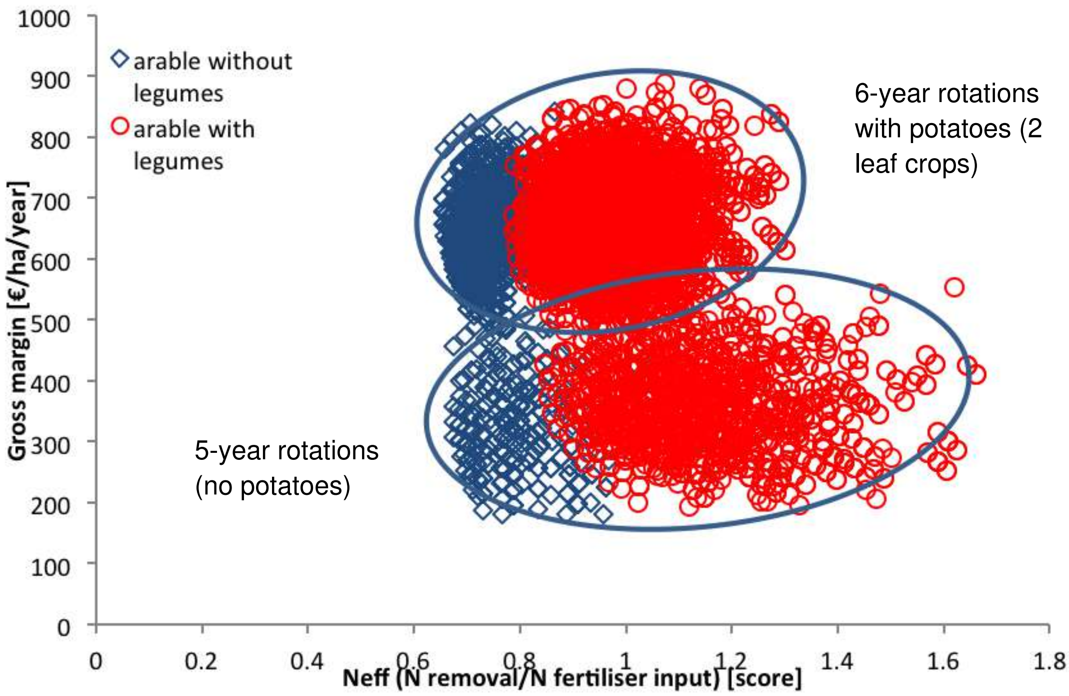


Figure 5: Neff calculated across the model generated rotations against GM calculated for arable orientated rotations with (red circles) and without (blue diamonds) legumes.

Clearly, more of the model generated arable rotations with legumes included were more efficient users of N inputs than the arable orientated rotations that didn't include legumes, as Neff values over 1.0 indicate more N being harvested than being added to the system through managed inputs, whereas a Neff value less than 1.0 indicates not all of the applied N is recovered in the harvested materials. All of the arable orientated rotations that had no legume component had Neff values of less than 1.0, whereas a large proportion of those rotations that did include legumes had Neff values greater than 1.0, some as high as 1.49 (fababean > sbarley > woat > swedes > sbarley > woat) which indicates that averaged across this rotation, around 1.5 kg N / ha is harvested for every 1 kg N / ha applied. Many of the legume-containing arable rotations with positive Neff scores also had GM towards the upper end of the GM scale (Euro 700-800). The inclusion of potatoes by the model rotation generator in every single non-legume arable orientated rotation may be influential in the poor performance of these rotations against this environmental indicator. The reason for highlighting this is that when the Neff values of the model generated legume-containing arable orientated rotations were considered, by far the greatest proportion of rotations with a Neff score greater than 1.0 did not include potatoes, I whereas the majority of rotations with a Neff score below 1.0 did contain potatoes.

The Neff estimated across the model generated rotations for forage orientated rotations with and without legumes is compared against the GM data in Fig 6. All of the forage orientated rotations, with and without legumes, had Neff scores below 1.0 when averaged across the rotation, although those without legumes were significantly lower at around 0.55 compared to 0.85 for those rotations including legumes. There was little variation around these values irrespective of the average GM calculated across each of the rotations.

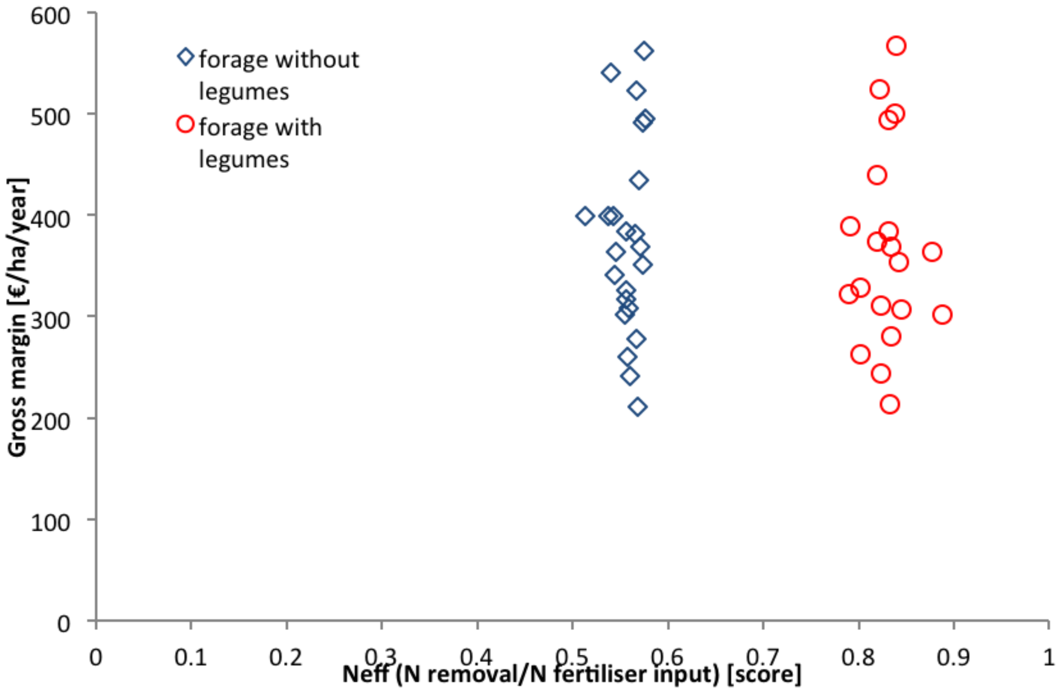


Figure 6: Neff values estimated across the model generated rotations against GM calculated for forage orientated rotations with (red circles) and without (blue diamonds) legumes

Nitrous Oxide (N_2O) Emission Potential

The N_2O emission potential across the model generated arable orientated rotations with and without legumes is compared against the GM data in Fig 7. The estimated N_2O emissions range from just under 3 kg N_2O / ha / yr to just over 7 kg N_2O / ha / yr averaged across the rotation. The model generated rotations with no legume component are all towards the upper range of N_2O emissions, whereas for an equivalent GM, the rotations that include legumes produce lower N_2O emissions. The highest GM performing legume containing arable orientated rotation (Euro 888.7) produced 5.25 kg N_2O / ha / yr compared to the highest performing non-legume containing arable orientated rotation (Euro 843.7) produced 5.33 kg N_2O / ha / yr. In this comparison, the inclusion of legumes in the rotation gained an estimated Euro 45 without increasing N_2O emissions, in fact there was estimated to be a marginal reduction.

When what might be considered the slightly more typical arable orientated rotations for the region were compared, the non-legume containing model generated rotation (2nd highest GM) averaged 6.64 kg N_2O / ha / yr compared to 5.45 kg N_2O / ha / yr for the legume containing rotation (10th highest GM). In this case, there was an over 1 kg N_2O / ha / yr reduction from the inclusion of legumes, in addition to a Euro 27.67 benefit.

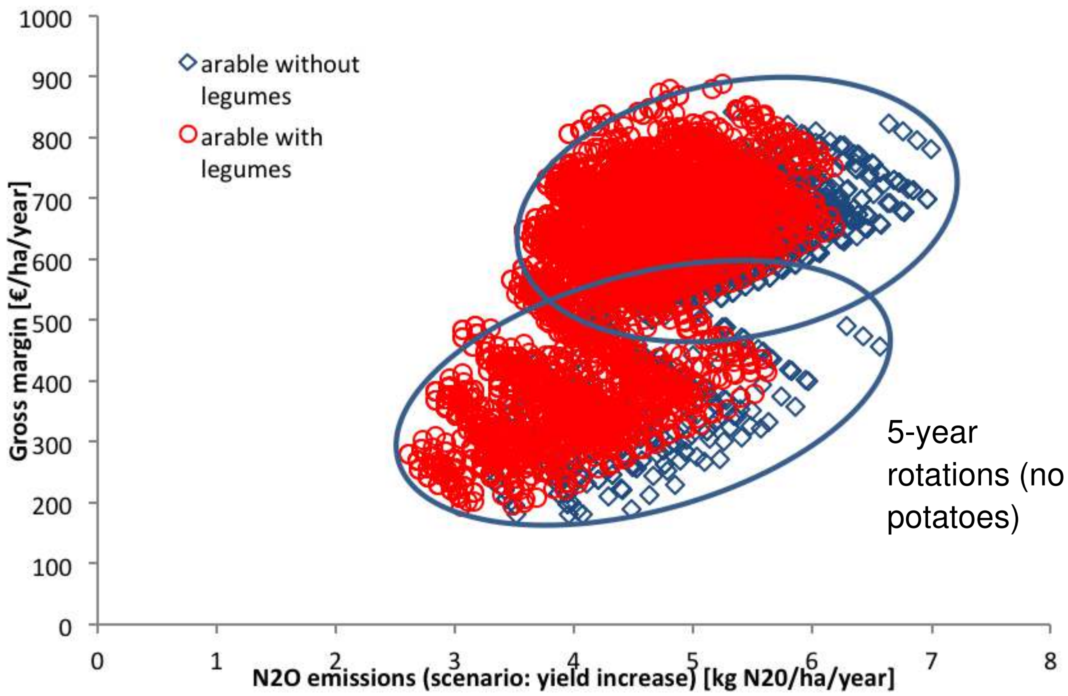


Figure 7: N_2O potential estimated across the model generated rotations against GM calculated for arable orientated rotations with (red circles) and without (blue diamonds) legumes

The average annual N_2O emissions from the model generated forage based rotations were generally estimated to be higher, at between 7 and 12 kg N_2O / ha / yr than those from the arable based rotations, the majority of which were emitting less than around 7 kg N_2O / ha / yr. Figure 8 highlights this, as well as confirming that the forage orientated rotations with legumes were clearly producing less N_2O than those without legumes.

The model generated legume–containing forage orientated rotation with the highest GM (Euro 567.60) produced 7.2 N_2O / ha / yr, whereas the non-legume forage orientated rotation with the highest GM (Euro 562.60) produced 9.25 kg N_2O / ha / yr, i.e. over 2 kg more N_2O / ha while also having a slightly lower estimated GM.

From the rotation data generated by the model, it is clear that a number of the rotations either with or without legumes towards the upper end of the GM scale would be unusual in the region of Eastern Scotland. The inclusion of potatoes in many of the rotations, and to a lesser extent swedes, has a tendency to skew the results, because as stated previously, these are specialist crops that can have a high degree of risk associated with them and therefore are grown on a limited area on which the farmer is prepared to take the risk of a poor season (either due to the weather, disease or market changes for example).

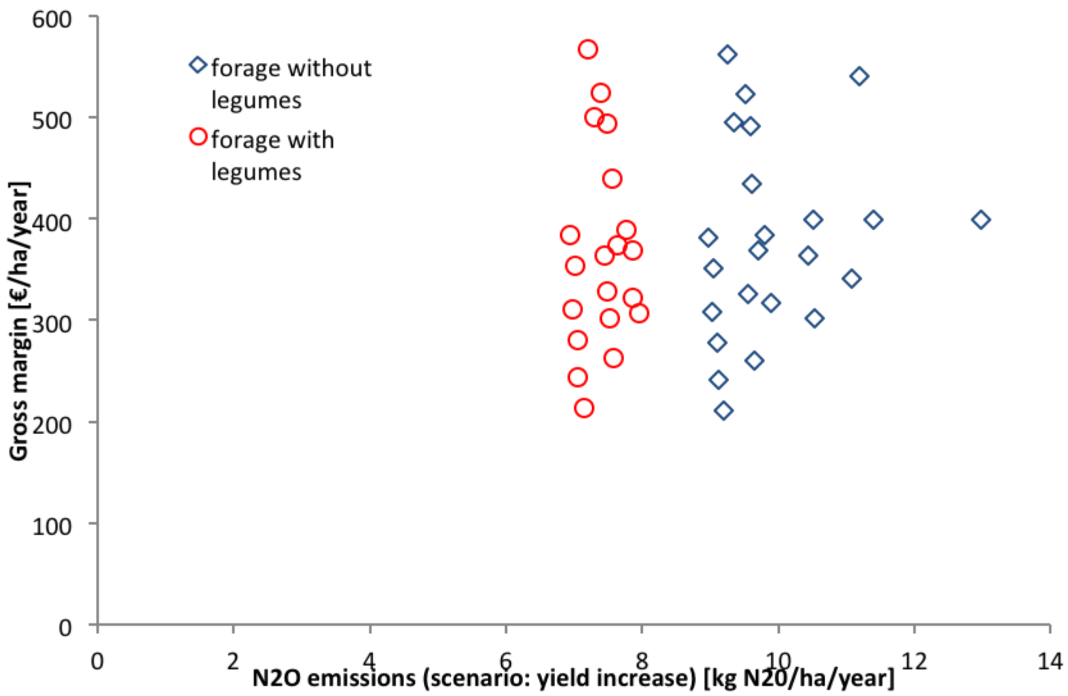


Figure 8: N_2O potential estimated across the model generated rotations against GM calculated for forage orientated rotations with (red circles) and without (blue diamonds) legumes

Many of the model generated legume-containing rotations, for both arable orientated and forage orientated systems for Eastern Scotland do appear in the most part to provide good GM as well as a number of positive environmental benefits over their non-legume counterparts. This is not true for all rotations, but there is a definite tendency for this to be the case. When a model generated legume-containing rotation has a similar or slightly lower GM than a similar non-legume containing rotation, the legume-containing rotation invariably has the less harmful environmental footprint across the measures discussed (N leaching potential, N Balance Index, Coefficient of N Performance (Neff) and N_2O emission potential).

In terms of GM, the rotation generator model appeared to target potatoes for the arable orientated potatoes, and all of the non-legume arable orientated rotations included this crop, and a large proportion of the legume-containing arable orientated rotations also included them. Rotations containing potatoes tended to be fairly profitable, however, they also tended to be more harmful to the environment based on the environmental indicators investigated. As stated previously, potatoes are a niche crop grown by specialist producers, and the area that is likely to be grown will be limited to some extent by the characteristics that have resulted in the land being given Class 3 status, as well as the financial risk that the farmer or grower is prepared to take in case of either a poor growing season, or a poor market for the potatoes produced. It is therefore unrealistic to state that due to estimated potential GM values, that all farms on Class 3 land in Eastern Scotland should include potatoes in their rotation.

With regard to legumes, many farms are comfortable and familiar with their use in forage orientated rotations. However, there is grassland in the region that has no clover or other forage legumes in the sward, or only at low proportions. As such there is a need to emphasise through KT methods that there are potential benefits of utilising BNF in the system through reducing bought in N fertiliser costs and that this approach often leads to a number of environmental benefits as well. As part of this KT exchange, it also needs to be made clear to growers either already using, or considering using, BNF that the use of additional N sources, either from mineral N sources, or organic materials is likely to have a detrimental effect on the actual amount of biological N fixation (BNF) taking place in the sward, compared to the potential amount. The approach needs to be balanced, or the potential cost savings will not be realised.

The breeding of forage legumes suitable for use in Eastern Scotland is generally good, mostly based around white and red clover varieties. There is some scope to broaden out the range of species that could be included in forage mixtures, for example vetches, Lucerne or trefoils all have some potential, although work to date on these crops is limited. However, when it comes to arable orientated rotations and grain legumes, the story is different. There are severe limitations in the current grain legume crops that can be grown in Eastern Scotland (more or less restricted to peas, field beans and lupins), and of these, the number of varieties available is relatively small. One of the main reasons that farmers don't grow grain legumes is that they have a reputation for being inconsistent yielders. A lack of agronomic knowledge may be partly to blame for this, and there is some evidence that natural levels of soil rhizobia suited to peas and field beans may not be as effective at creating N fixing nodules as commonly thought. However, lupins would routinely be inoculated with complimentary rhizobia, but there are still consistency issues with this crop.

There is currently plenty of scope to improve the range of breeding characteristics of grain legumes that would benefit these crops in Eastern Scotland, including hardier varieties with short growing seasons, early maturing, good standing ability, disease resistant and weed suppressive characteristics. If soya varieties could be developed to grow successfully and consistently in the soils and climate of the region, there could be huge potential as all soya is currently imported to Scotland at great expense, but as its feed value (amino acid lysine is important) is far superior to most of the other grain legumes that can be grown in the region, this helps drive the market. If higher levels of lysine content could be bred into the other grain legumes currently more suited to Scottish conditions, this might also be a driver for more farmers to try growing the crops.

ANNEX 2. South Muntenia, Romania

Romanian case study is chernozem area of the South Muntenia region with 1 388 040 ha of arable land. Cereals with 1 029 724 ha (winter wheat with 519 236 ha, maize for grains with 405 455 ha, winter barley with 82 955 ha and spring oats with 22 078 ha), sunflower with 228 393 ha, perennial fodder, mostly alfalfa with 61 920 ha and annual fodder (grass) with 55 199 ha play a major role here. In this area, the annual legumes with 12 804 ha (pea with 6 420 ha, soybean with 5 412 ha and bean with 972 ha) play a minor role.

For chernozem area of South Muntenia region a number of 137 rotations were generated by the model, 4 non-legume arable rotations and 133 legume arable rotations. Each legume arable rotation contains one annual legume - pea, common bean or soybean. Also, the rotations generated by the model contain only 5 non-legume crops: 3 cereals - winter wheat, winter barley and maize and 2 oil crops - winter rapeseed and sunflower. Regarding length of rotations generated by the model, 105 are 5 years long, 30 are 4 years long and 2 are 3 years long.

Agronomic analyses of generated non-legume and legume crop rotations

Gross Margin (GM) comparisons

The non-legume arable rotation generated by the model that provided the greatest average GM (€ 430 – 432/ha/year) was found to be 3 years long rotations: wrape > maize_g > wwheat and wrape > maize_g > wbarley (table 1). These rotations would be unusual for the region, because maize for grains is, usually, to late as preceding crop for wwheat and, especially, wbarley. According to local and European market, a few farmers prefer 3 years crop rotation: wrape > wwheat > wwheat, but it was rejected by the rotation generator model because, maybe, of the low crop rotation score. Also, in the 3 years crop rotation the maize can be replaced by other crops grown in South Muntenia, like annual grasses.

Table 1 Average gross margin in non-legume arable rotation generated by the model for South Muntenia

Crop 1 (year 1)	Crop 2 (year 2)	Crop 3 (year 3)	Crop 4 (year 4)	Crop 5 (year 5)	Average GM (€/ha/year)
wrape	maize_g	wwheat			431.976667
wrape	maize_g	wbarley			429.686667
wrape	wwheat	wwheat	sunfl	wbarley	371.184
sunfl	wwheat	wwheat	wrape	wbarley	271.774

The best gross margin of non-legume arable 5 years rotation generated by the model was provide by rotation: wrape > wwheat > wwheat > sunflower > wbarley (€371/ha/year), with €100/ha/year more than second 5 years crop rotation generated by the model: sunflower > wwheat >wwheat > wrape > wbarley. This is because the second 5 years crop rotation has lower crop rotation score (9), and wrape after wbarley is less risky as sowing time than wrape after wwheat.

For the South Muntenia area, it was expected to be generated by the model some 4 years non-legume rotations too.

With regard to the legume arable rotations, the model generated only 4 and 5 years rotation long - 63 pea rotations (14 crop rotations 4 years long and 49 crop rotations 5 years long), 35 common bean rotations (8 crop rotations 4 years long and 27 crop rotations 5 years long) and 35 soybean rotations (8 crop rotations 4 years long and 27 crop rotations 5 years long).

The top 10 legume arable rotations generated by the model (table 2) that provide the greatest average GM (€751–850/ha/year) are 4 or 5 years rotation long with common bean. Winter wheat, winter barley and maize for grains can benefits of the N residuals after common bean. Concerning effect of length of arable rotations generated by the model on GM, it is quite clear that 4 years crop rotation is better than 5 years crop rotation, except 4 years crop rotation – bean>wwheat>wrape>maiz_g, which has the lowest average annual gross margins (€ 751/ha).

These bean rotations generated by the model are plausible, although the common bean is, for the moment, a minor crop in pilot because of the dry climate during bean flowery. However, common bean can be rehabilitate by innovation of traditional intercropping systems “maize for grains and common bean” and by a common bean breeding program for drought and heats resistance.

Table 2. Top 10 legume arable rotations as gross margin (GM) in South Muntenia

Crop 1 (year 1)	Crop 2 (year 2)	Crop 3 (year 3)	Crop 4 (year 4)	Crop 5 (year 5)	Average GM (€/ha/year)
combean	wwheat	wrape	wwheat		814.8225
combean	wwheat	wrape	maize_g		750.985
combean	wwheat	wwheat	wrape		814.8225
combean	maize_g	wwheat	wrape		850.105
combean	maize_g	wbarley	wrape		848.3875
combean	wbarley	wrape	wwheat		823.495

combean	wbarley	wrape	maize_g		759.6575
combean	maize_g	wwheat	wrape	wwheat	753.794
combean	maize_g	wwheat	wwheat	wrape	753.794
combean	maize_g	wbarley	wrape	wwheat	752.42

The second arable legume rotations generated by the model for chernozem area of South Muntenia (fig.1) have gross margin between €434 and €750. All of these are legume rotations with different gross margin range: €560–€735 for 25 common bean rotations, €434–€453 for 9 pea rotations and €437–€518 for 24 soybean rotations. As regards length of rotation, the gross margin for these legume rotations varied between €449 and €671 in 12x4 years rotations and between €434 and €735 in 46x5 years rotations.

According to legumes structure and climate conditions of chernozem area of South Muntenia region, the best solution for farmers is to choose rotations generated by the model for pea and/or soybean with gross margin between €450 and €520 (table 3).

Table 3. Top 10 pea and soybean rotations as gross margin (GM) in chernozem South Muntenia

Crop 1 (year 1)	Crop 2 (year 2)	Crop 3 (year 3)	Crop 4 (year 4)	Crop 5 (year 5)	Average GM (€/ha/year)
pea	maize_g	wwheat	wrape		451.675
pea	wrape	maize_g	wwheat		452.66
soybean	wwheat	wrape	wwheat		482.5725
soybean	wbarley	wrape	maize_g		496.4075
soybean	maize_g	wwheat	wrape		517.855
soybean	wbarley	wrape	wwheat		491.245
soybean	wwheat	wrape	maize_g	wwheat	462.734
soybean	wwheat	wrape	wwheat	maize_g	463.898
soybean	wbarley	wrape	wwheat	maize_g	470.836
soybean	maize_g	wwheat	wrape	wwheat	487.994

The last legume crop rotations generated by the model for Romanian pilot area as gross margin are 54 pea rotations with a gross margin in the €258–€430 range and 11 soybean rotations with gross margin in the €316– €429 range. Also, depending on length of crop rotation, the gross margin of these rotations varied between €316 and €429 in 4 years crop rotation and €258 and €429 in 5 years crop rotations. In context of previous results, these legume crop rotations can be important only if have less environment impact.

Sunflower, the third major crop in chernozem area of South Muntenia region, lies in all gross margin groups, except top 10 arable crops group generated by the mode, with a large variation of gross margin between €265 and €695. Also, sunflower rotations are only 5 years rotations.

Environmental impact of the rotation

The evaluation of environmental impact plotted against gross margin will be due for the same non-legume and legume arable rotations generated by the model as well as in case of gross margin. Also, this evaluation refers to 4 environment parameters connected with Nitrogen, alike useful for non-legume and legume crops – N Balance Index (NBI) and Coefficient of N performance (Neff) and dangerous for environment – N leaching and Nitrous Oxide (N_2O) emission potential.

N leaching

According to data of all arable rotations generate by the model, the average N leaching varied between 10.0 and 12.8 kg N/ha/year in non-legume rotations, and between 8.4 and 15.4 kg N/ha/year in legume rotations generated by the model. This annual N leaching rate is low enough, maybe according to climate characteristics of the pilot area.

N leaching for the top 10 arable crop rotations as gross margin varied between 8,84 and 12,37 kg N/ha/year (Fig.1). All these crop rotations are common been crop rotations, 7 are 4 years long with N leaching rate varied between 8,84 and 11,57 kg N/ha/year and 3 are 5 years long with N leaching rate varied between 10,70 and 12,37 kg N/ha/year. Although all arable crop rotations are plausible, 4 years bean rotation has the lowest N leaching.

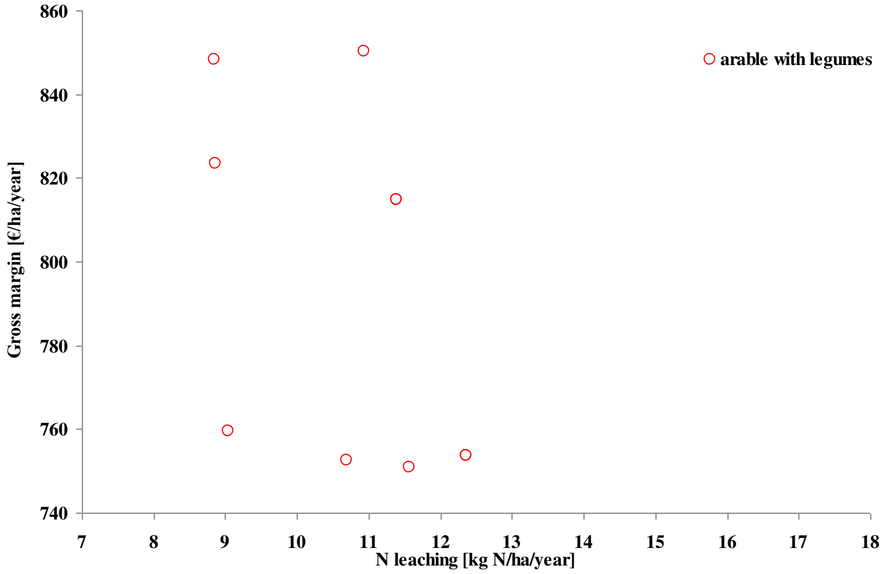


Fig.1. N leaching for top 10 arable legume rotations as gross margin

N leaching for arable crop rotations with gross margin less than €750 and higher than €430 was in the 8,37–15,37 kg N/ha/year range (Fig.2).

These rotations generated by the model are 25 common bean rotations with a N leaching rate varied between 8,37 and 13,53 kg N/ha/year, 9 pea rotations with the N leaching rate varied between 11,40 and 14,41 kg N/ha/year and 24 soybean rotations with N leaching rate in the 11,33 – 15,36 kg N/ha/year range. Depending on length of rotations the N leaching rate varied between 9,05 and 14,25 kg N/ha/years in 4 years rotations and 8,37 and 15,36 kg N/ha/year in 5 years rotations.

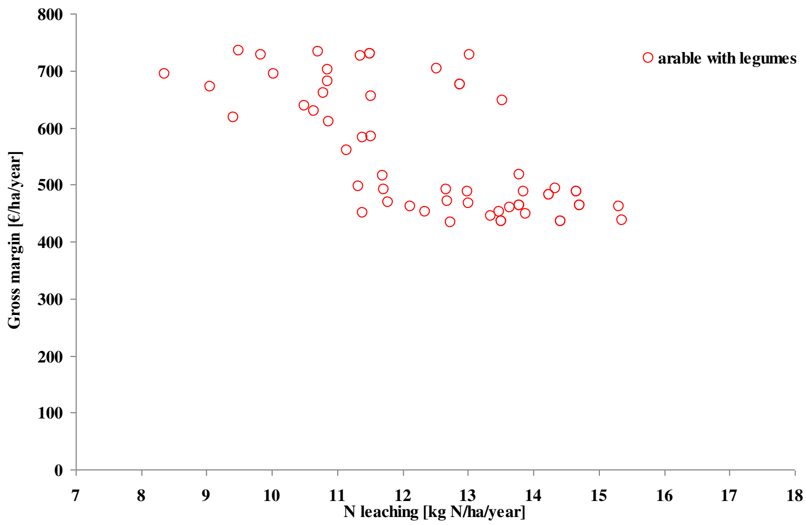


Fig.2. N leaching rate for arable legume rotations with gross margin between €430 - 750

N leaching for arable crop rotations with gross margin less than €430 varied in the 9,99 and 15,38 kg N/ha/year range (Fig.3). Also, these rotations generated by the model are 4 non-legume rotations with N leaching rate varied between 9,99 and 12,77 kg N/ha/year, 54 pea rotations with N leaching rate varied between 10,12 and 15,38 kg N/ha/year and 11 soybean rotations with leaching rate in the 10,65 – 13,68 kg N/ha/year range.

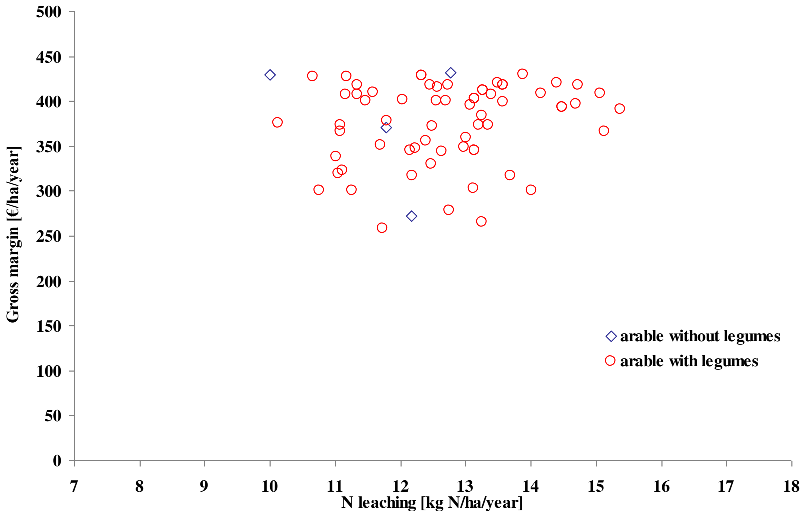


Fig.3. N leaching rate for arable crop rotations with gross margin less than €430

N leaching in sunflower crop rotations generated by the model varied in a large range too, between 8,37 and 13,68 kg N/ha/year.

N Balance Index (NBI) score

NBI score was calculated as a result of N balance/N input. Also, it is analyzed against the same gross margin rate as N leaching.

NBI score for top 10 common bean rotations as gross margin varied between -0,091 and 0,005 (Fig. 4). This NBI score is according to N balance, negative for 4 years long crop rotations and positive for 5 years long rotations.

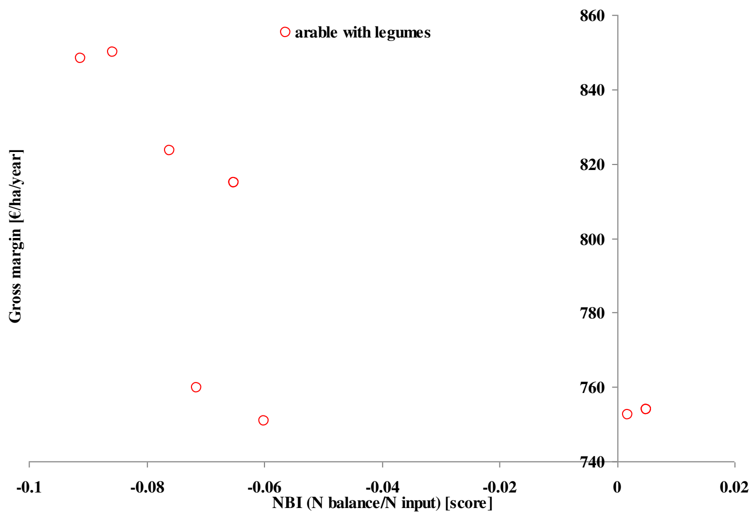


Fig. 4. The NBI of top 10 arable rotations with greatest gross margin

NBI score for arable crop rotations with gross margin less than €750 and higher than €430 was negative for 13 common bean rotations, and positive for 12 common bean rotations, 9 pea rotations and 24 soybean rotations (Fig.5).

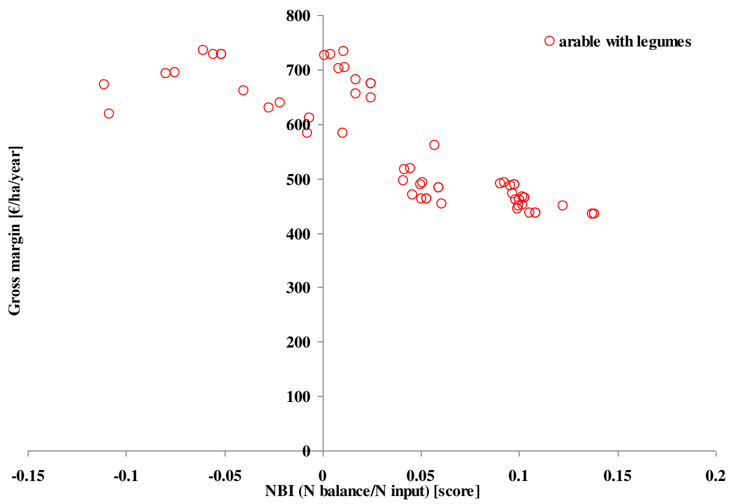


Fig.5. NBI score for arable legume rotations with gross margin between €430 - 750

NBI score for arable crop rotations with gross margin less than €430 was positive for all crop rotations generated by the model: 0,078–0,163 for non-legume rotations, 0,045–0,160 for pea rotations and 0,013–0,140 for soybean rotations (Fig.6).

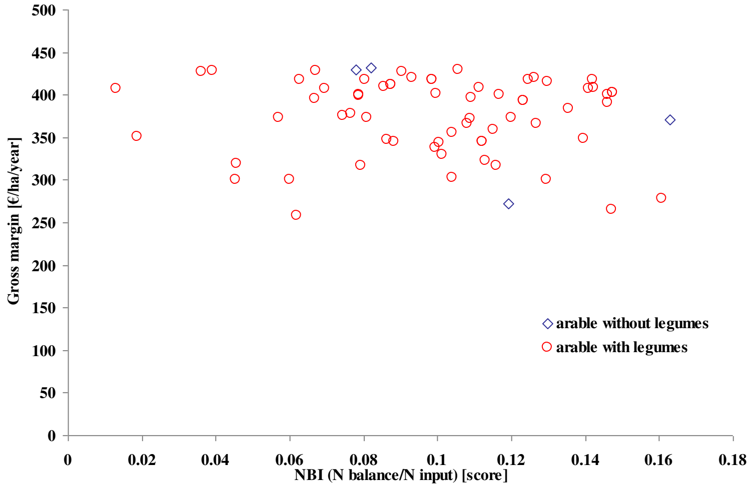


Fig.6. NBI score for arable crop rotations with gross margin less than €430

The arable rotations with NBI's below 0 suggest that soil organic matter is being exported from the system, and arable rotations with NBI's above 0 suggest that soil organic matter is accumulated and/or conserved.

Therefore, most of arable crop rotations generate by the model for Romanian chernozem area accumulate and/or conserve soil organic mater, except 4 years crop rotations of top 10 common bean rotations as gross margin and 13 crop rotations from second level of gross margin which export soil organic matter from the system. Also, all the NBI in sunflower crop rotations generated by the model were positive.

Coefficient of N performance (Neff)

Neff was calculated as a result of average N removal (N output that is harvested in kg N/ha/year) divided by N input from organic + mineral fertilizers. Also, it is analyzed against the same gross margin rate as N leaching and NBI.

Neff score varied between 0,732 and 1,275, but the highest values (0,909 – 1,275) are showed from legume rotations generated by the model.

Neff score for top 10 common bean rotations as gross margin generated by the model varied between 1,027 and 1,241 (Fig.7) and, depending on length of rotation, between 1,140 and 1,241 in 4 years crop rotations and 1,027 – 1,049 in 5 years crop rotations.

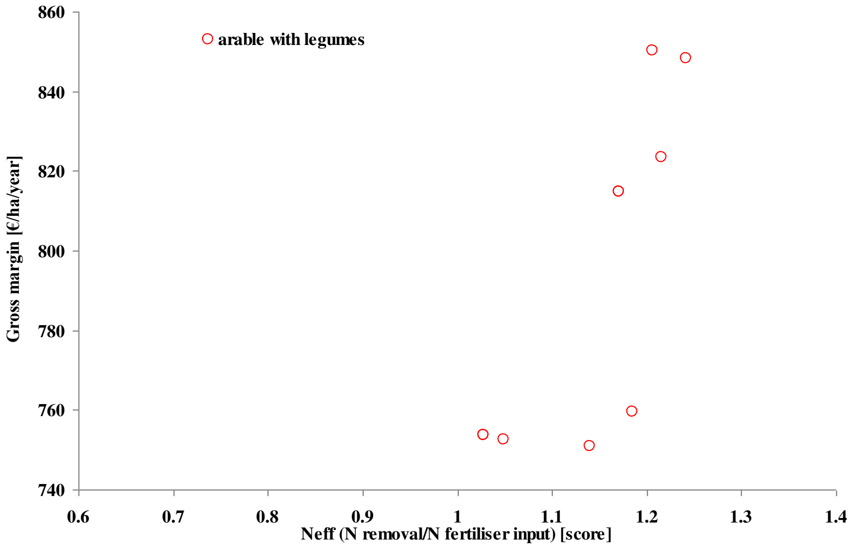


Fig.7. Neff score of top 10 arable legume rotations with greatest gross margin

Neff score for arable legume rotations with gross margin less than €750 and higher than €430 varied between 0,922 and 1,275. Also, this Neff score varied depending on type of legumes: 0,965–1,245 for common bean rotations, 1,006 – 1,275 for pea rotations and 0,922–1,147 for soybean rotations, as well as on length of crop rotations: 1,065–1,275 in 4 years crop rotations and 0,922–1,218 in 5 years crop rotations (Fig.8).

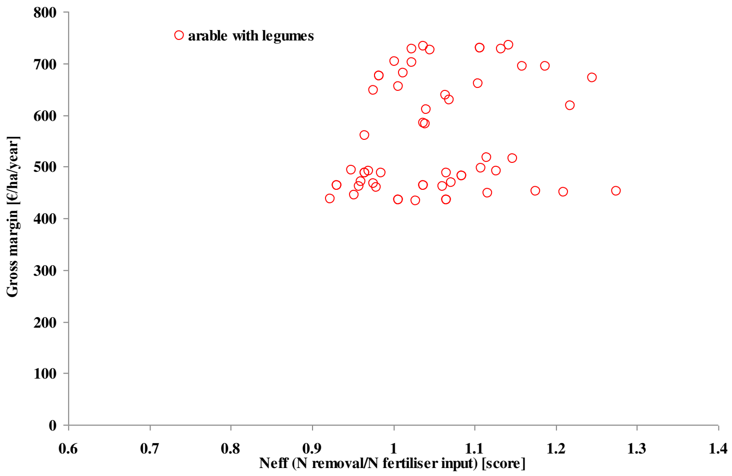


Fig.8. Neff score for arable legume rotations with gross margin between €430 - 750

Neff score for arable crop rotations with gross margin less than €430 generated by the model varied between 0,732 and 0,826 for non-legume crop rotations and between 0,923 and 1,261 for pea rotations and in the 0,908–1,160 range for soybean rotations (Fig.9).

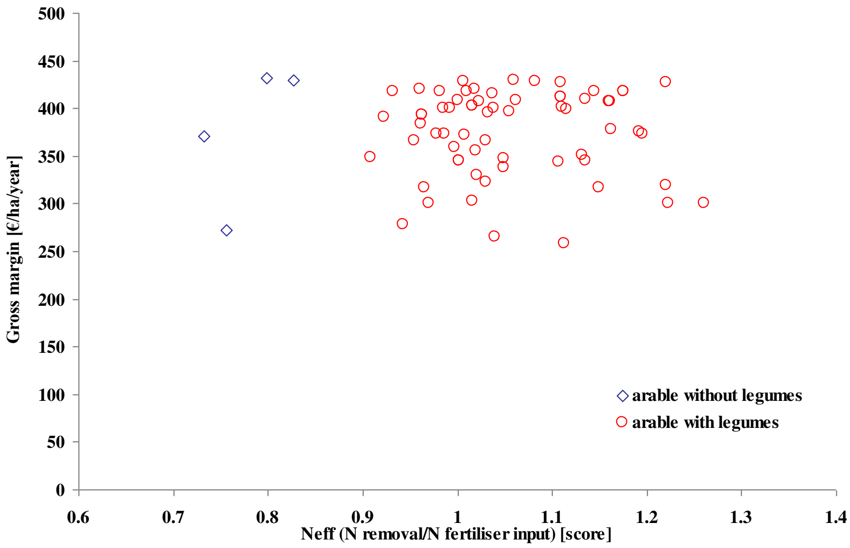


Fig.9. Neff score for crop rotations generated by the model with gross margin less than €430

Nitrous Oxide (N_2O) emission potential

N_2O emission potential was estimated in kg N_2O /ha/year for increased yield SCRUC scenario. Also, it is analyzed, as previous environment parameters, against gross margin.

N_2O emission potential for all arable crop rotations generated by the model varied in a range between 2,383 and 3,712 kg N_2O /ha/year.

N_2O emission potential for top 10 common bean rotations as gross margin generated by model varied between 2,838 and 3,223 kg N_2O /ha/year (Fig.10). Also, depending on length of rotation, N_2O emission varied in a 2,838–3,025 kg N_2O /ha/year range for 4 years crop rotations and 3,210–3,223 kg N_2O /ha/year range for 5 years crop rotations.

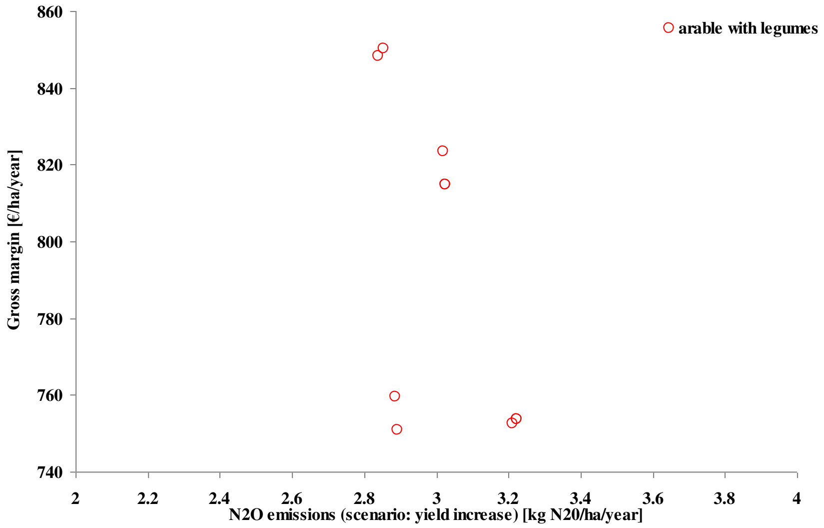


Fig.10. N_2O emission of top 10 arable legume rotations with greatest gross margin

N_2O emission potential for arable legume rotations with gross margin less than €750 and higher than €430 varied between 2,477 and 3,355 kg N_2O /ha/year (Fig.12). Also, this N_2O emission potential variation depending on type of legumes: 2,477–3,355 kg N_2O /ha/year for common bean rotations, 2,712 – 3,261 kg N_2O /ha/year for pea rotations and 2,757 – 3,290 kg N_2O /ha/year for soybean rotations, as well as on length of crop rotations: 2,681 – 3,223 kg N_2O /ha/year in 4 years crop rotations and 2,477 – 3,355 kg N_2O /ha/year in 5 years crop rotations (Fig.11).

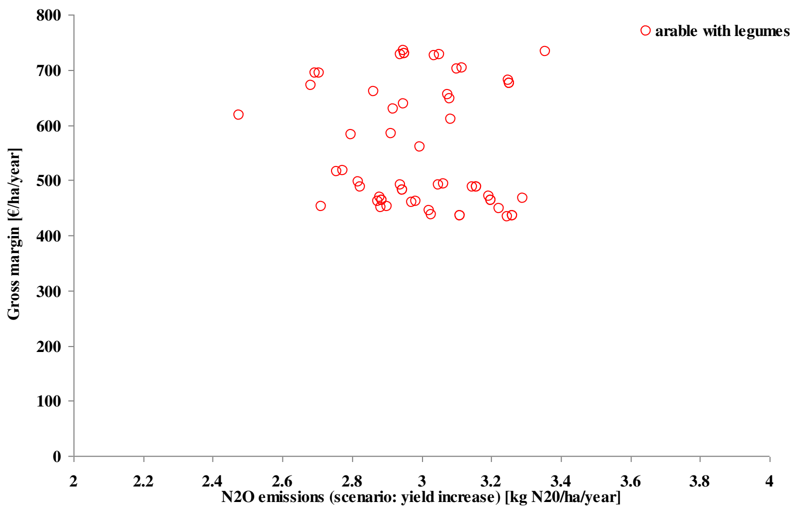


Fig.11. N_2O emission potential for legume rotations with gross margin between €430 - 750

N_2O emission potential for arable crop rotations with gross margin less than €430 generated by the model varied between 3,242 and 3,712 kg N_2O /ha/year for non-legume crop rotations and between 2,383 and 3,393 kg N_2O /ha/year for pea rotations and in the 2,411–3,031 kg N_2O /ha/year range for soybean rotations (Fig.12).

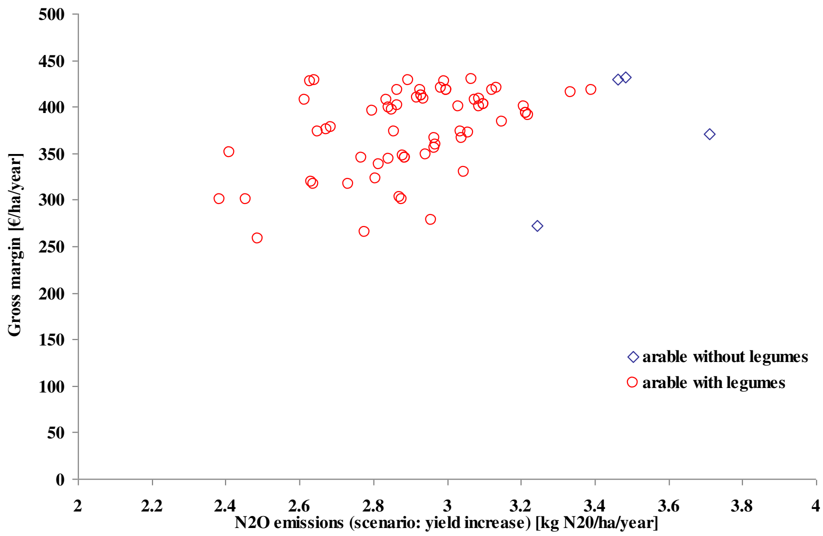


Fig.12. N_2O emission potential for arable non-legumes and legumes rotations generated by the model with gross margin less than €430

N_2O emission potential of sunflower crop rotations generated by the model varied according to presence ore absence of legumes: 2,383 – 3,148 kg N_2O /ha/year in legume crop rotations and 3,242 – 3,711 kg N_2O /ha/year in non-legume crop rotations.

Conclusions

Chernozem area of the Romanian South Muntenia region is a large arable land, with good soil and some climate problems for main cereals (winter wheat, winter triticale, winter barley, and maize for grains), sunflower and/or winter rapes, perennial fodder, mostly alfalfa and annual fodder. In this area, the annual legumes (pea, soybean with common bean) should play a major role, by breeding programs for frost resistance of pea and drought and heats resistance of common bean and soybean, as well as by innovation of farming systems and cropping systems to prevent negative effects of climate change.

The gross margin of crop rotations generated by the model is influenced, mostly by the level and price of yield. Also, the arable crop rotation generated by the model that provided the greatest average appears to be 3 - 4 years long legume crop rotations..

The environment impact of the arable crop rotations generated by the model is not very clear, except the higher coefficient of N performance (Neff) and lower N_2O emission potential in legume crop rotations than in non-legume crop rotations.

During Legume Futures project many biodiversity and environmental parameters were studied in the organic field of NARDI Fundulea, but the crop rotation generator model did not generated any similar crop rotation. It is, maybe, because of time as well as weeds, pests and diseases restrictions, which are not confirmed by the practice in context of long term crop rotations and release of new cultivars.

ANNEX 3. Calabria, Italy

For Calabria a number of 960 potential rotations were generated by the model, divided as follows: 989 for rainfed; 36 for irrigated highlands and 6 for irrigated lowlands. 314 are rotations for grain productions while about the double (646) are potential rotations for forage production. The largest number of rotations include at least one legume crop (949) while only 11 generated rotations not consider legume crops. With regard to the length of the rotations, 645 are 5 years long; 288 are 4 years long and 27 are 3 years long.

Gross Margin evaluation

Grain crop rotations

Within the grain crop rotations without legume the best gross margin (549 €/ha/year) is given by the rotation with the following 5 years sequence: potato, winter rape, winter wheat, winter rape, winter wheat (Tab.1). This is a common rotation used in the irrigated highland of the region where potato is possible to be returned after 4 years due to nematode infestation.

The best gross margin for including-legume rotation is given by the same rotation used in irrigated highland for potato production, with lupin instead of winter wheat or winter rape (Tab.1). A net increase of 160 €/ha/year (+29%) resulted for the following rotation: potato, lupin, winter rape, lupin, winter wheat if compared with the best rotation without legumes.

Rotations including forage

For forage production without legume the best gross margin is given by a 4 year rotation (winter rape, winter barley, winter rape, winter barley) generated for rainfed areas (335 €/ha/year). Using winter barley in the rotation it results more profitable than other cereals like winter wheat, triticale or oat (Tab 2).

Also for rotation including forage crops the use of legumes increased the gross margin. In the rainfed area, the inclusion of two year of vetch intercropped with oat in the rotation results in a gross margin increase of about 1000 €/ha/year (+300%) (Tab. 2). Due to its good agronomy performance in terms of yield and weed control Oat/vetch intercropping harvested to flowering stage is one of the traditionally cultivated crop as forage in the rainfed area of Calabria.

Results of rotations generated for irrigated highland are not comparable with the rotations generated for rainfed and irrigated lowlands. For this reason the evaluation in terms of environmental impact plotted against gross margin will be due separately for the two different sites.

Environmental impact of the arable rotations

Rotation for irrigated highland

In the irrigated highlands N leaching was directly related with the gross margin reaching 80 kg/ha/year in the best rotation. The presence of legume increase the leaching of about 20 kg (33%) but the difference in the gross margin is too high (161 €/ha/year) between the no legume rotation and the best including-legume rotation. Using a different including-legume rotation a reduction of 10 kg/ha/year of N leaching could be permitted with a sacrifice of 44 €/ha/year (Fig.1a).

The NBI index show a generally out of balance situation both for rainfed site and irrigated highlands. In both the management systems the presence of legumes limited the imbalance reducing the detriment of soil organic N content. In irrigated highland the best rotation in terms of gross margin showed one of the better NBI index values (-0.1), while the rotation without legumes with the highest gross margin show a value of -0.3 (Fig. 1b).

For irrigated highlands the highest Neff value (0.91) were showed from the best legume-containing rotations. The presence of legume in the rotation increase the Neff of about 50% (Fig. 1c).

N_2O emission resulted very low in all the rotations generated both for rainfed and irrigated highlands. For the irrigated highland values ranged between 2.1 and 2.4 kg/ha/year with the lowest potential emission in the rotation with the best gross margin (potato, lupin, winter rape, lupin, winter wheat: 709 €/ha/year) (Fig. 1d).

Rotations for rainfed sites and irrigated lowlands

For the rotations generated for the rainfed sites N leaching ranging between 12 and 52 kg N/ha/year. Lowest values were found in a rotation without legume with the highest gross margin (winter rape, winter wheat, winter rape, winter wheat). The use of legume in rotation generally increased the N leaching amount (Fig.2a).

The presence of legume increase the capacity for the crops to use natural resources with a more balance between input and output. For rainfed sites the best rotation in terms of gross margin gave a NBI index value of -0.5. The use of the best including-legume rotation could reduce the index of 0.1 with a sacrifice of 34 €/ha/year (fig. 2b).

For the rainfed site the 4 year rotation: winter rape, faba bean, winter rape, faba bean showed a Neff value of 3. The potentially choice of this rotation instead of the rotation with the highest gross margin could results in a reduction of 100 €/ha/year but in an increase of the coefficient of performance of nitrogen (+1.7) (Fig.2c).

For rainfed sites the choice of rotations with lower gross margin can results in a very low advantage in terms of N_2O emission, no more than a kilogram scarifying about 100€/ha/year of gross margin (Fig. 2d).

Environmental impact of the forage rotations

Rotations for irrigated highland

Rotations without legumes were not generated for irrigated highlands. For environmental impact for these sites, only legume-containing rotations will be evaluated.

N leaching ranged between 45 and 65 kg N/ha/year. Two five year rotations showed the best gross margin (996 €/ha/year) differing for alfalfa and clover in the first 2 years and followed by potato, lupin and winter wheat. The presence of alfalfa instead of clover in the rotation determined a 6 kg/ha/year N leaching reduction. A sacrifice of 74 €/ha/year (7.4%) in terms of gross margin could save until 15 kg N/ha/year (Fig.3a).

NBI index is positive for all the rotations tested ranging between 0.18 and 0.56. The presence of clover in the rotation instead of alfalfa increased the NBI. The best clover-containing rotation showed a value of 0.52 (Fig. 3b).

The Neff index showed the same tendency of NBI index with two groups of values. If compared with clover, the presence of alfalfa in the rotations generally determined an higher Neff. The best rotation containing alfalfa showed the highest Neff value (2.1) (Fig. 3c).

The amount of N_2O emission was very low ranging between 2.1 and 2.7 kg N_2O /ha/year. The presence of clover instead of alfalfa reduced the emission of only 0.4 kg N_2O /ha/year (Fig. 3d).

Rotations for rainfed sites and irrigated lowlands

With the increase of gross margin a general tendency in the reduction of N leaching is showed. The legume-containing rotation with the highest gross margin (*winter rape, oat/vetch, winter rape, oat/vetch)* do not determined N leaching (0.1 kg N/ha/year) (Fig. 4a).

The NBI index values were negative for most of the rotations. Rotations with positive values showed a very low gross margin if compared with the best. The rotation with the highest gross margin showed a NBI index of -0.57. A potentially imbalance reduction until -0.34 determine a reduction of 238 €/ha/year in terms of gross margin. Less negative NBI index are showed from the best legume-containing rotations compared with all the rotations without legume (fig. 4 b).

Neff index varied in a high range between 0.6 and 13.2. Higher values are showed from rotation with very low gross margin (until 545 €/ha/year). Limiting the evaluation to the higher gross margin rotations, increasing the gross margin the Neff increase (3.9 for the best rotation). All the rotation without legume presented a very low Neff (under 1.6 compared with the others (Fig. 4c).

Also for rainfed and irrigated lowlands N_2O emission resulted very low ranging from 0.9 to 3.6 kg N_2O /ha/year). Indifferently of the rotation results show a clear tendency in the increase of N_2O emission with the increase of gross margin, with the best rotation resulting in the highest N_2O emission (Fig. 4d).

Conclusions

Calabria is a region with very different climate conditions that determined different crop management in a relative limited area (15,000 km^2). As a case study 3 different site were chosen representative of semiarid, mediterranean and continental climatic conditions. For this reason, there is no only one rotation adapted to the different sites and we taken in mind this differences in the discussion of results.

Compared with arable crop rotations, forage crops generally showed the best index in terms of gross margin and environmental impact both for irrigated highlands and rainfed or irrigated lowlands. The presence of legume in rotation had a general positive effect on the gross margin and the environmental index also, with the exception of N leaching for grain crop rotations in the irrigated highland.

On the basis of gross margin and the environmental impact evaluation, for the irrigated highland is suggested to use the 5 year rotation: *alfalfa, alfalfa, potato, lupin, winter wheat* that showed the best gross margin and Neff index with the lower N leaching. This so long rotation is generally used in the Calabria's irrigated highland cultivated with potato. Due to nematode infestation for potato is not possible to return in the soil before 4 years. High quality livestock for meat production are generally in this site that can profitably use the alfalfa as grazing and grain of lupin instead of soya.

For rainfed sites the 4 year forage rotation: *winter rape, oat/vetch, winter rape, oat/vetch* is suggested to be used on the basis of gross margin and environmental impact. oat vetch is the most common crop used as forage in the rainfed area normally in rotation with winter wheat or barley. The model showed a better economic and environmental results using winter rape instead of winter cereals. Probably farmers prefer to use cereals because winter rape can result as weed in the years in which oat vetch intercrop is planted.

Forage crop showed to give better results compared with arable crops in all the sites considered, but the development of forage crops in the region is limited by the very low number of livestock farms many of these with a very limited SAU (under 10 ha). Probably this is the reason because arable crops are still the most cultivation in the rainfed Calabria's areas.

Table 1. Generated rotations for the Calabria's case study with the best Gross Margin (GM) for any type of cultivation.

rotation	Siteclass	Year 1	year 2	year 3	year 4	year 5	Avg GM
grain without legume	irrigated_highland	potato	wrape	wwheat	wrape	wwheat	549
grain with legume	irrigated_highland	potato	lupin	wrape	lupin	wwheat	709
	irrigated_highland	potato	wrape	lupin	wrape	wwheat	665
	irrigated_highland	potato	lupin	wwheat	lupin	wwheat	641
forage without legume	Rainfed	wrape	wbarley	wrape	wbarley		335
	Rainfed	wrape	wwheat	wrape	wbarley		301
	Rainfed	wrape	woat	wrape	wbarley		285
	Rainfed	wrape	tritica	wrape	wbarley		253
forage with legume	Rainfed	wrape	oatvetc	wrape	oatvetc		1343
	Rainfed	wrape	oatvetc	wbarley	oatvetc		1258
	Rainfed	wrape	oatvetc	wwheat	oatvetc		1224
	Rainfed	wrape	oatvetc	woat	oatvetc		1208

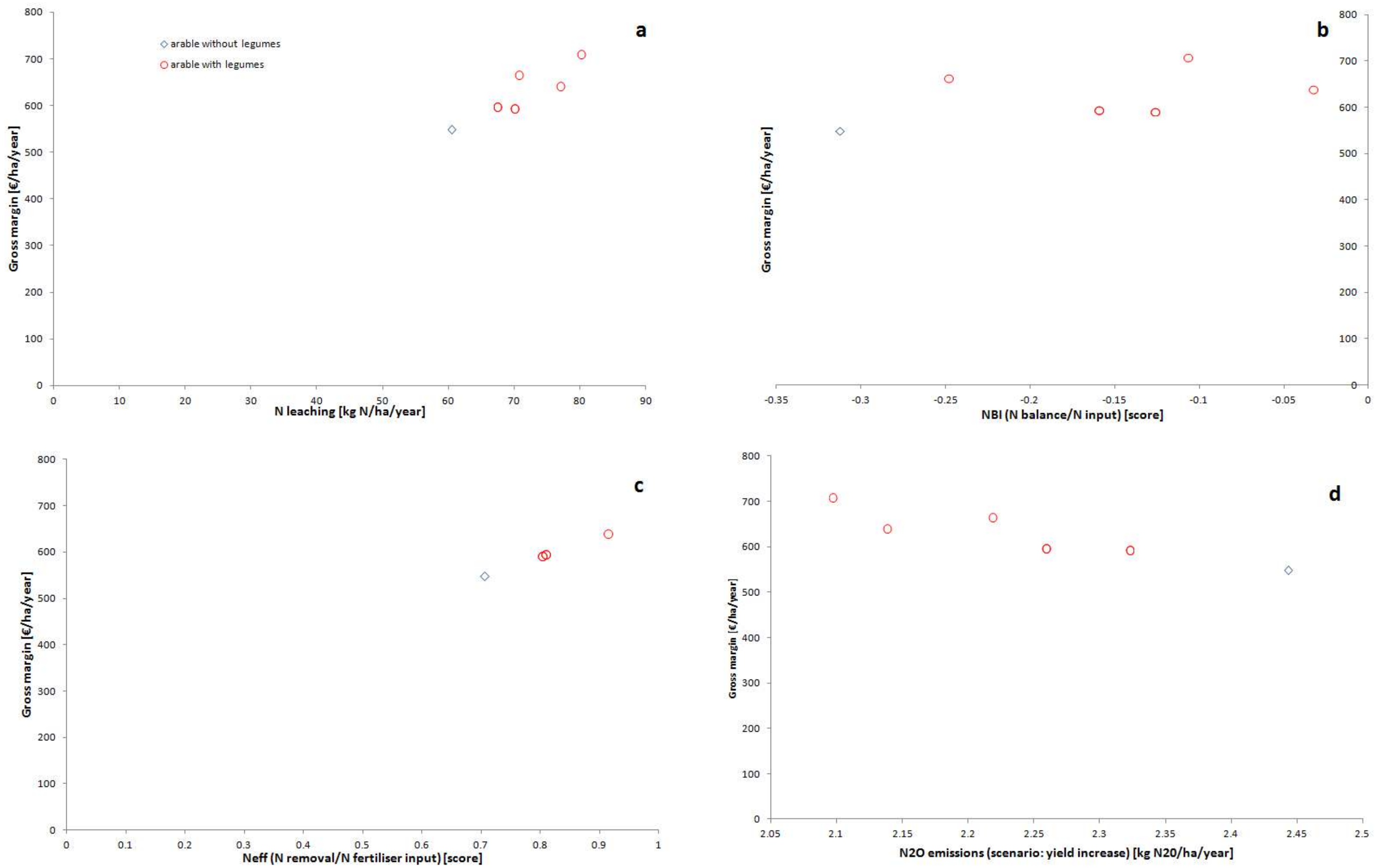


Figure 1. N leaching, NBI, Neff and N_2O emission plotted against gross margin for the generated arable rotations of the irrigated highlands of Calabria's case study.

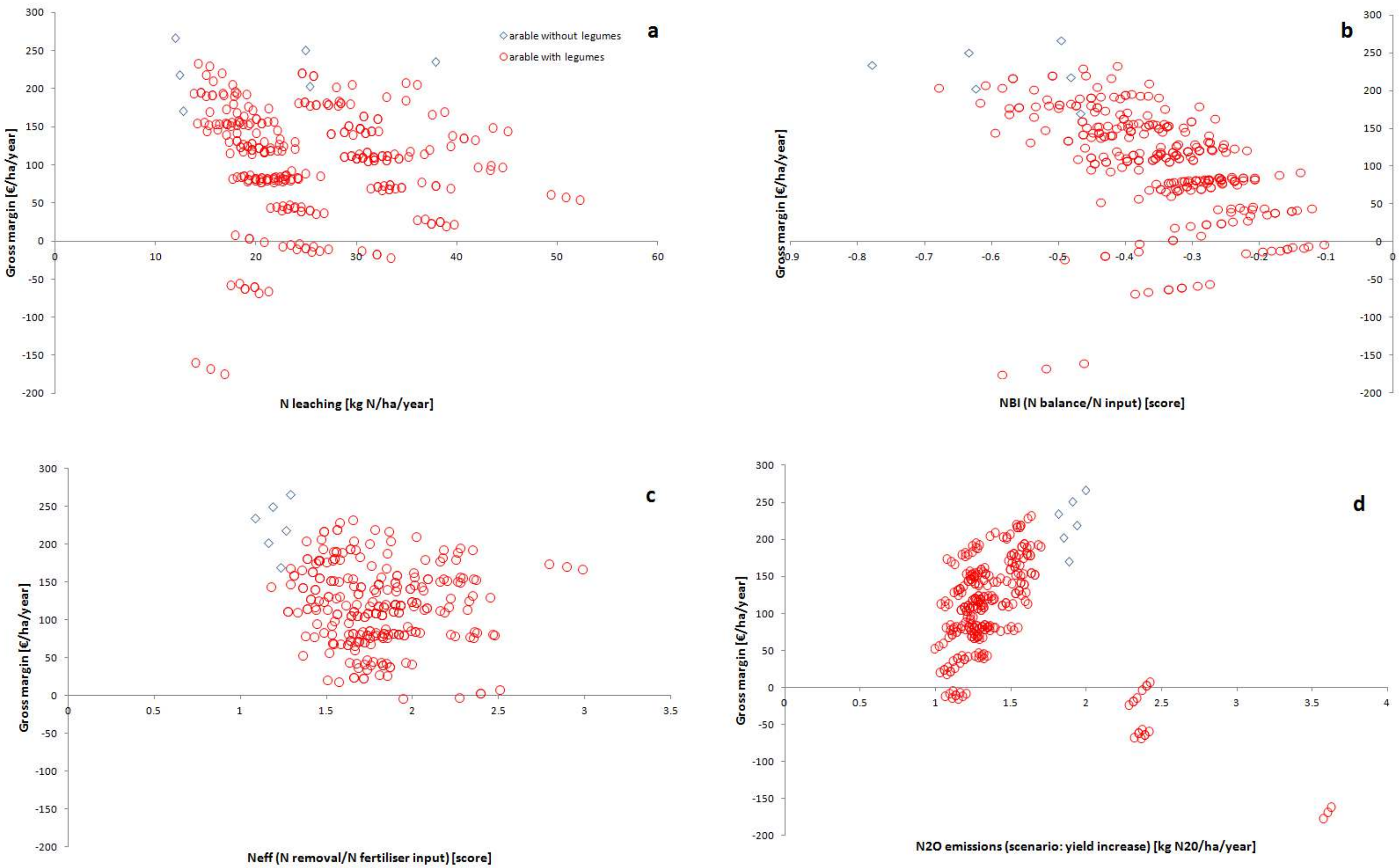


Figure 2. N leaching, NBI, Neff and N_2O emission plotted against gross margin for the generated arable rotations of the rainfed and irrigated lowlands of Calabria's case study.

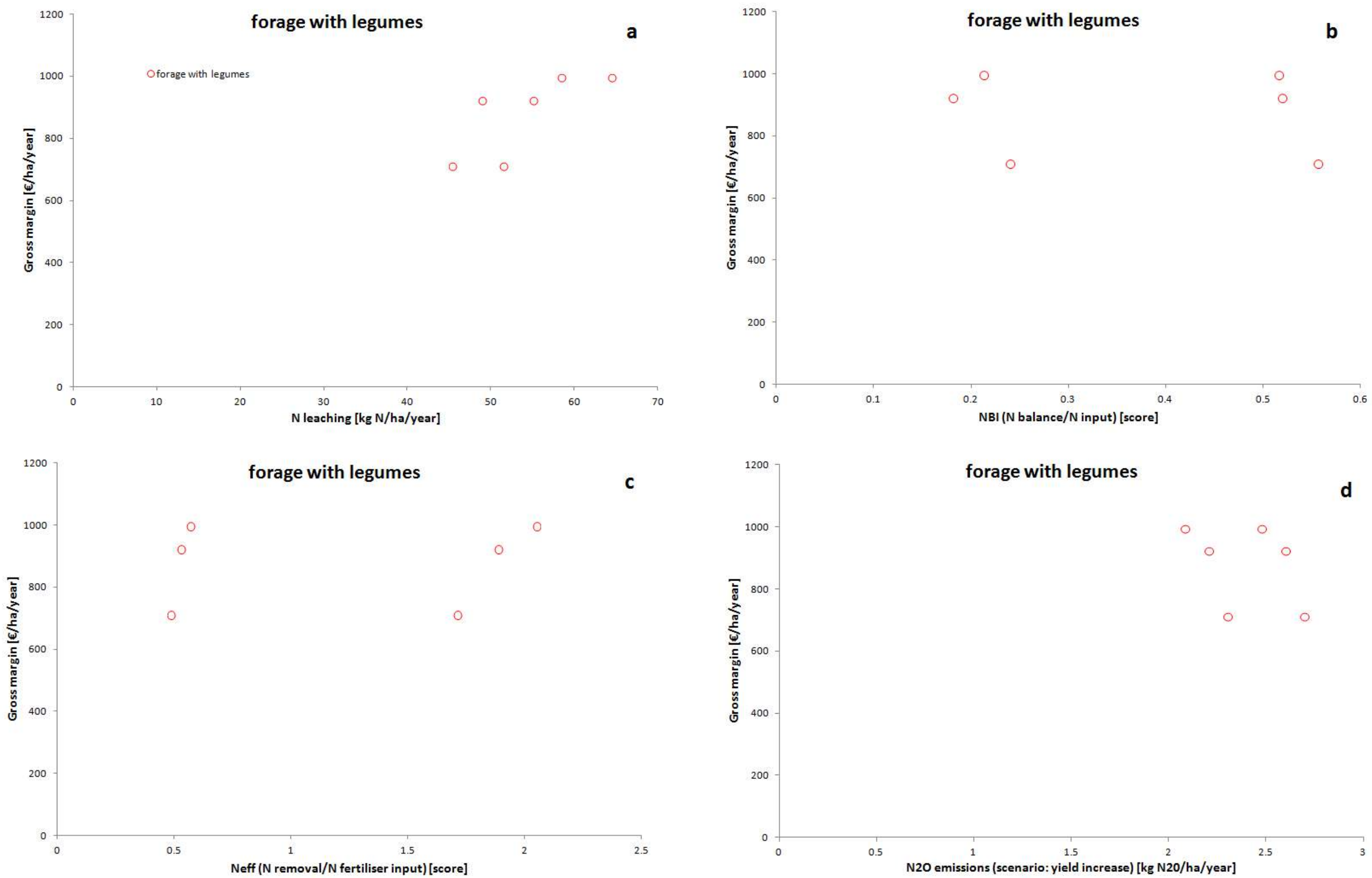


Figure 3. N leaching, NBI, Neff and N_2O emission plotted against gross margin for the generated forage rotations of the irrigated highlands of Calabria's case study.

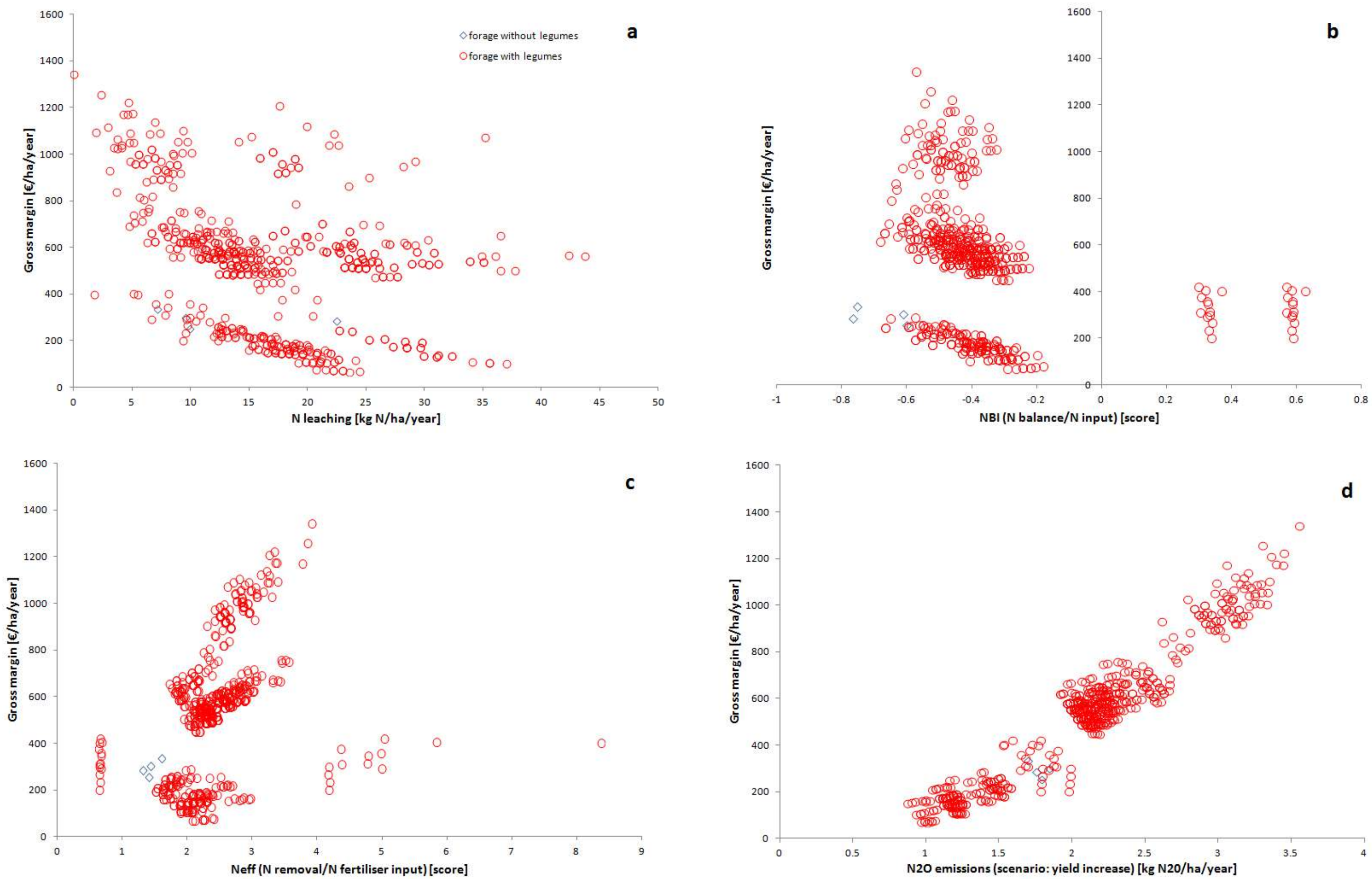


Figure 4. N leaching, NBI, Neff and N_2O emission plotted against gross margin for the generated forage rotations of the rainfed and irrigated lowlands of Calabria's case study.

ANNEX 4. Brandenburg, Germany

In Germany our case study region is the federal state of Brandenburg with 1 035 900 ha of arable land. Legumes play a minor and decreasing role here with 16 900 ha of grain and 26 100 ha of forage legumes as sole crops and in mixtures with grasses in 2009. Lupins and pea are grown on 16 200 ha and other grain legumes including faba bean, play only a very minor role. Clover and alfalfa are the major forage legumes but data on the actual shares especially when grown in mixtures is not precise.

Gross margin comparisons

Table 1. Top 10 arable oriented rotations <u>without legumes</u> on sub-site LBG2

year 1	year 2	year 3	year 4	year 5	rank	avg GM €/ha
wrape	wwheat	sbarley			1	130
wrape	wwheat	wbarley			2	128
wrape	wwheat	wrye	sbarley		3	115
wrape	tritica	sbarley			5	107
wrape	wwheat	wrye	wrye	sbarley	6	105
wrape	wrye	sbarley			9	91
wrape	wwheat	soat	sbarley		12	90
wrape	wwheat	soat	wbarley		13	89
wrape	wwheat	soat	wrye	sbarley	18	86
wrape	wwheat	wrye	soat	sbarley	19	86

- Compared to other grain crops winter rape followed by winter wheat has the highest gross margin and therefore included in all of the top ten crop rotations, which is similar to present arable crop rotations in Brandenburg at richer soils.
- Winter rape every third year is also rather common, even if these is less recommendable from the phytosanitary point of view. As a result increasing problems with *Plasmodiophora brassicae* occur, currently unknown in this region.
- Under practical conditions there is much more winter barley than spring barley in the fields, probably because of farmers try to avoid the higher yield variability of spring crops.
- The use of spring barley In contrast to oat would allow for the integration of cover crops to improve the soil organic status and the biotic resilience of the current cropping systems, without financial losses.

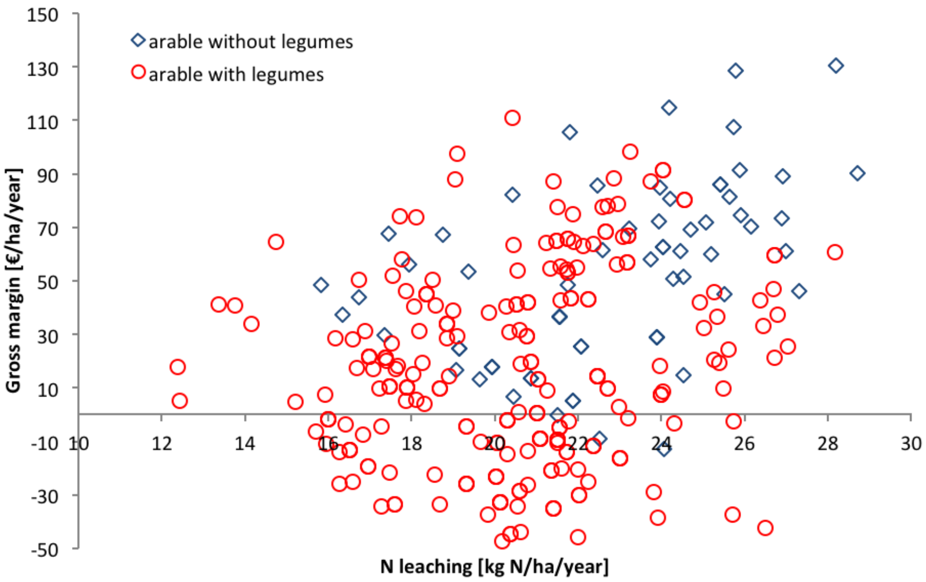
Table 2. Top 10 arable oriented rotations with legumes on sub-site LBG2

year 1	year 2	year 3	year 4	year 5	rank	avg GM €/ha
wrape	wwheat	wrye	wrye	pea	4	111
wrape	wwheat	soat	tritica	pea	7	98
wrape	wwheat	wrye	pea	wbarley	8	97
wrape	wwheat	soat	wrye	pea	10	91
wrape	wwheat	wrye	soat	pea	11	91
wrape	tritica	pea	wwheat	sbarley	14	88
wrape	wrye	wrye	wrye	pea	15	88
wrape	tritica	pea	wwheat	wbarley	16	87
wrape	wwheat	sbarley	tritica	pea	17	87
wrape	wwheat	sbarley	wrye	pea	25	80

The top ten of arable oriented rotations with legumes show the economic superiority of peas at the sub-site class LBG2 in combination with the subsequent winter rape which benefit twice from the preceding peas. (i) Winter rape can benefits best of the N residuals and soil structure after peas compared to the other winter grain crops (ii) After peas the temporal margin for sowing winter rape is distinctly longer and the seedbed preparation much more easier than after winter barley. So peas followed by wrape has the highest potential for integration of grain legumes which is also reflected in only slightly lower mean annual gross margins of the economic best legume included rotation.

Environmental comparisons

Arable oriented rotations on sub-site LBG2:

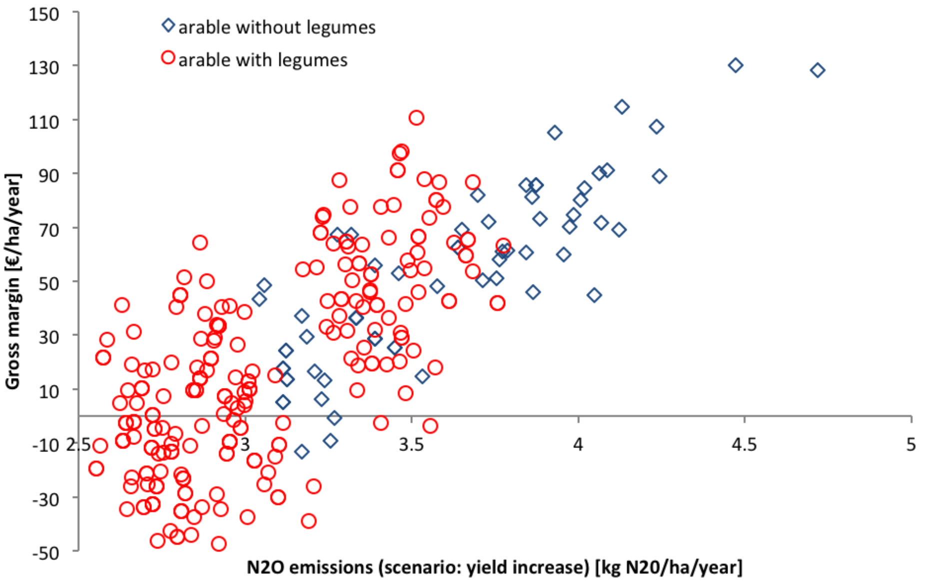


Comparison of rotational gross margins and N leaching for arable oriented rotations with (red circle) and without legumes (blue diamond) (sub site LBG2)

The positive correlation between gross margin and N-leaching in the arable rotations without legumes is caused by an increasing percentage of winter rape with its highest gross margin and also highest potential of N leaching of all grain crops.

Grain legumes with low economic return show a rather high of N leaching potential so their integration in crop rotations leads to the economic most unfavorable crop rotations with comparable high N-losses.

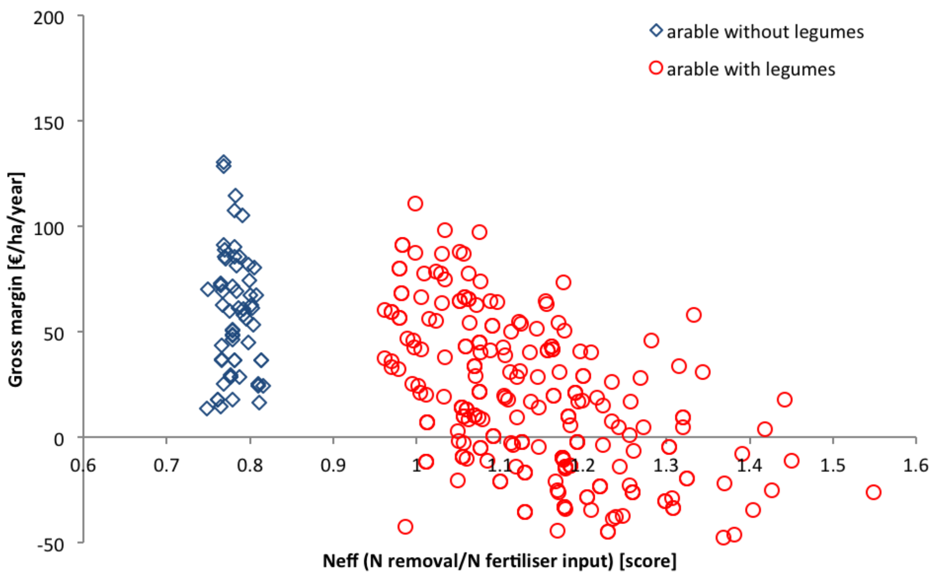
On the other hand an optimized integration of grain legumes in crop rotations (pea – winter rape) can provide one of the highest mean gross margin with comparably low N-leaching.



Comparison of rotational gross margins and N_2O emission potential for arable oriented rotations with (red circle) and without legumes (blue diamond) (sub site LBG2)

Rotation with grain legumes show on average lower N_2O emissions due to reduced use of N fertilizers.

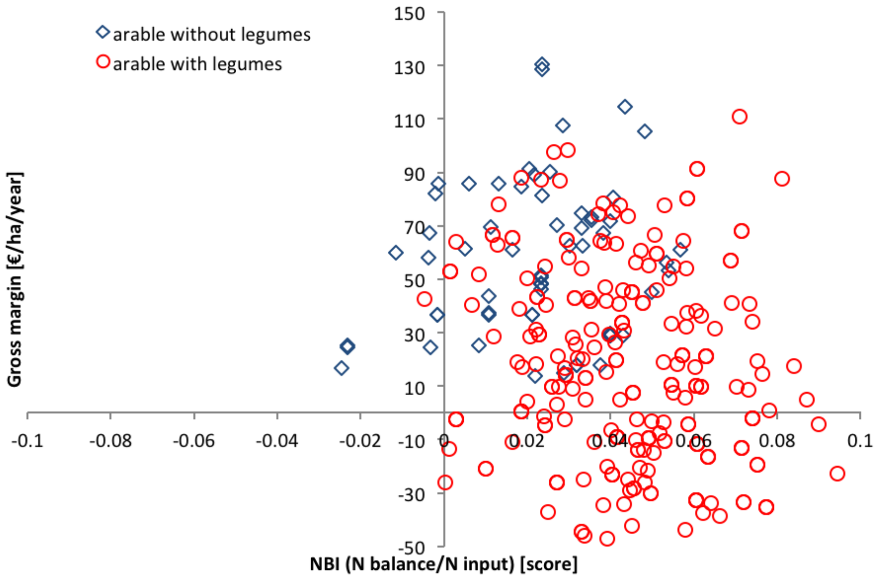
The positive correlation between gross margin and N_2O emissions in the arable rotations without legumes is mainly caused by an increasing percentage of winter rape followed by winter wheat with it highest gross margin but also highest N fertilizer input.



Comparison of rotational gross margins and N efficiency for arable oriented rotations with (red circle) and without legumes (blue diamond) (sub site LBG2)

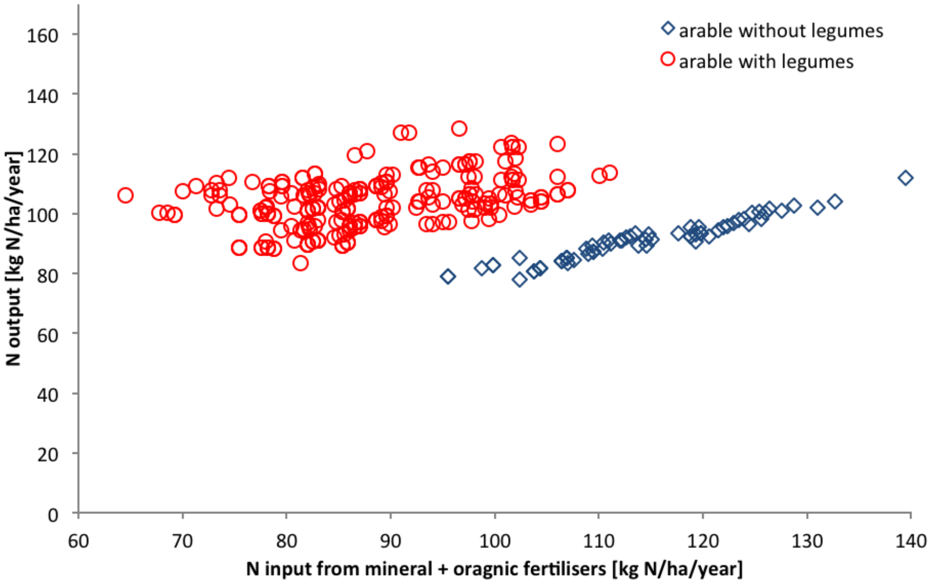
Compared to the legume rotation the rotations without legumes show a similar but significantly lower N efficiency due to the symbiotic N-Fixation of the grain legumes.

The strong differentiation within the legume rotation needs a more detailed examination of the underlying rotations



Comparison of rotational gross margins and N balance index for arable oriented rotations with (red circle) and without legumes (blue diamond) (sub site LBG2)

Based on the underlying assumptions of the N-budget, the rotations with legumes higher and mostly positive NBI indicates a slightly higher sustainability concerning the N status of the soil organic matter (SOM)



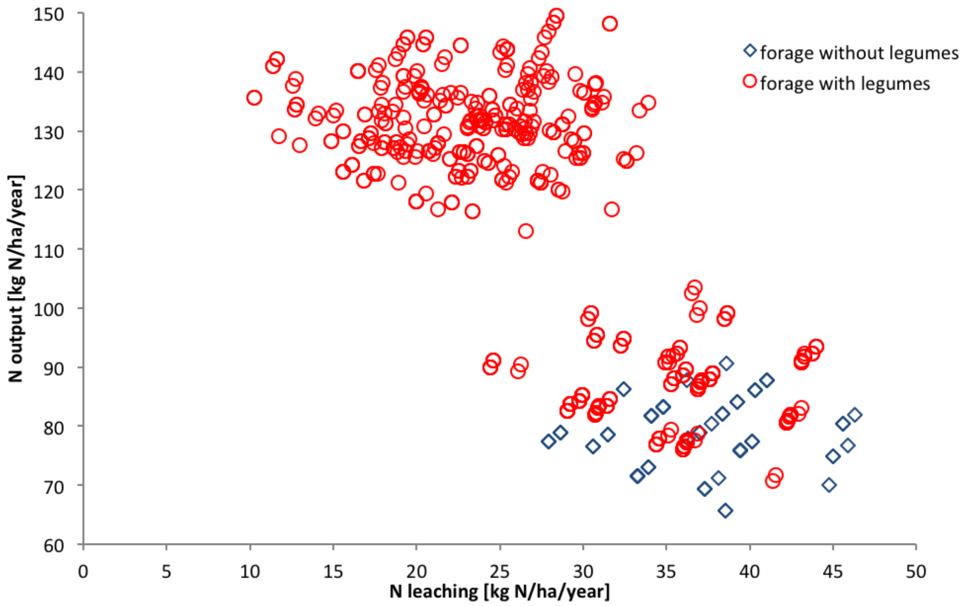
Comparison of rotational N output and N input from mineral and organic fertilizer for arable oriented rotations with (red circle) and without legumes (blue diamond) (sub site LBG2)

The N_2 fixation of the legumes leads to an reduced N-Input through mineral and organic fertilizers at a comparable N-Output at the rotational level.

There is a much more stronger correlation between N-Input and N-Output within the rotations without legumes with an disproportionately low rise of N-output to N-Input.

Due to the yield insecurity of grain legumes, the lack of actual cropping experiences and marketing difficulties caused by the actual marginal production volumes, there is still an obvious reservation in producing grain legumes in practice.

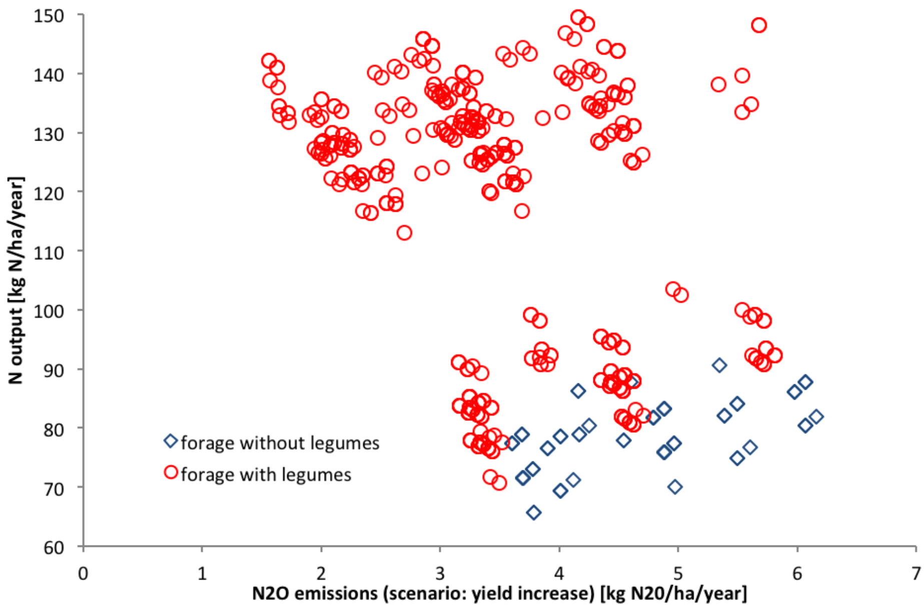
Forage oriented rotations on the sub-site LBG3:



Comparison of rotational N output and N leaching for forage oriented rotations with (red circle) and without legumes (blue diamond) (sub site LBG3)

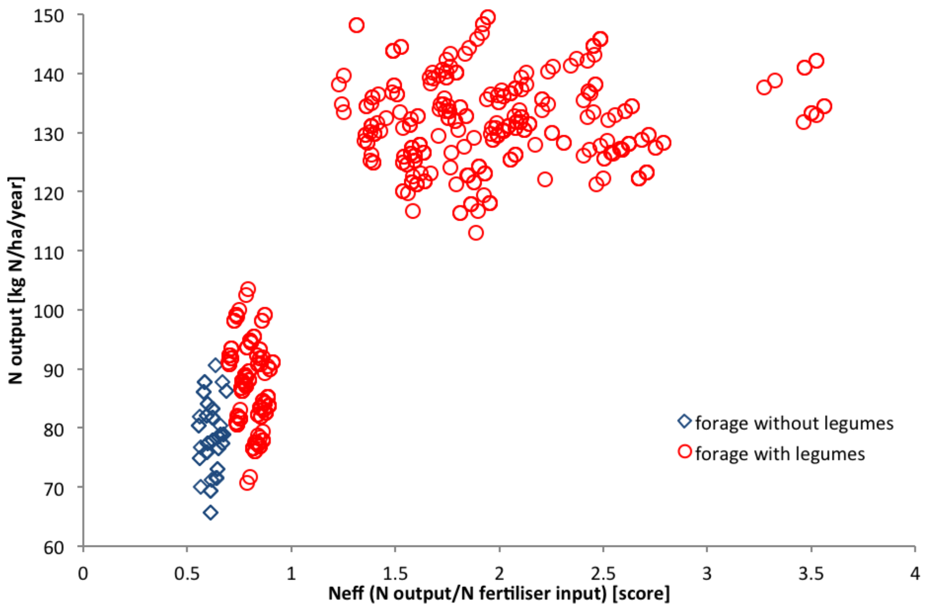
The forage oriented rotation with clover-grass and alfalfa show a much higher N-output with a simultaneously lower N leaching.

Lower portions of forage legumes combined with higher portion of silage maize with lower protein content and thus N output leads to an c convergence of the rotations to thus without forage legumes with different portions of silage maize. The later leads to higher N leaching with could be reduced significantly by integrating cover crops prior to silage maize, which is not modeled in the presented rotations.

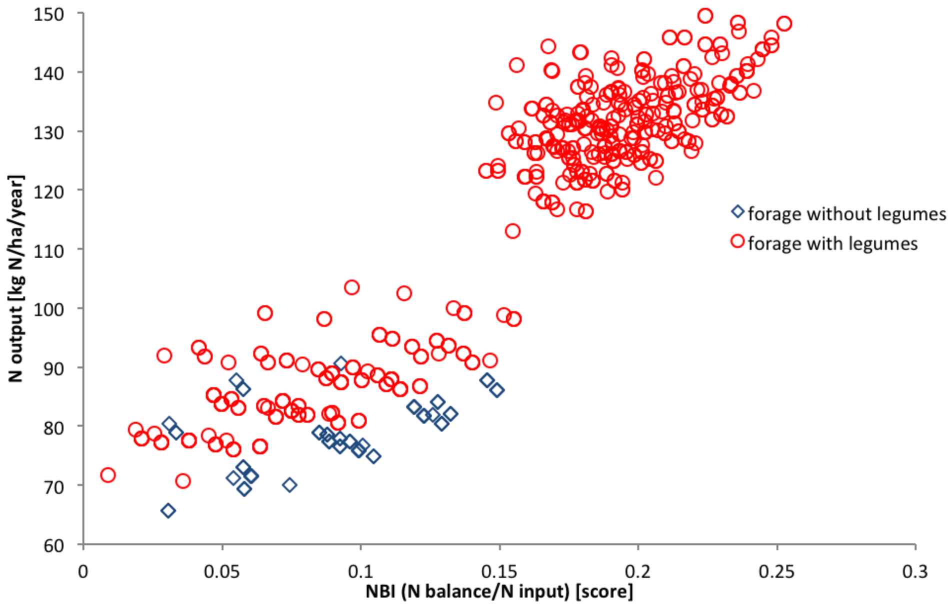


Comparison of rotational N output and N_2O emission potential for forage oriented rotations with (red cycle) and without legumes (blue diamond) (sub site LBG3)

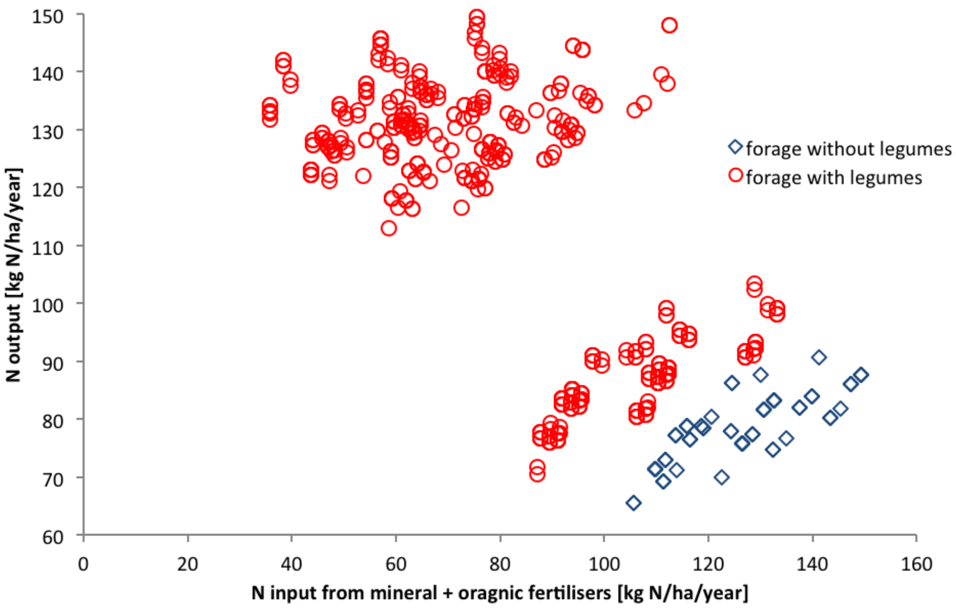
The significantly lower use of mineral N fertilizer within forage oriented crop rotations with forage legumes results in a significant lower N_2O emission rate of these rotations



Comparison of rotational N output and N efficiency for forage oriented rotations with (red circle) and without legumes (blue diamond) (sub site LBG3)



Comparison of rotational N output and N balance index for forage oriented rotations with (red circle) and without legumes (blue diamond) (sub site LBG3)



Comparison of rotational N output and N input from mineral and organic fertilizers for forage oriented rotations with (red circle) and without legumes (blue diamond) (sub site LBG3).

All in all higher portions of forage legumes in rotations leads to higher N output, lower N leaching, reduced N-Input through fertilizers and thus a higher N efficiency combined with a lower N_2O emission.

Some of dairy farmers in the regions of Brandenburg start again with forage legumes which were rather common in the former DDR. Most of them appreciate the soil fertility building capacity of forage legumes.

ANNEX 5. Västergötland, Sweden

The non-legume arable rotation

The model generated about 4000 arable rotations without legumes in Västra Götaland, which fulfil the restrictions given. The most profitable rotations all contain winter oilseed rape and almost all of the more profitable rotations have one or more crops of winter wheat in the rotation. Four of the five most profitable rotations include linseed between the cereal crops. Otherwise, the most important difference among the five top rotations is in which cereal crop that is grown before winter oilseed rape. The rotations resemble the common rotations in the area, except that they are more diverse than the typical rotations in the region. Winter oilseed rape, linseed, winter rye and triticale are grown in the region, but are not at all as common as winter wheat, spring barley and spring oats. Both spring oats and spring barley are grown much more than could be anticipated from the gross margins. The rotation number four resembles a rotation that many farmers aim for, but very often both winter oilseed rape and some of the winter wheat have to be replaced by spring cereals on the farms due to time constraints during autumn.

Table 1. The five non-legume arable rotations with the highest gross margins

Order of profitability	Crop 1	Crop 2	Crop 3	Crop 4	Crop 5	Average gross margin (€/ha/year)
1	wrape	wwheat	linseed	wwheat	sbarley	644
2	wrape	wwheat	linseed	wwheat	wrye	638
3	wrape	wwheat	wwheat	linseed	wrye	637
4	wrape	wwheat	wwheat	wwheat	sbarley	631
5	wrape	wwheat	linseed	wwheat	tritica	626

The legume arable rotation

More than 15000 possible rotations with legumes were generated. The rotations with legumes were generally less profitable than the rotations without. The most profitable rotation without legumes are about 9% or 51 € ha^{-1} more profitable than the most profitable rotation with legumes. Peas and faba bean are to a similar extent incorporated in the most profitable rotations. The rotations are similar as the rotations without legumes, except that the legumes are incorporated between two winter cereal crops. The crops in positions one, two and four are the same in all rotations.

Table 2. The five legume arable rotations with the highest gross margins.

Order of profitability	Crop 1	Crop 2	Crop 3	Crop 4	Crop 5	Crop 6	Average gross margin (€/ha/year)
1	wrape	wwheat	fababea	wwheat	sbarley		593
2	wrape	wwheat	linseed	wwheat	pea	wrye	590
3	wrape	wwheat	pea	wwheat	linseed	wrye	590
4	wrape	wwheat	fababea	wwheat	wrye		587
5	wrape	wwheat	pea	wwheat	wwheat	sbarley	585

The non-legume forage rotation

The under-sowing of grass is done in a pea/oat mixture and then stays for three years in the most profitable rotations. The grass crop is followed by winter oilseed rape and then typically of winter cereals. Winter wheat is more profitable than rye, which is more profitable than triticale. Maize replaces the winter cereal in the fourth rotation and in the fifth rotation the grass is under-sown in oats.

Table 3. The five non-legume forage rotations with the highest gross margins.

Order of profitability	Crop 1	Crop 2	Crop 3	Crop 4	Crop 5	Crop 6	Average gross margin (€/ha/year)
1	peaoat	grass	grass	grass	wrape	wwheat	860
2	peaoat	grass	grass	grass	wrape	wrye	810
3	peaoat	grass	grass	grass	wrape	tritica	770
4	peaoat	grass	grass	grass	wwheat	maize_s	688
5	soat	grass	grass	grass	wrape	wwheat	684

The legume forage rotation

Except for the clover in the forage crop, the most profitable rotations are similar to the rotations with pure grass in the forage crops. The clover adds about 4% or 30 € ha^{-1} to the result.

Table 4. The five legume forage rotations with the highest gross margins.

Order of profitability	Crop 1	Crop 2	Crop 3	Crop 4	Crop 5	Crop 6	Average gross margin (€/ha/year)
1	peaoat	graclov	graclov	graclov	wrape	wwheat	894
2	peaoat	graclov	graclov	graclov	wrape	wrye	845
3	peaoat	graclov	graclov	graclov	wrape	tritica	805
4	peaoat	graclov	graclov	graclov	wwheat	maize_s	800
5	soat	graclov	graclov	graclov	wrape	wwheat	708

The analyses of the arable rotations

Nitrogen leaching

The leaching from the top five arable legume rotations will according to the model be about 4.5% or 1.4 kg N ha^{-1} $year^{-1}$ smaller than in the top five rotations without legumes (Figure 1). The treatments with spring barley before winter oilseed rate had the highest leaching.

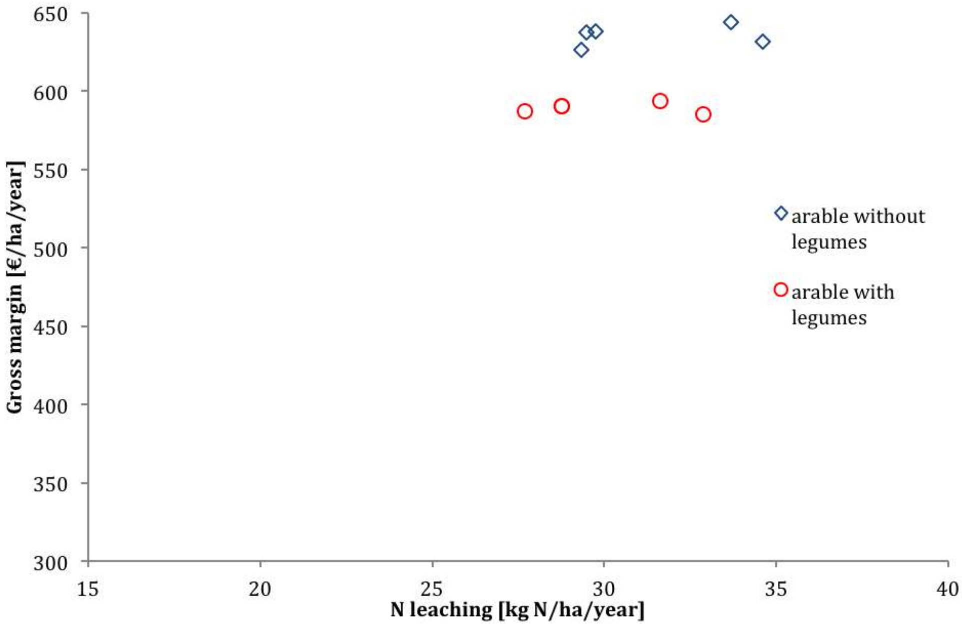


Figure 1. Modelled leaching of nitrogen from the five legume and non-legume rotations with highest gross margin.

Nitrogen balance index (NBI)

The Nitrogen balance index (NBI) is, on average, slight higher with legumes than without, but it differs more among the rotations within groups. The only difference between the legume rotations with the lowest and the highest NBI is that the lowest have spring rape in position five, while the highest has winter rye in that position. The non-legume rotations with the highest and the lowest NBI differs in position three, where the rotation with the lowest NBI have linseed and the highest winter wheat. Major reasons for a high NBI in the region might be low yields due to weather constraints. Leaching is a problem on the more sandy soils, but compared to many other regions in Sweden leaching losses should be small. Wet conditions could make denitrification a problem.

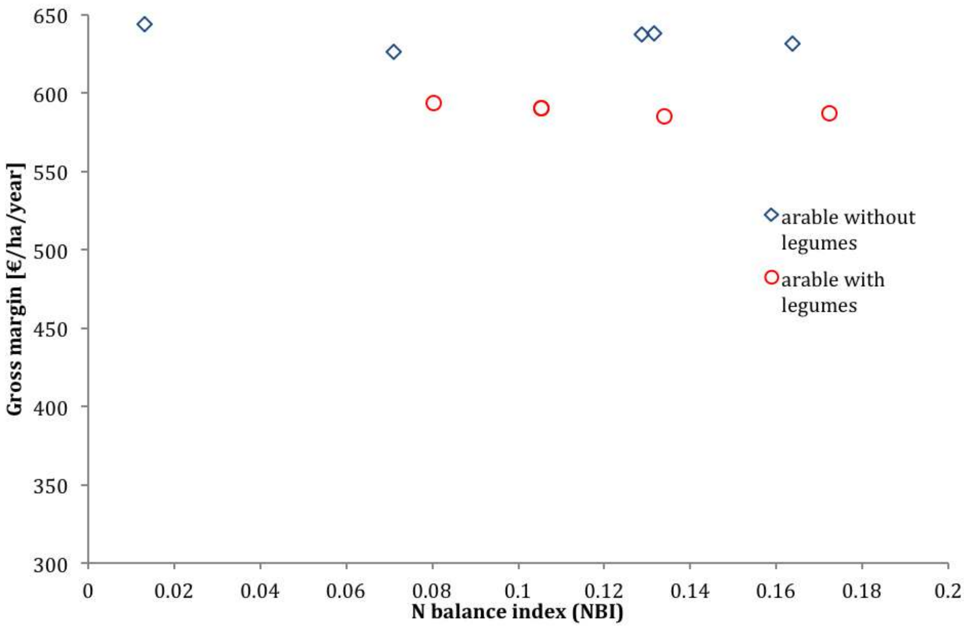


Figure 2. Modelled N balance index (NBI) for the five legume and non-legume rotations with highest gross margin.

Nitrogen efficiency (Neff)

As an average of the five top legume rotations, 86% of the N is recovered in the harvested products according to the model, while only 64% was recovered in the non-legume rotations. The most efficient rotation was the legume rotation with the highest gross margin. Thus substituting linseed for faba beans, which is the only difference between the non-legume rotation with the highest gross margin and the legume rotation with the highest gross margin, makes the rotation less profitable, but more N efficient.

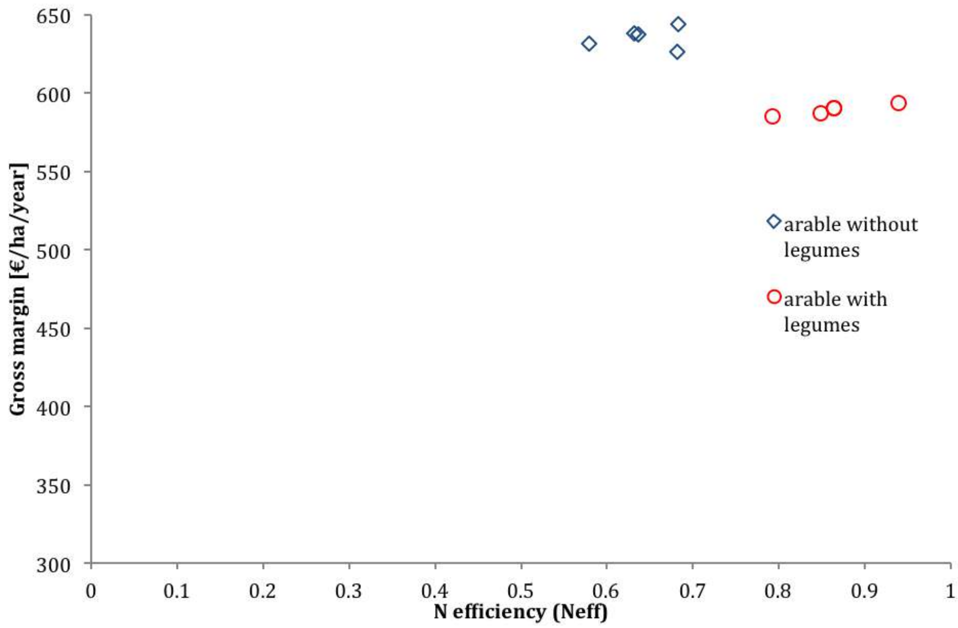


Figure 3. Modelled N efficiency (Neff) for the five legume and non-legume rotations with highest gross margin.

Nitrous oxide (N_2O) potential

The N_2O emissions were on average 11% or 0.47 kg N_2 0 ha^{-1} $year^{-1}$ smaller in the top five legume rotations than in the top five non-legume rotations. The results were identical between the two methods of calculating N_2O emissions. The rotation with the highest gross margin also had the lowest N_2O emissions within each group of rotations.

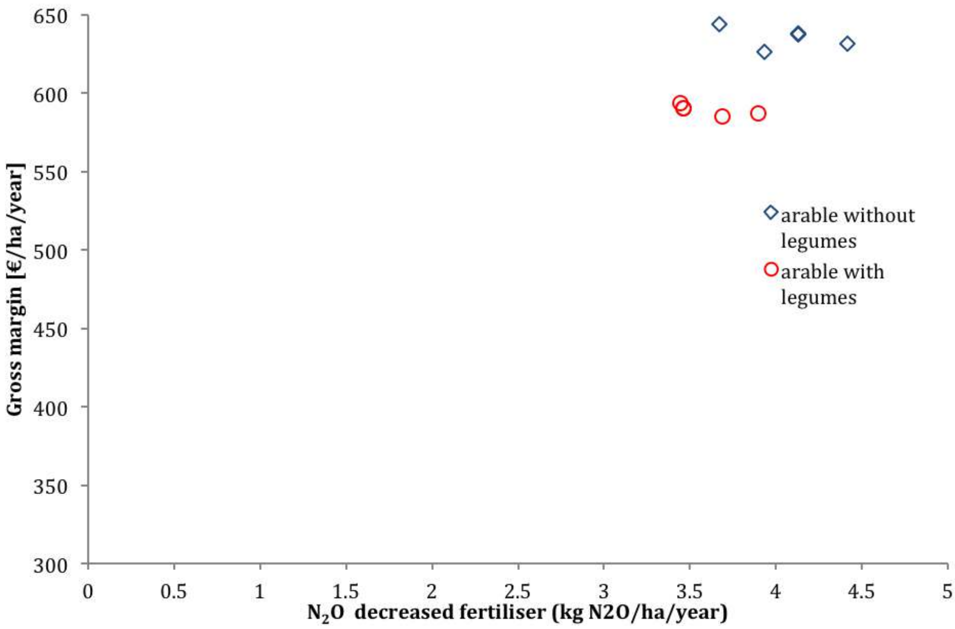


Figure 4. Modelled N_2O emissions for the five legume and non-legume rotations with highest gross margin.

Discussion of arable rotations

The rotations without legumes generally have a higher gross margin than the rotations without, but all of the environmental indicators show benefits with the legume rotations. The rotations with the highest gross margins within each group are also in top when it comes to the environmental indicators. The most profitable rotation is winter oilseed rape – winter wheat – linseed – winter wheat – spring barley. In the most environmentally friendly rotation the linseed is replaced with faba beans. That is the rotation with the highest N efficiency and lowest N_2O losses, but the N leaching was 4 kg ha^{-1} higher than the rotation with the lowest N leaching, in which the spring barley was replaced with rye in the fifth position.

Most farmers would probably not be willing to reduce the gross margin by 51 € ha^{-1}, which would be the cost of replacing linseed for faba bean. However, there might be exceptions. The value of the faba beans to a farmer that need protein to the pigs are probably higher than the market price used in the model. It is also likely that if the acreage of linseed increases as suggested by the good results in the present study, market prices would go done. This dynamics cannot be seen in the model. The environmental savings are evident, but their robustness must be tested in a sensitivity analyses and important assumptions checked before any major conclusions should be drawn regarding the environmental effects.

Among the possible reason for the discrepancy between the suggested rotations and the actual rotations is probably that farmers consider the risk of winter oilseed rape failure due to poor overwintering greater than the model. The time for establishing winter crops are very short in the region, which means that good conditions for sowing of winter oilseed rape never appears or only appear during a very short time some years, because the preceding crops mature late or because of dry conditions that d not allow germination of the rape seeds.. We have restricted the use of winter wheat before winter oilseed rape in the model because of this time constraint, but when conditions are right farmers use this option, because winter wheat is considered more profitable on fertile soils than rye and spring barley. If barley and winter wheat matures at the same time, which I often the case, farmers would like to priorities the winter wheat at harvest, because of the greater risk of losing quality if the crop is not harvested in time with winter wheat than with barley. Since the time for autumns sowing is short, farmers are only rarely able to do as much sowing during autumn as they would like. This opens up for spring cereals. Oats do very well in the region, but it is possible to get a better price for barley with malting quality. Pig producers also like to grow spring barley for feed. The rotation number five as really number six but I excluded the real number five because spring wheat appeared before winter oilseed rape, which should have been restricted in the model. Spring wheat matures late and a winter oilseed crop sown after spring wheat would not be large enough before winter to survive. It also seems that the model appreciate the use of break crops more than farmers do. Linseed is used by farmers in the region as suggested by the model, but only by a minority of them. The most profitable rotations all have winter wheat after winter oilseed rate, which is a good choice because of the large preceding crop effect and because of the ease of establishment. Almost no farmers use the plough between winter oilseed rape and winter wheat.

The inclusion of legumes between the cereal crops increase yield of the subsequent winter cereal crop with about one ton ha^{-1}, reduce the need for tillage before the winter cereals, diversify the use of herbicides and reduce the need for fungicides. The problem is that the legumes are not very profitable themselves. Yields are not stable and the market prices vary more than the price of cereals and are generally considered to be too low. The trend is that peas are grown less and field bean more during later years. The most likely reasons for this is that the problem with *Aphanomyces* pea root rot has increased during recent years, especially on the more clayey soils. Farmers also consider the peas more difficult to harvest than the field bean. It is a problem that field bean matures too late, even if earlier varieties have become available in recent years and that the average time for spring sowing is earlier today than a couple of decades ago. Farmers can solve that by defoliating the field beans with chemicals, but this is not considered a good option because they are not allowed to use the most efficient product, i.e. glyphosate.

The top ranked rotations are feasible. Due to time constraints farmers will not be able to sow this high percentage of winter crops in all years, which will in practice increase the acreage of spring cereals. I have restricted the use of winter wheat before winter oilseed rape in the model, because it is not possible in many years due to late maturing of the wheat. However, in practice farmers sometimes take this option when it appears. Without this restriction there might have been even more winter wheat in the rotations. The model suggests break crops to a much larger extent than is practiced. The reason why many farmers don´t use break crops is unclear. One might be that we have overestimated the gross margin of linseed and winter oilseed rape, e.g. crop failure might be more common than we have anticipated. Another reason might be that the farmers are not comfortable with crowing those crops and that they could get better prices of spring cereals than the official market price by delivering according to certain contracts.

The analyses of the forage rotations

Nitrogen leaching

The nitrogen leaching increased by 3% or 0.46 kg N ha-1 with the introduction of clover in the forage crops considering the top five rotations with and without clover (Figure 5.). Still leaching is reduced by about 50% compared to the best rotations with only arable crops. The largest leaching losses are found in rotations with winter wheat and maize in position six and the smallest with rye or triticale in position six.

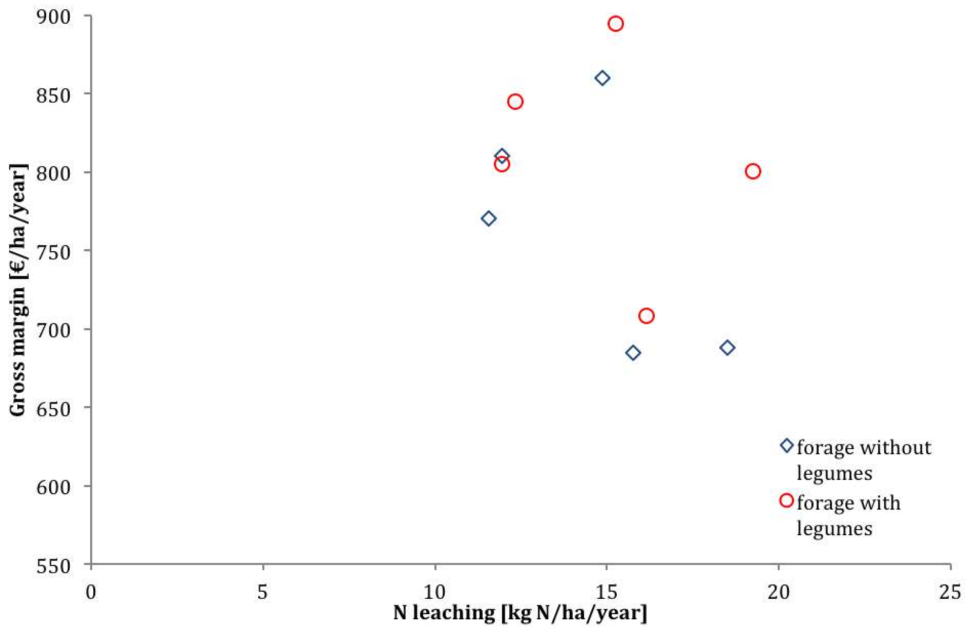


Figure 5. Modelled leaching of nitrogen from the five legume and non-legume forage rotations with highest gross margin.

Nitrogen balance index (NBI)

The nitrogen balance index (NBI) is generally high in all the top rotations, but highest in the treatments with largest gross margin, i.e. in the rotations with winter oilseed rape and winter wheat in positions five and six (Figure 6.). The NBI is, on average, 24% higher in the rotations with clover than in the rotations without clover.

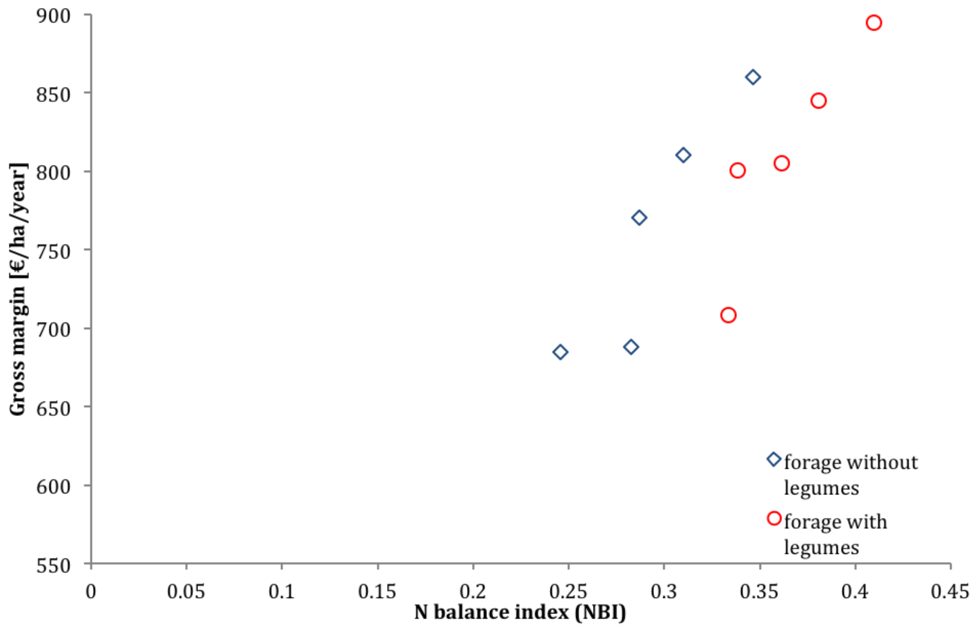


Figure 6. Modelled N balance index (NBI) for the five legume and non-legume rotations with highest gross margin.

Nitrogen efficiency (Neff)

The recovery of nitrogen was, on average, 67% in the top five rotations without clover and 85% in the rotations with clover. The recovery was least efficient in the rotation with winter oilseed rape and winter wheat in positions five and six with the highest gross margin than in the other rotations.

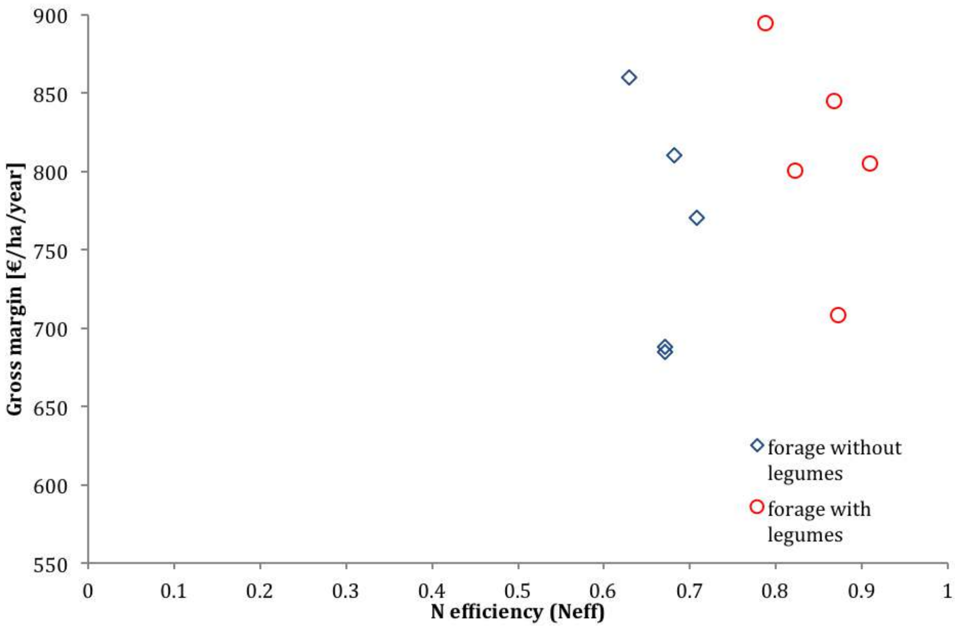


Figure 7. Modelled N efficiency (Neff) for the five legume and non-legume rotations with highest gross margin.

Nitrous oxide (N_2O) potential

The N_2O emissions were on average 17% or 1.1 kg ha^{-1} year^{-1} smaller in the top five rotations with clover than in the top five rotations with pure grass as forage crop. The results were identical between the two methods of calculating N_2O emissions. The rotation with winter wheat and maize in position five and six lost 17% or 0.94 kg ha^{-1} more than the average of the other top five rotations in both groups. The losses from the rotations with under-sowing of the forage crops in oats was 8% or 0.44 kg ha^{-1} smaller than in rotations with under-sowing in a mixture of pea and oats, excluding the maize rotation.

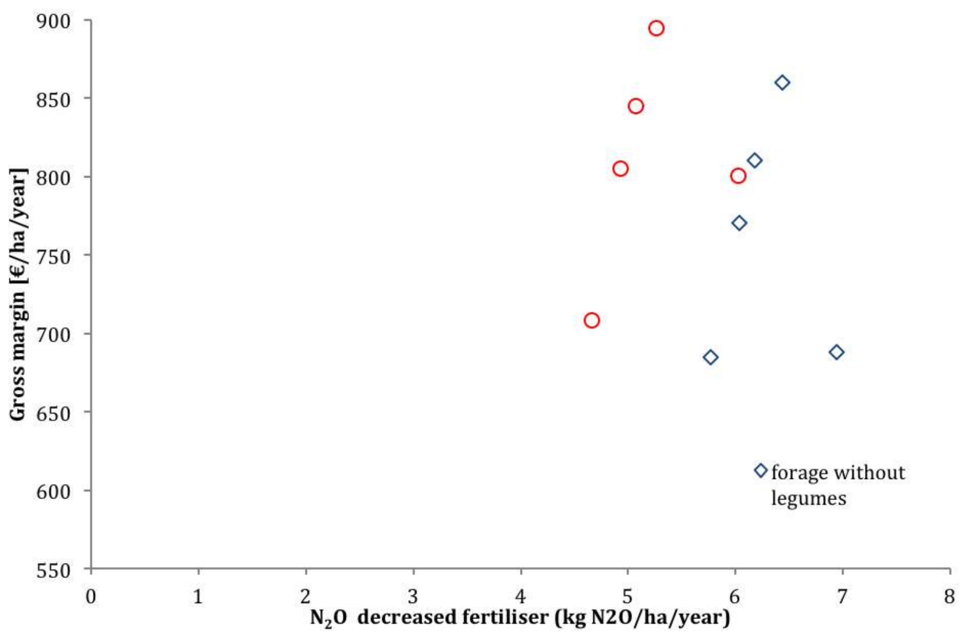


Figure 8. Modelled N_2O emissions for the five legume and non-legume rotations with highest gross margin.

Discussion of forage-rotations

The gross margin was higher in rotations with legume based forage crops than with pure grass. All of the most profitable rotations had forage crops for three years that was established by under-sowing in a mixture of pea and oats. The positions five were generally winter oil seed rape and position six winter cereals. The rotation with the highest gross margin had winter wheat in position six. The fourth ranked rotation in terms of gross margin had winter wheat and maize in the fifth and sixth year, respectively. The largest losses of N through both leaching and N_2O happened in the fourth ranked rotation with maize. The leaching losses were similar with and without clover, but clover increased NBI and Neff, and reduced N_2O losses.

It is unusual to grow a pure grass forage crop and the results show no reason why they shall abandon that practice. It has both economic and environmental benefits according to the model. Winter oilseed rape is more uncommon with farmers that grow forage crops than with pure arable farmers, but since they can not only sell the oil, but also have good use of the feed it produces it is a good option. The reason why they don´t grow it more is probably lack of interest in arable crops that are more difficult to grow than cereals. This region differs from other regions in Sweden in that the under-sowing of the forage crops is generally done in oats, while in the rest of Sweden it is generally done in spring barley. The reason for this is that the under-sown crops generally grow well during summer in the region, because of the moist climate, and could cause problems at harvest of the short growing spring barley. Therefore, it is surprising that it shows to be much more profitable to do the under-sowing in a pea/oat mixture. The percentage of clover is not always as high as it could be in farmer´s fields. It might be possible to increase the benefits of the clover further by reducing the rate of N-fertilizer and to use a fertilizer strategy that benefit the clover.

The top-ranked rotations are feasible, but there are no reasons presented in the analyses to exclude clover in the forage crops. The rotations with clover are both more profitable and environmentally reliable. Maize is becoming increasingly popular and a rotation with maize ranks among the top five. However, it come out worse in the environmental analyses and from this analyses it is not possible to recommend maze. One big advantage with maize is that it helps spreading the farmers work load over the year, which could have an extra value that is not accounted for.