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MITIGATION COSTS THROUGH ALTERNATIVE CROP ROTATIONS IN AGRICULTURE:

AN ASSESSMENT FOR 5 EUROPEAN REGIONS

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To develop a better understanding of the agriculture sector in the context of climate change and the corresponding issue of cutting greenhouse gas (GHG) emissions, this paper aims at assessing regional mitigation potential and cost due to changing crops rotations at farm-scale in five European regions. For this purpose, we use rotation database from Reckling et al (2014) bringing accurate and exhaustive data about crop management in these areas. First, we complete the database with nitrous-oxide (N2O) emissions calculations and bring an additional hypothesis on pre-crop effect so as to capture the diversity of knowledge outlined in the agronomic literature. Then, GHG abatement cost is assessed using a bottom-up approach and assuming that farmers are maximizing their profit.

In the literature on mitigation cost assessment, the abatement effort is generally considered as marginal and hence is added to previous cumulated efforts of reduction. In contrast, this study analyses rotation switch which implies a complete switch of cropland systems on several years (up to 6 years). Results show that aggregated "win-win" abatement potential in the five European regions could reach a maximum of 35% of the baseline soil N2O emissions of arable areas. The total dry matter production is increasing, while the area under cereal production is decreasing to this level of GHG abatement. Consequently, these findings tend to indicate that variations in agricultural production linked to a mitigation policy, while generating important changes in cropping systems, would not necessarily endanger food security.

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1 Introduction

In its last communication on climate policy framework, the European Commission set an ambitious target of greenhouse gas (GHG) emissions reduction of 40% compared to the 1990 level by 2030 (European Commission, 2014). This effort follows the recommendations of scientists of the Intergovernmental Experts Group on the Climate Change (IPCC) to contain the average temperature increase below 2°C globally by the end of the century. According to the Annual European Union Greenhouse Gas Inventory, the EU-27 emitted 4,550 million ton CO_2 equivalents ($MtCO_2eq$) in 2011, with the agricultural sector being the second largest emitter, with 461 $MtCO_2eq$ emissions (10.1 %)(UNFCCC, 2013).

Among the numerous practices suggested to mitigate GHG emissions, one is to modulate the area of crops implanted in cropland. Since crops do not have the same needs in nitrogen application, favouring those requiring less fertilisation could bring significant abatement of GHG emissions. At the forefront, increasing the cultivation of legumes in crop rotations and on grasslands has been highlighted by many studies (Dequiedt and Moran, 2015; Cavaillès, 2009). These crops are able to fix nitrogen from the atmosphere. Therefore, not only they need no or very little nitrogen fertiliser for their own growth but also provide substantial amount to the subsequent crop in rotation (Charles et al, 2001; Köpke and Nemecek, 2010). Additionally, legumes provide a range of other potential rotational benefits that are not directly related to nitrogen such as increasing phosphorus availability (Hassan et al, 2010), reducing soil strength that contributes to the development of better root systems (Rochester et al, 2001) or reducing diseases or pest (Jensen et al, 2010). These properties allow higher yields from succeeding crops at the same fertiliser rate or a reduced fertiliser use for the same yield or a combination of both. Grain and forage legumes are currently grown on 180 million hectares worldwide and their extent is expected to increase as the demand for legume production for dietary protein increases. However, the European context is less promising; the cultivation of legumes as grains and forage has declined throughout the EU from 11.3 million ha in 1961 to about 3.4 million ha in 2005[1]. Having said that, the interesting properties of legumes should not hide the potential of other crops with low nitrogen need and which could participate as well in carbon mitigation. Rapeseed (Justes et al, 1999), some kinds of grass and leaf crops are also well known to limit nitrogen leaching and hence restrict resulting greenhouse gases.

To assess GHG abatement cost in European agriculture via increasing low GHG emitting rotations, an abatement cost curve analysis is carried out. The latter shows the cost of one additional abatement option for different levels of total emission reduction. Abatement cost curves have been developed in several other studies to illustrate the economics of climate change mitigation in croplands. De Cara and Jayet (2011) assess the marginal abatement cost of agriculture in Europe and focus mainly on fertilisation reduction regarding N_2O emissions abatement. The UK government has used marginal abatement cost curves (MACCs) to evaluate climate policy in all sectors of the economy (MacLeod et al, 2010) and an agricultural abatement cost assessment was also developed for France (Pellerin et al, 2013). They both appraise the

[1] FAOSTAT 2011 data, accessed: January2014 for the year 2011.

potential of crops requiring few nitrogen fertilisations (legumes, forage plant varieties, intermediate and cover crops) and estimate the associated cost of mitigation per ton CO_2 equivalent unit. According to the latter, legumes could reduce GHG emissions by 1.4 $MtCO_2eq$, with a mean abatement cost of -52€/tCO_2eq and estimate intermediate crops introduction potential to be 115 to 260 €/tCO_2eq. In the UK, Moran et al (2010) assess an abatement potential of 16 to 43 £/tCO2eq for legume and a potential of -31,35 to -71,60 £/tCO2eq with plant varieties.

Nationwide MACCs (Pellerin et al, 2013 ; Moran et al, 2010 and Wang et al, 2013), assessing different mitigation options, estimate a national average mitigation cost. Although these studies bring useful insights of the most effective options in term of abatement cost, there is still a need to investigate the cost at a more detailed area so as to observe the variability hidden behind the average national cost. Accordingly, following a bottom-up approach, we focus on disaggregated regional levels and within these levels on different site class characteristics. A classification of low emitting rotations is obtained for each of them which allows creating abatement cost curve for individual geographical area unit. Consequently, we obtain an increasing abatement cost curve and not a single average abatement cost for the overall level. Dequiedt and Moran (2015) also reach a more disaggregated geographic level in France and obtain increasing MACCs. However, they strictly focus on legume introduction in cropland up to two years without taking into account, first, the potential of other crops and, second, the sequence of crops on a longer period. Here, following rotations database generated by Reckling et al (2014), we hope to match the potential of a mix of crops, and not specifically legumes, following agronomic rotation planning up to 6 years. Lastly, a noteworthy difference between the present assessment and the above-mentioned studies is that, here, the abatement cost is not marginal but implies a complete change of rotation on several years. Thereby, we do not use the term "*marginal abatement cost*" but rather "*abatement cost*" since at each site class level the last mitigation option, i.e. the most cost-efficient rotation regarding a specific abatement objective, substitutes the potential of the previous rotation potential.

This report assesses five regions in Europe, representing a diversity of land types and agroecological zones: Eastern Scotland (UK); Västsverige (Sweden); Brandenburg (Germany); South-Muntenia (Romania); Calabria (Italy). These regions are depicted by 13 representative site classes with different soil features, agricultural practices and crops. Information related to crops like production costs, yield, or crop prices has been collected in an agronomic survey by Reckling et al (2014). Based on agronomic practices and rules, the authors used the survey data to generate possible rotations for the 13 site classes and obtained in total 79,340 potential rotations. The current article uses the information of fertilisation and yield data of the above mentioned survey and completes the database by calculating soil-based nitrous-oxide (N_2O) emissions from crop cultivation. Two agronomic scenarios are examined to tackle the diversity of pre-crop effect from legumes depicted in the agronomic literature. In the 'Yield' scenario, we assume that the pre-crop effect causes an increase in the following crop's yield with no change in the fertilization practice. The 'Fertilization' scenario assumes that chemical fertilisation is reduced by 20% for the following crops with no change in their yield.

Constructing the abatement cost curve follows two steps. First, using mixed integer programming, we generate an abatement classification of the different available rotations for each site class. The purpose here is to select for successive abatement goals the rotations that reduce emissions at the least cost. Second, results are aggregated at the level of the five European regions, using the cost-effectiveness ranking of rotations, so as to draw the overall abatement cost curve.

The rest of this paper is structured as follow. The next part describes the methodology used to calculate data and to generate abatement cost curves. Section 3 presents the results of the assessment with the abatement cost curve, crop production and crop area evolution. Section 4 discusses the accuracy of the abatement cost assessment regarding the frame of the methods and is followed by conclusion in Section 5.

2 Methodology

Data description

The database generated by Reckling et al (2014) captures the bio-physical and socio-economic variability of different regions across Europe: five contrasting regions were selected as case study regions. Within the case study regions, a local typology of site classes was formulated. On total, 13 site classes were defined: 5 for Brandenburg, 1 for Sud-Muntenia, 3 for Calabria, 3 for Eastern Scotland and 1 for Västsverige (see Appendix 1 for more details on the site class characteristics).

The database includes 544 agricultural activities. Each agricultural activity concerns the cultivation of one crop grown for one year and is characterized by a site class location, a preceding crop type, and specific agro-economic data (yield, dry matter content, synthetic and organic fertilizer amount and the production cost of fertilization, pesticides products and labour). Based on these data, gross margins were calculated by Reckling et al (2014). The gross margin is the difference between the revenue and costs per hectare for each crop (see Appendix 2 for more details), not considering subsidies received.

In addition to gross margin data in Reckling et al (2014), N_2O emissions are calculated in this prsent paper, using the IPCC Tier 1 methodology (IPCC 2006). The emissions include direct and indirect N_2O emissions from synthetic fertilizers applied, manure and from crop residues.

Legume preceding crop effect

Among the 544 agricultural activities, 317 are characterized by a so-called pre-crop effect. This pre-crop effect results from the additional nitrogen amount left in the soil from residues from the crop grown the year before. This effect is triggered by legumes but also by potato, rape, leaf crops and some kinds of grass and mainly consists in changes of fertilisation, yield and agro-chemical applications.

In the "Yield" scenario, the pre-crop effect is assumed to increase the following crop's yield, while keeping the fertilization rate constant. We follow here the assumption made by Reckling et al (2014) in their database. On average, crops that benefit from the so-called pre-crop effect have a 17.8% higher yield than the same crops without pre-crop effect.

In the "Fertilisation" scenario, we assume that the pre-crop effect induces a 20% decrease in nitrogen fertilisation while keeping the yield constant. We follow here a part of the agronomic literature considering, conversely, that N-fixing crops cannot trigger an increase of yield in reason of cropland over-fertilisation (Martin and Meynard, 1997). The rate of 20% decrease of nitrogen application is based on the UK's Fertiliser Manual (Defra, 2011), which assumes that the soil nitrogen supply is 30 kg N/ha higher after peas and beans than after cereals and suggests reducing the nitrogen applied accordingly. Organic fertiliser application is assumed to be reduced in practice by 20% as well, but the resulting organic nitrogen surplus is considered to be used on other fields where it substitutes the application of other synthetic nitrogen. Therefore, assuming a replacement rate of 33% (a value in the lower range used in the different European countries according to Webb et al 2010), the total nitrogen reduction effect from organic fertilisation is estimated to be 6.66%.

Figure 1 shows the differences of data between the two different scenarios for pre-crop effect. We observe that the “Yield” hypothesis induces higher gross margin but also higher emissions than in the “Fertilisation” one.

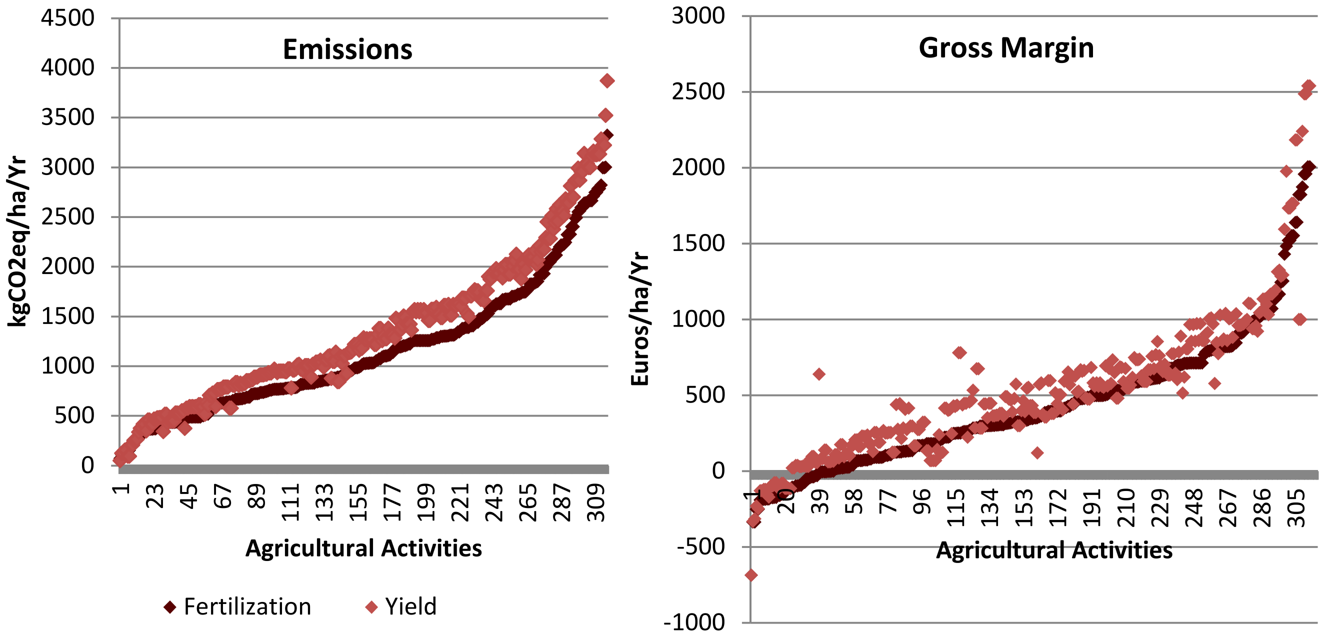

Figure 1 – Characterization of the pre-crop effect between the two scenarios.

These two graphs represent 317 of 544 agricultural activities characterized by a pre-crop effect. The abscissa axis shows the different agricultural activities ranked according to emissions (left-hand chart) or gross margin (the right-hand chart)

Rotation Data

In Reckling et al (2014) crop rotations are generated for each case study region separately. Region-specific crop rotation rules are the basis for generating crop rotations of 3 to 6 years. The latters represent agronomically feasible cropping options for the arable areas, including crops that are currently grown and potential grain and forage legumes. A total of 79,340 rotations are finally available for the 13 site classes, though the number of rotations per site class are variable, ranging from 117 rotations in South-Muntenia to 44,606 rotations in Västsverige.

Table 1 compares rotations data: gross margins, emissions and yields of the overall the potential rotations in each region are averaged to show the difference between regions and between the two scenarios. Average emissions and average gross margins are higher for rotations built on the “Yield” hypothesis than on the “Fertilisation” one in all regions, in line with what we observe in crop data. In both scenarios the average gross margin for rotations with legumes is lower than the average gross margin for rotations without legumes in three regions: Calabria, Eastern Scotland and Västsverige. In Brandenburg and in South Muntenia, the gross margin for rotations with legumes is higher, but the standard deviation is far more important when rotations include legumes[2].

Table 1 – Comparison of rotations data between the five European regions

		Number of Available Rotations	**Gross Margin (GM)**				**Emissions**		**Yield**	
			Average euros/ha/yr		**Standard Deviation euros/ha/yr**		**Average tCO2eq/ha/yr**		**Average t Dry Matter/ha/yr**	
			“Yield”	**“Fertilizer”**	**“Yield”**	**“Fertilizer”**	**“Yield”**	**“Fertilizer”**	**“Yield”**	**“Fertilizer”**
Brandenburg	**Without Legumes**	557	58,53	53,47	45,82	40,70	1,51	1,50	6,25	6,21
	With Legumes	3507	102,07	74,54	87,64	90,33	1,15	1,10	6,28	6,04
Calabria	**Without Legumes**	13	330,93	327,68	94,91	77,67	0,57	0,52	2,44	2,41
	With Legumes	496	191,00	162,61	86,59	78,63	0,41	0,37	2,39	2,29
South Muntenia	**Without Legumes**	4	340,14	340,14	70,62	70,62	1,04	1,04	3,48	3,48
	With Legumes	113	409,32	342,32	128,54	126,70	0,88	0,83	3,52	3,23
Eastern Scotland	**Without Legumes**	2516	820,03	795,47	69,80	74,39	1,38	1,30	5,95	5,76
	With Legumes	27528	624,39	598,68	195,23	192,38	1,21	1,12	5,58	5,38
Västsverige	**Without Legumes**	3190	467,85	461,69	58,38	62,91	1,14	1,11	3,91	3,80
	With Legumes	41416	385,88	370,36	67,74	59,29	1,06	1,01	3,71	3,60

Baseline rotations

For each site class, a baseline rotation is identified to represent common and regional specific cropping practices. The baseline rotation is selected on the basis of three main criteria: (1) crop sequence constraints, (2) crop composition and (3) gross margin. On the first point, rules on crop type frequency constraints are applied to help to control soil-borne pests and diseases that are relevant for crops of the same type e.g., cereal nematodes. Timing restrictions implementation ensures 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. Regarding crop composition, the purpose is to match the crops composition of the

[2] The Standard deviation is a common statistic that can be used to measure the volatility (so the associated risk) of the gross margin.

rotation with region-specific agricultural statistics of crops areas[3]. Hence, in Brandenbourg, crops in baseline rotations are the 5 most widespread in current croplands. In Calabria, crops in baseline rotations take over 7 of the first 12 crops established in the region. In Västeverige, chosen crops correspond to 2 of the first 3 grown crops. In South Muntenia, baseline crops are the first 4 cereals cultivated in the region. Lastly, in Eastern Scotland, crops composing baseline correspond to the first 5 crops of the region. Since in all the five case study regions the proportions of area covered by legumes is below 6%[4], and the smallest possible legume proportion is 16.6% in the modelled rotations (as the longest rotation in each site class lasts 6 years), only rotations without legumes were selected as baselines. Thirdly, at the level of one site-class, when several potential baseline rotations have the same crop composition and sequence, the rotation with the highest gross margin is defined as the baseline rotation. The baseline rotations are presented in Table 2 which display the average annual gross margin, emissions and yield. Appendix 6, shows the relative position among all the possible rotations in the different site classes.

Table 2 – Baseline rotations for the 13 site classes (for crop abbreviations see Appendix 7)

Region	**Site Class**	**CropSequence**						**GM**	**Emissions**	**Yield**
		Year 1	**Year 2**	**Year 3**	**Year 4**	**Year 5**	**Year 6**	**€/year/ha**	**tCO2eq/year/ ha**	**kgDM/year/ ha**
Brandenburg	LBG1	Winter Rape	Winter Wheat	Winter Barley				225	1,43	5,14
Brandenburg	LBG2	Winter Rape	Winter Wheat	Winter Barley				109	1,32	4,31
Brandenburg	LBG3	Winter Rape	Winter Rye	Maize S	Winter Rye	Spring Barley		35	1,21	4,81
Brandenburg	LBG5	Winter Rye	Winter Rye	Winter Rye	Winter Rye	Spring Barley		273	0,99	6,28
Brandenburg	LBG4	Winter Rye	Winter Rye	Winter Rye	Winter Rye	Spring Barley		242	0,96	5,88
Calabria	Rainfed	Winter Rape	woat	Winter Rape	Winter Barley			286	0,49	2,33
Calabria	Irrigated highland	potato	Winter Rape	Wwh eat	Winter Rape	Winter Wheat		551	0,67	2,54
Calabria	Irrigated lowland	maize_s	Winter Barley					503	1,21	7,53
South-Muntenia	chernozem	Sun flower	Winter Wheat	Winter Wheat	Winter Rape	Winter Barley		314	1,03	3,30
Eastern Scotland	Grade 1&2	potato	Winter Wheat	Winter Wheat	Winter Wheat	Winter Wheat	Winter Rape	986	1,87	7,12
Eastern Scotland	Grade 3	potato	Winter Wheat	Winter Wheat	Winter Wheat	Winter Barley	Winter Rape	724	1,99	6,15
Eastern Scotland	Grade4	grass	grass	grass	Spring Barley			518	2,56	9,00
Västsverige	Clay Soil	Winter Wheat	Winter Wheat	Winter Wheat	Winter Wheat	Spring Oat		562	1,31	3,70

[3] To check the correspondence with the crop composition, we use Eurostat Data (2012). Accessed: January 2015.
[4] Data for winter rye, rape, barley, maize, wheat, sunflower and soybean from Eurostat (2010), data for faba bean, lupin, oat, pea from FAOSTAT (2011).Accessed: January2014

Building Abatement Cost Curve

After the generation of the different possible rotations in each site class, a mixed integer programming model is used to define the rotations that maximize t he total gross margin (π) for different CO_2 reduction levels. In its most general form, the generic model can be written as follows:

$$\text{Max } \pi = \sum_{k=1}^{13} (GM_{rot})$$

$$\text{s.t.}(Em_{baseline} - Em_{rot}) \geq AbatementGoal$$

where π is the total profit earned over the 13 site classes, GM_{rot} the gross margin of the rotation that maximizes the profit in euros per hectare in one site class, and Em the emissions of the rotation in ton CO_2 equivalent per hectare. Successive abatement goals of 5% are endogenously computed in the model through equality constraints. The abatement goal ranges from 0 to 50% for each site class.

This model allows building low cost carbon reduction pathways which show the behaviour of site class independently from the other when they are submitted to CO_2 reduction objectives. Figure 2 illustrates the carbon reduction pathway for the site class "clay-soil" in Västsverige. The figure represents the gross margin and the emissions of every rotation in this site class. The rotations selected by the model are those whose emissions are below the baseline's emissions and are chosen by increasing abatement cost. Starting from the baseline rotation, the selection pathway follows the external boundary of the panel. We observe that first rotations with a higher gross margin are selected. As long as the target of abatement increases, less profitable but lower emitting rotations are selected. Selection ends when the reduction of 50% of CO_2 emissions has been exceeded.

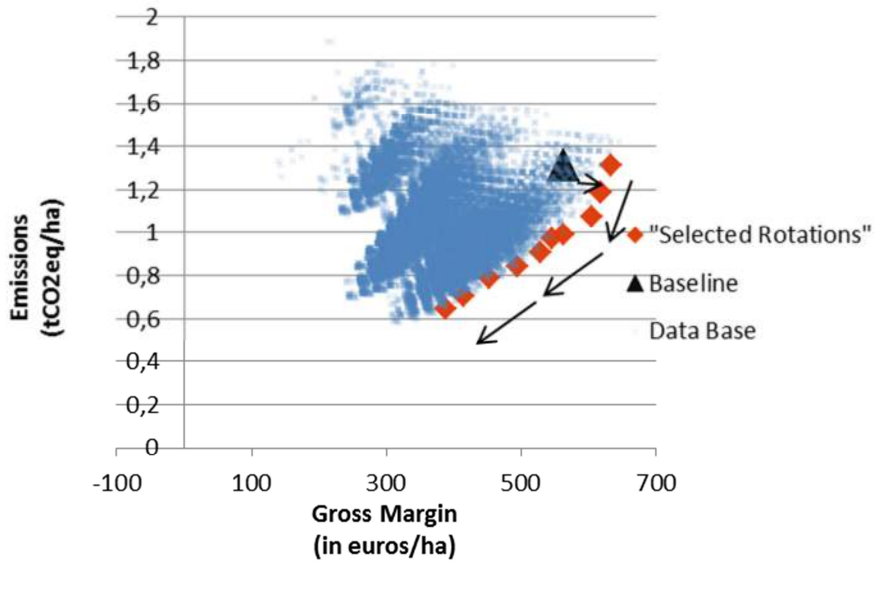

Figure 2 – Selection of rotations to reduce GHG emissions - Example in site class "Clay-Soil" region Västsverige (under the "Fertilisation" data)

The alternative rotations selected in the low carbon reduction pathway can be represented in the form of an abatement cost curve. This kind of curve represents the abatement potential and the abatement cost per tCO_2eq unit of the successive options to reduce GHG emissions. The options are classified by rank of cost and each of them is represented through a specific square. The height represents the abatement cost and the width characterises the abatement potential. Traditionally in the literature on MACC, the abatement potential of the marginal option to be implemented is added to the previous implemented options. Here, conversely, successive rotations are implemented on the same site class. It follows that, they substitute each other when the abatement cost increase, and substitute the potential of previous rotations accordingly.

Figure 3 illustrates the abatement cost curve of the site class “clay soil”. Each square represents the 9 rotations of the low carbon selection pathway. We observe that three rotations have a negative abatement cost. Negative abatement cost can be obtained until an abatement of 0,32 tCO_2eq/ha/year. Beyond this abatement rate, rotations with positive abatement cost allow higher abatements.

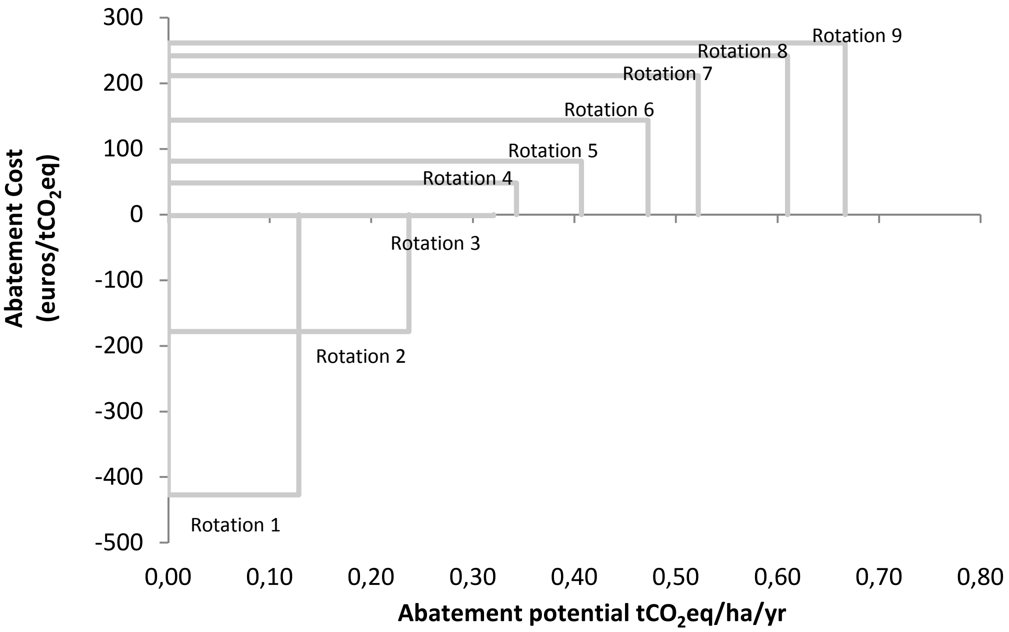

Figure 3 – Selected rotations in “Clay Soil” represented through an abatement cost curve

Aggregating the 5 regions results following abatement cost efficiency ranking

We use the abatement cost per tCO_2eq unit, that is to say the cost-effectiveness, used in particularly in the energy sector (Bertrand, 2012), to draw abatement cost curves. The purpose is to observe how the abatement of the overall level evolves at the lowest possible cost. Here, the behaviour of each site class is not considered independently from the others. Thanks to the low cost abatement pathway, rotations are classified by merit order of average abatement cost. As long as the amount of abatement requirement increases at the aggregated level (for the 5 regions regions), farms switch successively their initial rotation by rotation generating more abatement but with a higher cost. Each step in the aggregated curve represents one rotation change in one specific site class. This representation of results by carbon switching price allows representing, for instance, the impact of carbon pricing in agriculture if such economic tool was implemented. Along with GHG abatement and switching carbon price, the production, the land area covered by cereals, non-legume forages, grain legumes, and legume forages (including grass-legume mixtures) are also calculated.

For the aggregation of the results, we considered the representativity of the different site classes tacking into account their share in terms of arable area. The total arable area of the five regions is 2,56 M ha, representing 2.7% of the arable land in the EU-27[5]. For the aggregated results, the profit for each region are calculated based on the GM (see Appendix 1).

Economically efficient abatement

The economically efficient GHG abatement can be defined as the abatement up to a carbon price threshold. Here, this threshold is approximated by the carbon value used by the UK Government, which is €45 /t CO_2eq (£52 /t CO_2eq) in the non-traded sector in 2010 (central value) (DECC, 2009).

[5]Eurostat, 2010 data; Accessed: February 2014

3 RESULTS

The aggregated results of the five regions for the two scenarios, from a carbon switching price of -1000 to 800 €/tCO_2eq, in terms of abatement cost, profit, total crop, fodder legumes and grain legumes production, and the crop areas, are respectively illustrated in Figures 4-9. The GHG abatement is associated with financial savings up to 35% of the baseline emissions for the two scenarios; these "win-win" opportunities result in a strong increase in the total profit from €1 billion to €1,3 billion (Figure 4). Beyond this point, rotations switch toward less profitable rotations, making the total profit decrase. Then, when the abatement is higher than 40-44% the total cost becomes positive.

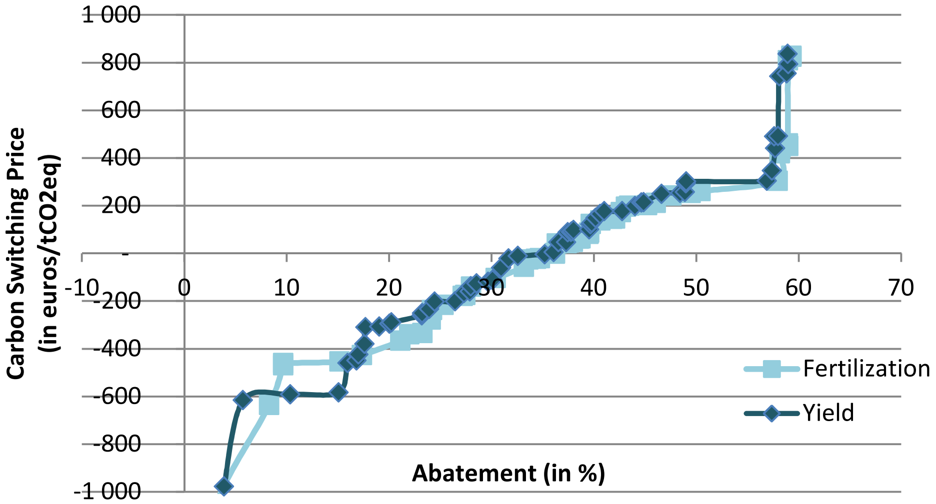

Figure 4 – Aggregated Carbon Switching Price for the 5 regions

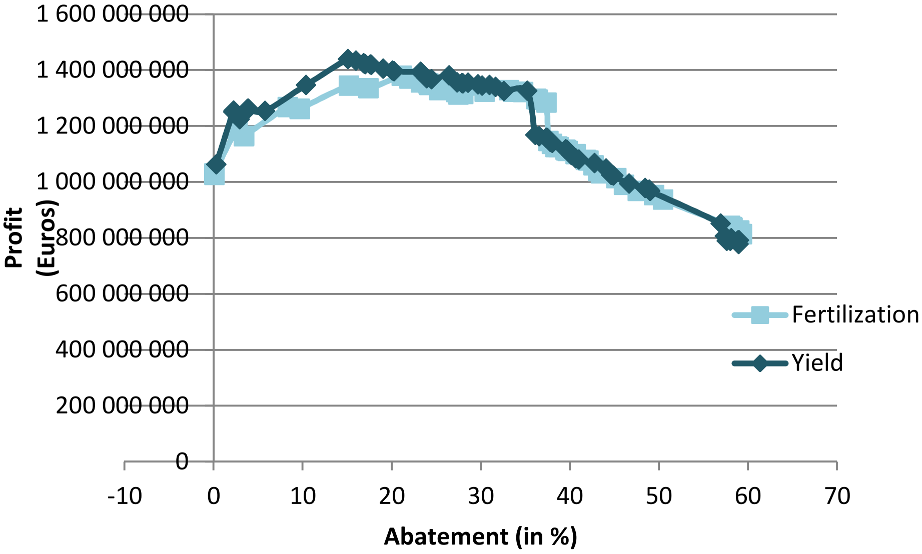

Figure 5 – Total profit in the 5 regions

In both scenarios, the total production first increases by around 10% (up to an abatement of 18-20%) and then decreases, ultimately falling below the level of the baseline production at around

40% abatement (Figure 6). The abatement is associated with an increase in grain and fodder legume production, as rotations with lower emissions are introduced. As explained in the methodology section, no baseline rotation in any site class includes legumes; hence legume production starts at zero. With increasing fodder legumes, production increases to 3.2-3.8 Mt dry matter at 35% abatement (Figure 7). The grain legume production reaches a maximum of 0.3-1.1Mt dry matter at an abatement of 40% (Figure 8).

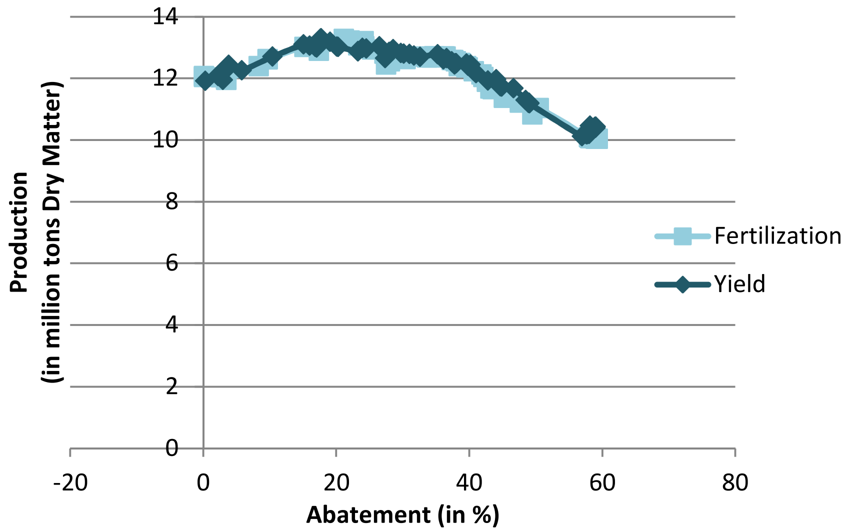

Figure 6 – Aggregated total crop production in the 5 regions

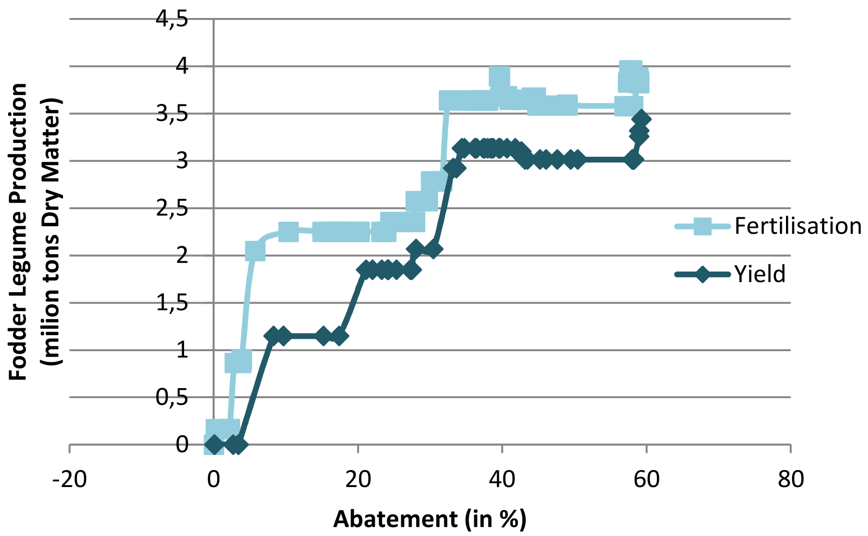

Figure 7 – Aggregated fodder legumes production in the 5 regions

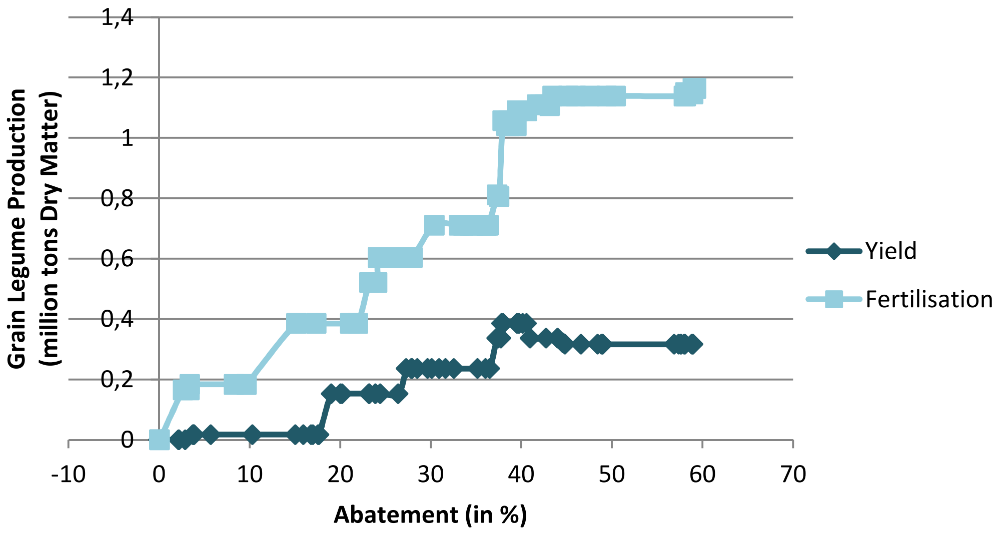

Figure 8 – Aggregated grain legumes production in the 5 regions

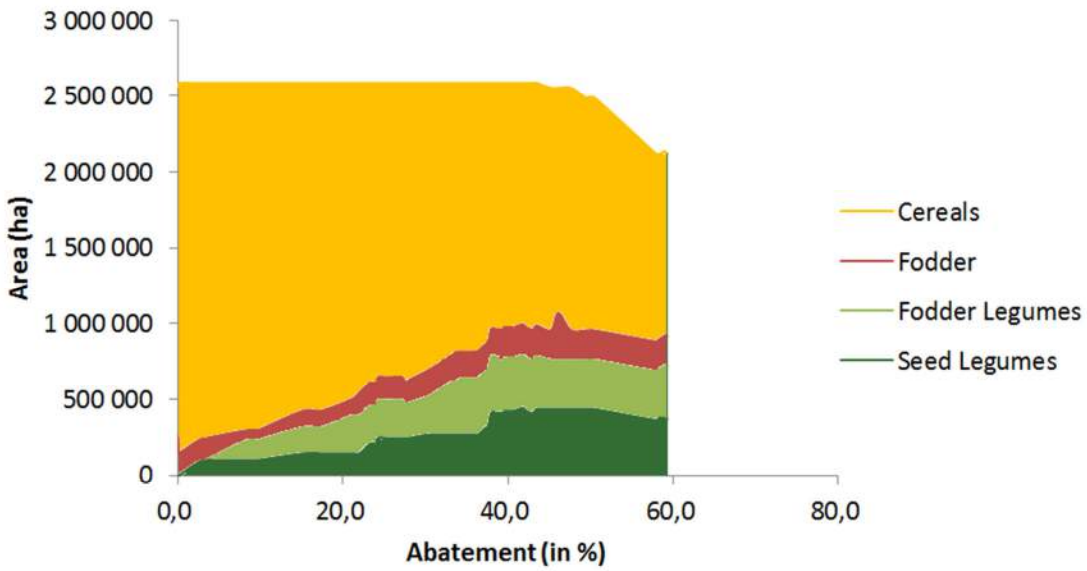

Figure 9 – Crops areas aggregated for the 5 regions, scenario "Fertilisation" (pre-crop effect decreases the nitrogen rate)

The cereal area shows a continuous decrease as it is substituted by grain legumes, fodder legumes and, to a lesser extent, by non-leguminous fodder. Most of this replacement happens along with the first rotation changes, up to an abatement of 38% (Figure 9). Then, abatement are generated without any change in the overall cropland repartition. After an abatement of 43%, the overall crop area starts to decrease. Beyond this point in some site classes, abatement cannot be realised without cutting off the production. Results on the changes in crop areas for each site class are given in Appendix 4.

Regional results for the economically efficient abatement (up to 45 €/t CO_2eq) for the "Fertilisation" scenario are summarized in Table 3 and highlights important disparity between regions. Brandenburg and Eastern Scotland offer the highest abatement: respectively 46% and 44% reduction of the baseline soil N_2O emissions.. Västsverige and South Muntenia's cost-effective abatement potentials are respectively 24% and 30%, while the potential abatement is lowest in Calabria (Italy), with only 2% of the baseline. Moreover, at the economically efficient abatement, the GHG abatement is associated with an increase in profit in every region (Table 3) except in South-Muntenia. The region with the highest relative increase in profit is Brandenburg, where average profit is augmented by 75.7%. Eastern-Scotland and Calabria benefit from a moderate profit increase (13.9% and 11.2%, respectively), while the profit increase in Västsverige is only 0.2%.

At the same abatement level, all regions, apart from Västsverige, present an increase in the share of legumes, and cereal areas decline in three regions (Sud-Muntenia, Eastern Scotland and Brandenburg). In Calabria, non-leguminous fodder are substituted by both grain legumes and cereals, while in Västsverige, non-leguminous fodder are replaced by cereals, with no area increase for legumes. In Eastern Scotland, the non-leguminous fodder area also increased alongside the legumes area. Rotations providing both GHG abatement and financial savings at the same time include both fodder and grain legumes in Brandenburg (grass-clover mix, alfalfa, lupin and pea), and in Eastern Scotland (grass-clover mix and pea), whereas in South-Muntenia and Calabria only grain legumes (common bean for South-Muntenia) or fodder legumes (alfalfa for Calabria) appear in these rotations. In Västsverige, there are no legumes in the 'win-win' rotations. More detailed results for the scenario "Fertilisation" on the composition of the rotations selected by the model are presented in Appendix 4.

Table 3 – Regional results for the baseline and for a cost-effectiveness of €45 /t CO_2eq, scenario Fertilisation (all rotations per site class; pre-crop effect decreases the nitrogen rate)

		Area Cereals	**Area Fodder Crops**	**Area Fodder Legumes**	**Area Grain Legumes**	**Cost**	**Production**	**Emissions**	**Abatement**	**Gross Margin**
		%	**%**	**%**	**%**	**euros/ha**	**kg Dry Matter/ha**	**tCO2eq/ha**	**tCO2eq/ha**	**Euros/ha**
South-Muntenia	Baseline	100,0	0,0	0,0	0,0	0	3296	1,03	0	314
	45 euros/tCO2eq	75,0			25,0	14,03	2962	0,72	0,31	300
Västsverige	Baseline	80,0	20,0	0,0	0,0	0	3703	1,31	0	562
	45 euros/tCO2eq	100,0	0,0		0,0	-0,56	3105	0,99	0,32	563
Eastern-Scotland	Baseline	94,3	5,7	0,0	0,0	0	6676	2,00	0	792
	45 euros/tCO2eq	40,9	32,3	11,4	15,4	-111,26	6495	1,11	0,89	903
Calabria	Baseline	71,7	28,3	0,0	0,0	0	3706	0,70	0	376
	45 euros/tCO2eq	81,8	13,0	0,0	5,1	-41,59	3881	0,68	0,02	418
Brandenburg	Baseline	92,7	7,3	0,0	0,0	0	5187	1,18	0	144
	45 euros/tCO2eq	54,4	0,0	31,3	14,4	-109,74	6136	0,63	0,55	253
Overall	Baseline	89,9	10,1	0,0	0,0	0	4735	1,29	0	384
	45 euros/tCO2eq	67,1	7,1	14,5	12,3	-63,27	4914	0,81	0,49	447

4. DISCUSSION

Abatement cost in the five regions can be compared with results of other studies focussing the comparison specifically on legumes to stay at the same scope. Pellerin et al (2013) considered using fodder and grain legumes as two options to mitigate agriculture emissions in France. Legumes abatement cost potential was estimated in according to a change in France farmlands and not according to rotation changes. The abatement potential was 1.4 $MtCO_2eq$ for a total cost of -72 M€, which induces an average cost of -52 €/tCO_2eq. Macleod et al (2010) assessment on legumes gave a high average abatement cost of 11,710 €/tCO_2eq (with cost of implementation of 16.8 €/ha), while accounting for interactions with other mitigation options which reduce the abatement potential of this option considerably. The present analysis find the average abatement cost to be -130€/tCO_2eq at a carbon switch price of 45 €/tCO_2eq, which is the lowest average abatement cost from legumes among the three studies (see Appendix 8 for a further detailed comparison). Most of this increase in the profit is due to the initial changes from the baseline rotations to other more profitable rotations. We remind that these more profitable rotations cannot be considered as baseline due to their high legume content.

Consequently, results suggest that there is significant potential win-win abatement in all five regions, i.e. a potential decrease in GHG emissions with a simultaneous increase in GM. These win-win mitigation opportunities (i.e. negative cost-effectiveness) will always raise further questions about the assumptions in the calculations. Indeed, a quite intuitive interrogation is: why farmers would currently refuse to reduce their GHG emissions whereas it would raise their profit? The most common explanations for the negative cost are the following: either simulation's estimates are robust but farmers do not have information about these opportunities and the assumption about their profit-maximising behaviour does not capture other barriers, either the model does not capture some important cost elements due to production system changes.

On this latter point, the 13 site classes are not farms. Consequently their production system (e.g. livestock or cereals) is not specified. Yet, in reality, farmers are constrained by their production system, for example farms with ruminant animals tend to utilise their land area for home-grown fodder, rather than producing crops for export and importing the feed. On the other hand, farms without ruminants have very limited ability to sell fodder, mostly due to the high transportation costs. Moreover, beyond the farm gate, structural barriers might be hidden in the supply chain of legumes contributing to the existence of seemingly win-win opportunities. For instance, legumes need adapted silos that are not currently established in all regions in Europe. Besides, the effect of an increased legume production and a decreased cereal production on the European crop market is not taken into account in this study, while in the meantime these feedbacks have the potential to increase the costs.

Barriers also exist in the diffusion of information in the agricultural sector. Farmers' decision making, including internal factors (cognition and habit) and social factors (norms and roles), can also explain the non-current exploitation of these negative costs. Besides, farmers may be exhibiting risk aversion behaviour in response to a potentially higher variation in the yield of legumes (Jensen et al, 2010) and their action on the pre-crop effect (as suggested in Appendix 3 in the standard deviation figure).

Lastly, assumptions about the baseline practices would also affect both the abatement and the cost of win-win opportunities. In the case of the current assessment, the choice of the baseline rotations and the fact that many low-emission leguminous crops are associated with a relatively high GM in the crop database is partly responsible for the win-win opportunities.

Consequently, given the fact that the scope of our research does not capture the aforementioned barriers and thus is underestimating costs, results should not be interpreted as actual estimation but rather as a maximum optimistic potential. The estimation of the weight of these implementation barriers is left aside for further research work.

5 CONCLUSION

The results emphasize the importance of rotation switch in European agriculture and underpin that a shift for rotational schemes implying lower nitrogen requirement is not only beneficial to the climate, but can be made without significant losses for the farmers and without a reduction in agricultural production. A significant part of the abatement potential can be achieved without the implementation of legumes in some area such as Västverige, but most of this abatement potential is fulfilled thanks to the cultivating of grain and fodder legumes. Over around 15% of the arable land areas, replacing non-leguminous fodder and cereal areas induces a maximum farm revenue increase at an abatement of 0.7 $MtCO_2eq$ (35% of the soil N_2O emissions from these land areas).

Though the increased cultivation of legumes would reduce cereal production, it would provide additional proteins both for animal and human consumption, reducing the need for feed protein imports (the additionnal grain legume production is 0.3-1.1 Mt DM at the five regions level, this accounts to 1.2-3.2% of the current 34.4 Mt DM/y soybean import in the EU-25[6]). The reduced cereal production would have implications on cereal production elsewhere, potentially resulting in a GHG leakage. Investigating the overall impact of such a shift in the place of production needs a life cycle analysis approach.

Increasing the switch toward less nitrogen consuming cropland systems in European could be promoted through providing better information on the agronomic issues (e.g. agronomic characteristics of clover varieties, nutritional values of legume fodder for animals) via existing advisory schemes, information tools, or through compulsory schemes, especially given that monitoring and enforcement is relatively straightforward. One opportunity is already implemented within the new Common Agricultural Policy (CAP): farmers can chose to comply with Ecological Focus Areas requirements by cultivating legumes. The demand for grain legumes can increase if it becomes practical for livestock farmers and feed producers to replace part of the soybean in the feed with peas and beans, and also if consumers become more willing to give up part of their livestock-protein consumption for plant-proteins (this aligns well with efforts promoting a shift in consumption towards a more sustainable pattern). A broad incentive that targets not only farmers producing crops, but also consumers and the agricultural supply chain as well, could be the implementation of a carbon price in the economy covering nitrous oxide emissions.

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[6]Sources:Friends of the Earth Netherlands, 2008. Soy consumption for feed and fuel in the European Union. A research paperprepared for Milieudefensie (Friends of the EarthNetherlands) by Profundo Economic Research, The Netherlands. Country-speci c data available from FO E on request.

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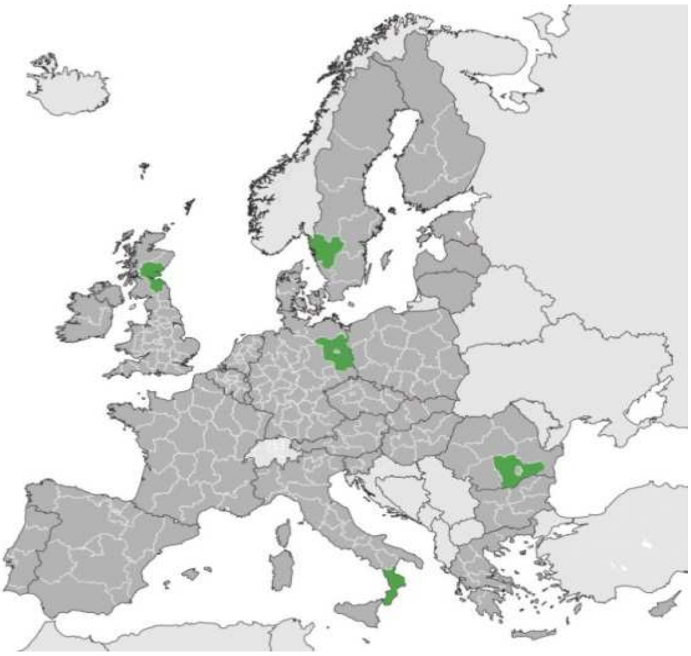
Appendix 1 – Site class descriptions

NUTS 2 region	Brandenburg					Calabria			Sud-Muntenia	Eastern Scotland			Vätstsverige
Country	Germany					Italy			Romania	UK			Sweden
Site class	LBG 1	LBG 2	LBG 3	LBG 4	LBG 5	irrigated highland	irrigated lowland	rainfed	Chernozem	Grade 1&2	Grade 3	Grade 4	claysoil
Soil type	Silty clay loam	Loam	Sandy clay loam	Sandy loam	Loamy sand	Sandy loam	Sandy loam	Loam	Chernozem	Dreghorn	Hobkirk	Yarrow	Silty clay loam
Share of site class from total area (%)	3,0	9,0	14,8	11,0	2,5	0,8	1,6	3,7	14,5	5,3	10,0	1,3	22,5
Area (ha)	75,944	230,952	378,677	281,927	64,500	20,034	40,603	95,363	371,800	134,909	256,970	32,121	577,000



Location of the 5 regions in Europe

Appendix 2– GM and GHG calculations

Gross margin (GM) calculation

$$GM_{crop} = (Yield * PA + YieldB * PB + YieldByProd * PByProd) – (Production\ Cost + Other)$$

Yield: main production yield (kg DM/ha/year) for instance the grain of wheat
Yield_B: second production yield if it is exist (kg DM/ha/year) for instance the wheat straw
YieldByProd: third production yield if it exist (kg DM/ha/year)
PA: main production price (€/t)
PB: second production price (€/t)
PByProd: third production price (€/t)
Production Cost: costof fungicides, pesticides, fertilisers, insecticides, harvest, irrigation, drying and cleaning, machinery and harvestingcost.
Other : Services including contraction costs.

$$GM_{rotation} = \sum_{t=1}^{n} \frac{GM_{crop}}{(1+r)^t}$$

n : overall length of the rotation from two to six years
GM_{crop} : crop gross margin.
r : discount Rate of 3% per year

N_2O emissions

The total of the N_2O emissions of the rotation is calculated according to IPCC 2006 guidelines[1]:

$$N20\ total_{emission_{rotation}} = \mathrm{N20\ indirect}_{\mathrm{emission}_{\mathrm{rotation}}} + \mathrm{N20\ direct}_{\mathrm{emission}_{\mathrm{rotation}}}$$

Direct N_2O emissions

$$\mathrm{N_2O\ direct}_{\mathrm{emission}_{\mathrm{rotation}}} = \sum_{i=0}^{ncrop} \left(\left(Fsn_{crop} + Fon_{crop} + Fcr_{crop} \right) * 0.01 \right) * \left(\frac{44}{228} \right)$$

Fsn = annual amount of synthetic fertiliser N applied on soils, kg.N.yr^{-1}
Fon = annual amount of animal manure, compost, sewage sludge and other organic N additions applied to soils (Note: If including sewage sludge, cross-check with Waste Sector to ensure there is no double counting of N_2Oemissions from the N in sewage sludge), 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}

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

Crop = harvested annual DM yield for crop, kg d.m. ha-1
Cf = combustion factor (dimensionless)
FracRenew = fraction of total area under cropthat is renewed annually.
RAG) = ratio of above-ground residues DM (AGDM) to harvested yield for crop(Crop), kg d.m.
NAG= N content of above-ground residues for crop, kg N (kg d.m.) -1
FracRemove = fraction of above-ground residues of cropremoved annually for purposes such as feed, bedding and construction, kg N (kg crop-N)-1.
RBG = ratio of below-ground residues to harvested yield for crop, kg d.m. (kg d.m.)-1.
NBG = N content of below-ground residues for crop, kg N (kg d.m.)-1

Indirect N_2O emissions

$$\mathrm{N_2O\ indirect}_{\mathrm{emission}_{\mathrm{rotation}}} = \sum_{i=0}^{ncrop} \mathrm{N_2Oadt}_{\mathrm{crop_i}} + \mathrm{N_2O}L_{crop_i}$$

[1]Paustian,K., N.H.Ravindranath, and A.van Amstel(2006) 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme, Volume 4: Agriculture, Forestry and Other Land Use. Eggleston, H. S., Buendia, L., Miwa, K., Ngara, T., and Tanabe, K. Japan, IGES.

N_2Oadt from atmospheric deposition of N volatilised from managed soils

N_2Oadt: annual amount of N_2O–N produced from atmospheric deposition of N volatilised from managed soils, kg N_2O–N yr-1

$$\mathrm{N_2Oadt_{crop}} = \left((Fsn * 0.1 + Fon * 0.2) * 0.01\right) * \left(\frac{44}{28}\right)$$

N_2OL from N leaching/runoff from managed soils in regions where leaching/runoffoccurs

N_2OL–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 N_2O–N yr-1

$$\mathrm{N20L_{crop}} = \left((Fsn + Fon) * 0.3\right) * 0.0075 * \left(\frac{44}{28}\right)$$

Appendix 3 – Pre-crop effect

	Change in yield in the "Yield" scenario		Change in fertiliser costs in the "Fertilisation" scenario	
	Tons Dry Matter M/ha	%	Euros/ha	%
Average	+1.33	+17.8	-31.0	-14.1
Standard deviation	+1.17	+10.7	-13.5	-4.7

Appendix 4 – Rotation Selection according to the mitigation cost efficiency (in the B N-Decrease Scenario)[1]

In the five Site Classes of Brandenburg - Germany

Crop1	Crop2	Crop3	Crop4	Crop5	Crop6	Abatement	Cereals	ClassicFodder	FodderLegumes	Grain Legumes	Cost	AbatementCost	Production	Emissions	GM
						tCO2eq/ha	%	%	%	%	euros/ha	euros/tCO2eq	kg Dry Matter	tCO2eq/ha	Euros/ha
LBG1															
alfalfa	alfalfa	Winter Wheat	Winter Barley	Winter Rape	tritica	0,24	66,7		33,3	0,0	-33,7	-139,4	6418	1,19	259
alfalfa	alfalfa	Winter Wheat	Winter Rye	Winter Rye	Winter Rye	0,41	66,7		33,3	0,0	-8,1	-19,9	6970	1,02	233
alfalfa	alfalfa	Winter Rye	Winter Rye	Winter Rye	Winter Rye	0,49	66,7		33,3	0,0	20,2	41,4	7013	0,94	205
alfalfa	alfalfa	Winter Wheat	Winter Rye	fababea	tritica	0,51	50,0		33,3	16,7	44,1	86,4	6512	0,92	181
alfalfa	alfalfa	Winter Rye	Winter Rye	fababea	tritica	0,59	50,0		33,3	16,7	72,4	122,9	6555	0,84	153
alfalfa	alfalfa	Winter Rye	Winter Rye	Winter Rye	Winter Rye	0,72	66,7		33,3	0,0	103,9	145,4	5465	0,71	121
LBG2															
graclov	graclov	Winter Rye	Spring Barley	Winter Rape	Winter Rye	0,54	66,7		33,3	0,0	-197,0	-366,8	5961	0,79	306
graclov	graclov	Winter Rye	Winter Rye	Winter Rye	Winter Rye	0,66	66,7		33,3	0,0	-182,2	-277,7	6563	0,67	291
graclov	graclov	Winter Rye	pea	Winter Rape	Winter Rye	0,67	50,0		33,3	16,7	-159,4	-237,7	5847	0,65	268
LBG3															
graclov	graclov	Winter Rye	Spring Barley	Winter Rape	Winter Rye	0,43	66,7		33,3	0,0	-270,7	-636,3	5961	0,79	306
graclov	graclov	Winter Rye	Winter Rye	Winter Rye	Winter Rye	0,54	66,7		33,3	0,0	-255,9	-470,1	6563	0,67	291
graclov	graclov	Winter Rye	Winter Rye	pea	Winter Rye	0,66	50,0		33,3	16,7	-219,5	-334,4	6161	0,56	255

[1]Crops abbreviations can be found in Appendix 8

LBG4															
graclov	graclov	Winter Rye	Winter Rye	Winter Rye	Winter Rye	0,32	66,7		33,3	0,0	-18,1	-56,2	6563	0,67	291
graclov	graclov	Winter Rye	Winter Rye	pea	Winter Rye	0,43	50,0		33,3	16,7	18,3	42,1	6161	0,56	255
graclov	graclov	Winter Rye	Winter Rye	lupin	Winter Rye	0,45	50,0		33,3	16,7	28,4	62,9	6104	0,54	245
graclov	graclov	Winter Rye	Winter Rye	pea	Winter Rye	0,51	50,0		33,3	16,7	100,2	195,6	5345	0,48	173
LBG5															
seradel	Winter Rye	ryevetc	Winter Rye	Winter Rye		0,18	100,0				147,7	809,7	4177	0,77	94
ryevetc	Winter Rye	Winter Rye				0,29	100,0				236,9	828,0	3663	0,67	5

In the three Site Classes of Calabria - Italy

						Abatement	**Cereals**	**ClassicFodder**	**FodderLegumes**	**Grain Legumes**	**Cost**	**AbatementCost**	**Production**	**Emissions**	**GM**
Crop1	**Crop2**	**Crop3**	**Crop4**	**Crop5**	**Crop6**	**tCO2eq/ha**	**%**	**%**	**%**	**%**	**euros/ha**	**euros/tCO2eq**	**kg Dry Matter**	**tCO2eq/ha**	**Euros/ha**
Irrigated Highland															
potato	lupin	Winter Wheat	lupin	Winter Wheat		0,08	60,0			40,0	-85,4	-1018,7	2489	0,58	636
potato	lupin	Winter Rape	lupin	Winter Wheat		0,11	60,0			40,0	-49,5	-460,7	2393	0,56	601
IrrigatedLowland															
alfalfa	alfalfa	alfalfa	Winter Barley			0,58	25,0		75,0		267,8	461,5	8249	0,63	235
alfalfa	alfalfa	alfalfa	durum	Winter Barley		0,61	40,0		60,0		273,3	449,8	7116	0,60	229

Rainfed															
Winter Rape	Winter Barley	Winter Rape	Winter Barley			0,01	100,0			0,0	-57,6	-6491,5	2643	0,48	343
Winter Rape	Winter Barley	fababea	Winter Barley			0,12	75,0			25,0	24,6	199,0	2418	0,37	261
Winter Rape	Winter Barley	fababea				0,18	66,7			33,3	76,7	419,1	2220	0,31	209
Winter Rape	Winter Barley	pea				0,19	66,7			33,3	81,4	420,8	2106	0,30	204
Winter Rape	Winter Barley	pea	Winter Barley	pea		0,22	60,0			40,0	96,6	443,6	2072	0,27	189
Winter Rape	fababea	Winter Barley	pea	Winter Barley		0,25	50,0			50,0	115,4	468,7	2107	0,24	170

In the Site Classe of Muntenia - Romania

						Abatement	Cereals	ClassicFodder	FodderLegumes	Grain Legumes	Cost	AbatementCost	Production	Emissions	GM
Crop1	**Crop2**	**Crop3**	**Crop4**	**Crop5**	**Crop 6**	**tCO2eq/ha**	**%**	**%**	**%**	**%**	**euros/ha**	**euros/tCO2eq**	**kg Dry Matter**	**tCO2eq/ha**	**Euros/ha**
chernozem															
Combean	Winter Wheat	Winter Rape	maize_g			0,23	75,0			25,0	-431,6	-1873,7	3192	0,80	746
combean	Winter Wheat	Winter Rape	Winter Barley			0,29	75,0			25,0	-355,7	-1213,0	2977	0,74	670
soybean	Winter Wheat	Winter Rape	Winter Barley			0,31	75,0			25,0	14,0	44,8	2962	0,72	300
soybean	Winter Barley	sunfl	Winter Wheat	Winter Rape		0,36	80,0			20,0	62,4	172,1	2540	0,67	252

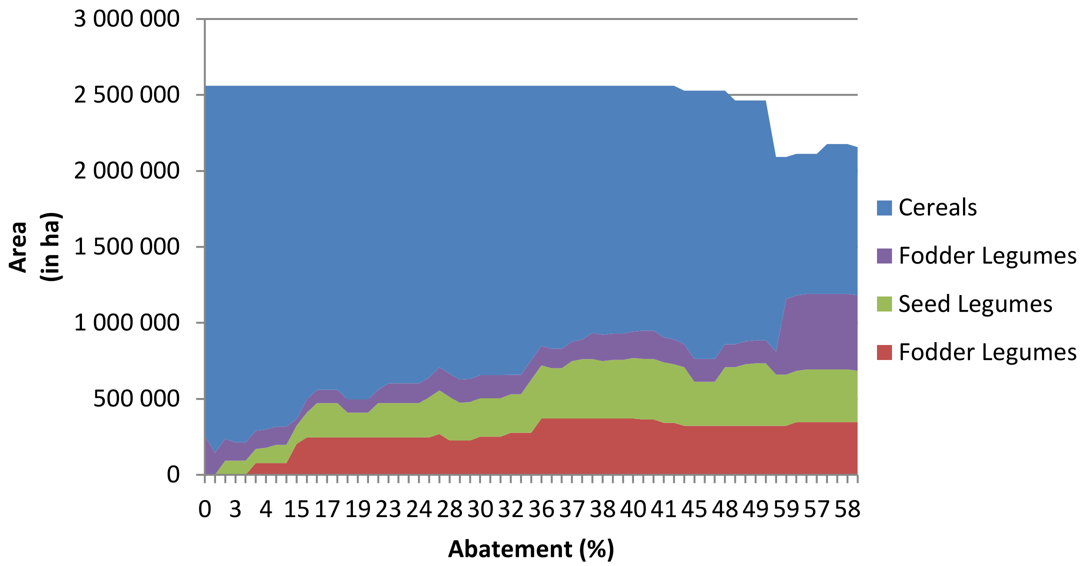
In the Site Class of Västsverige - Sweden

						Abatement	Cereals	ClassicFodder	FodderLegumes	Grain Legumes	Cost	AbatementCost	Production	Emissions	GM
Crop1	Crop2	Crop3	Crop4	Crop5	Crop 6	tCO2eq/ha	%	%	%	%	euros/ha	euros/tCO2eq	kg Dry Matter	tCO2eq/ha	Euros/ha
clay_soil															
Winter Rape	Winter Wheat	Winter Wheat	Winter Wheat	Spring Barley		0,00	100,0	0,0		0,0	-71,2	-20409,4	3556	1,31	634
Winter Rape	Winter Wheat	linseed	Winter Wheat	Winter Rye		0,13	100,0	0,0		0,0	-55,0	-427,3	3345	1,18	617
Winter Rape	Winter Wheat	linseed	Winter Wheat	Spring Barley		0,24	100,0	0,0		0,0	-42,2	-178,3	3119	1,08	605
Winter Rape	Winter Wheat	Spring Barley	linseed	Spring Barley		0,32	100,0	0,0		0,0	-0,6	-1,8	3105	0,99	563
pea	Winter Rape	Winter Wheat	Winter Wheat	linseed	Winter Wheat	0,34	83,3	0,0		16,7	16,6	48,3	3046	0,97	546
Winter Rape	Winter Wheat	pea	Winter Wheat	linseed	Spring Barley	0,41	83,3	0,0		16,7	33,1	81,4	3034	0,91	529
Winter Rape	Winter Wheat	fababea	linseed	Spring Barley		0,47	80,0	0,0		20,0	68,0	143,9	2856	0,84	494
fababea	Winter Wheat	linseed	Winter Wheat	Spring Oat		0,52	60,0	20,0		20,0	110,5	211,7	3003	0,79	452
srape	Spring Barley	linseed	Winter Wheat	fababea		0,61	80,0	0,0		20,0	147,5	241,9	2577	0,70	415
fababea	Spring Barley	Spring Barley	linseed	Spring Barley		0,67	80,0	0,0		20,0	174,1	261,2	2930	0,65	388

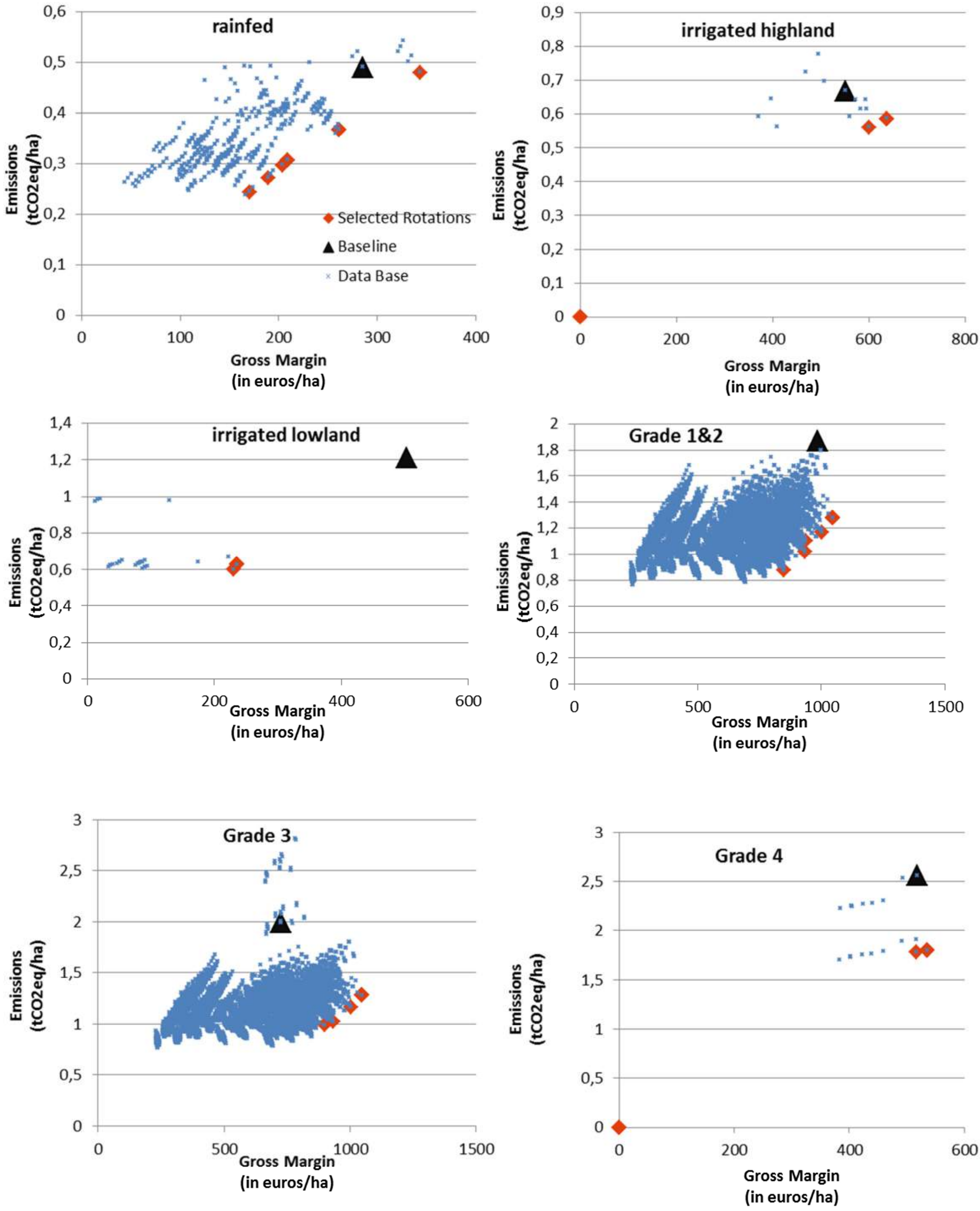
In the three Site Classes of Eastern Scotland – United Kingdom

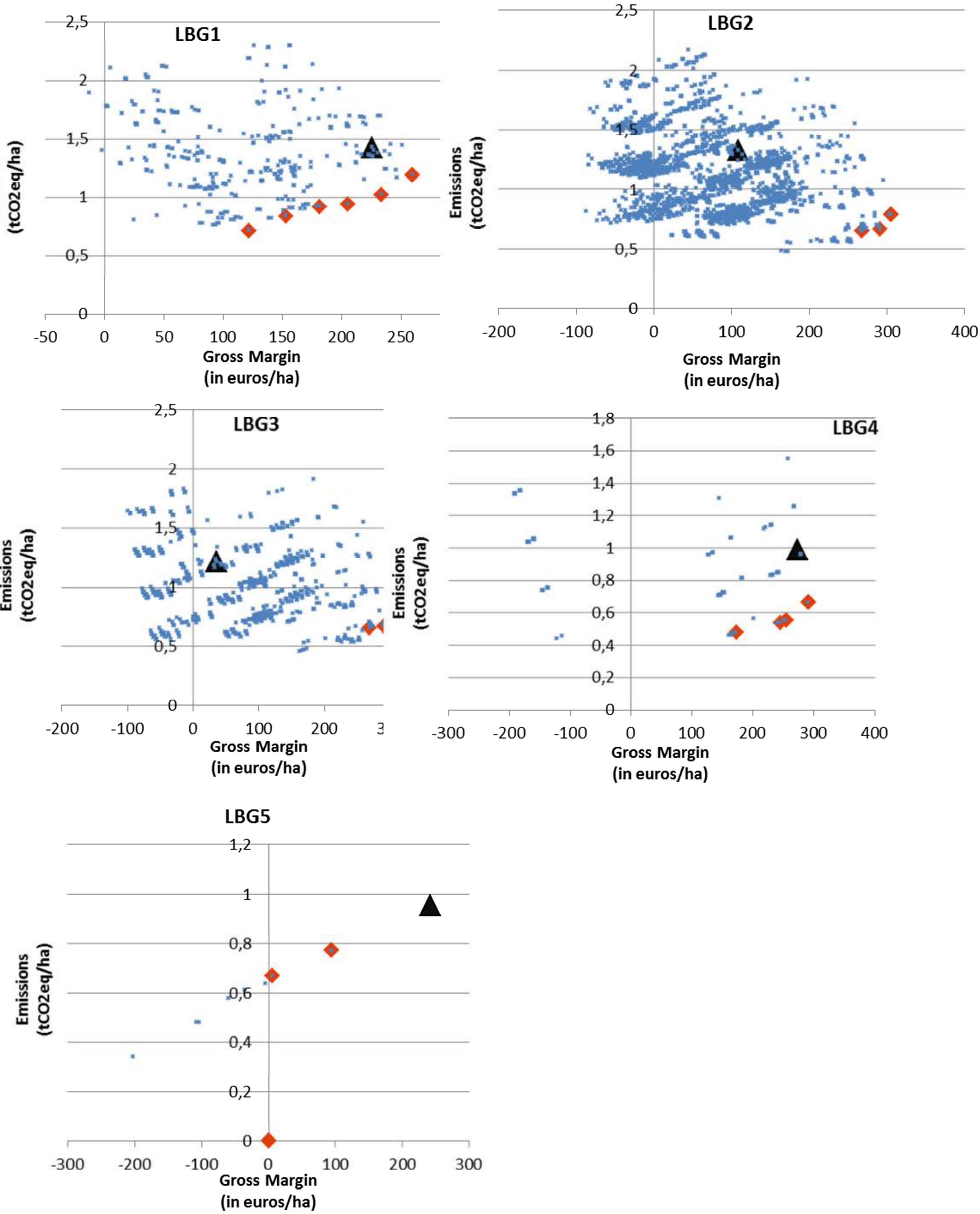
Crop1	Crop2	Crop3	Crop 4	Crop5	Crop6	Abatement tCO2eq/ha	Cereals %	ClassicFodder %	FodderLegumes %	Grain Legumes %	Cost euros/ha	AbatementCost euros/tCO2eq	Production kg Dry Matter	Emissions tCO2eq/ha	GM Euros/ha
Grade1et2															
potato	Winter Wheat	woat	pea	swedes	swheat	0,59	50,0	16,7	16,7	16,7	-61,1	-103,9	7698	1,28	1047
potato	Winter Wheat	woat	pea	swedes	Spring Oat	0,70	33,3	33,3	16,7	16,7	-17,6	-25,2	7493	1,17	1003
potato	Winter Wheat	woat	pea	woat	Spring Oat	0,76	33,3	50,0	0,0	16,7	48,5	63,5	6475	1,11	937
potato	Spring Barley	woat	pea	swedes	Spring Oat	0,85	33,3	33,3	16,7	16,7	51,7	61,1	7063	1,02	934
Grade3															
potato	Winter Wheat	woat	pea	swedes	swheat	0,71	50,0	16,7	16,7	16,7	-322,6	-454,0	7698	1,28	1047
potato	Winter Wheat	woat	pea	swedes	Spring Oat	0,82	33,3	33,3	16,7	16,7	-279,2	-339,4	7493	1,17	1003
potato	Spring Barley	woat	pea	swedes	Spring Oat	0,97	33,3	33,3	16,7	16,7	-209,8	-216,5	7063	1,02	934
potato	swheat	pea	woat	srape	woat	1,00	50,0	33,3	0,0	16,7	-174,5	-174,3	5698	0,99	899
Grade4															
graclov	graclov	graclov	swedes	Spring Barley		0,76	20,0	0,0	80,0		-18,0	-23,5	8848	1,80	536
graclov	graclov	graclov	swedes	Spring Oat		0,78	0,0	20,0	80,0		1,1	1,5	8682	1,78	517

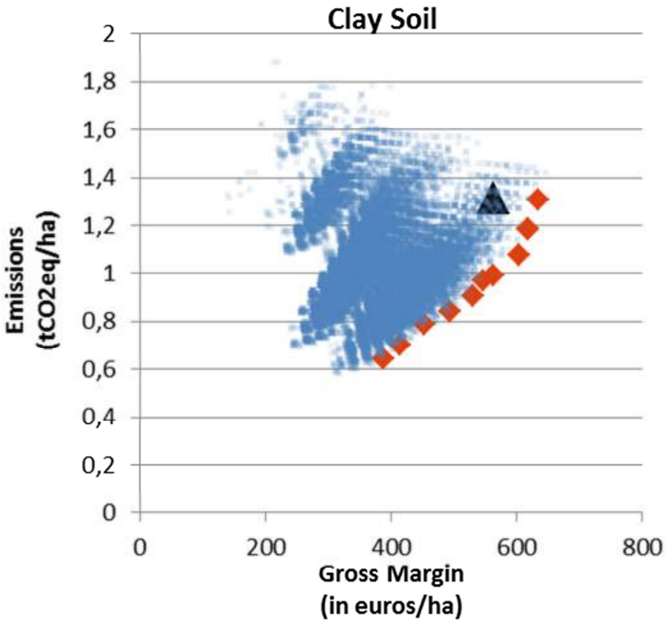
Appendix 5 – Aggregated crop areas in the 5 NUTS 2 regions in "Yield" scenarios



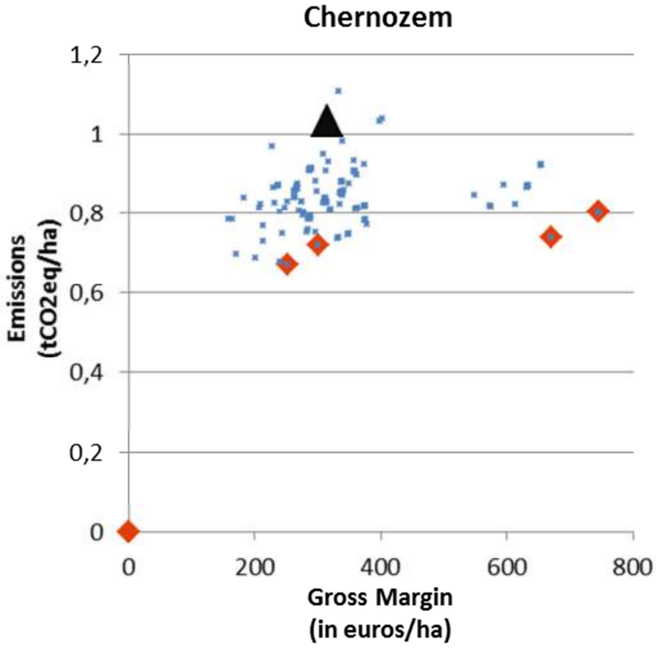
Appendix 6 – GM and GHG emissions for each rotation in each site class ("Fertilisation" scenario).




LBG1
Emissions (tCO2eq/ha)
2,5
2
1,5
1
0,5
0
-50
0
50
100
150
200
250
Gross Margin (in euros/ha)
LBG2
Emissions (tCO2eq/ha)
2,5
2
1,5
1
0,5
0
-200
-100
0
100
200
300
400
Gross Margin (in euros/ha)
LBG3
Emissions (tCO2eq/ha)
2,5
2
1,5
1
0,5
0
-200
-100
0
100
200
3
Gross Margin (in euros/ha)
LBG4
Emissions (tCO2eq/ha)
1,8
1,6
1,4
1,2
1
0,8
0,6
0,4
0,2
0
-300
-200
-100
0
100
200
300
400
Gross Margin (in euros/ha)
LBG5
Emissions (tCO2eq/ha)
1,2
1
0,8
0,6
0,4
0,2
0
-300
-200
-100
0
100
200
300
Gross Margin (in euros/ha)



Clay Soil
Emissions (tCO2eq/ha)
2
1,8
1,6
1,4
1,2
1
0,8
0,6
0,4
0,2
0
0
200
400
600
800
Gross Margin (in euros/ha)



Chernozem
Emissions (tCO2eq/ha)
1,2
1
0,8
0,6
0,4
0,2
0
0
200
400
600
800
Gross Margin (in euros/ha)

Appendix 7 – Abbreviation of crops

Abbreviation	Common name	Legume?	TYPE
Seradel	Serradella	yes	Fodder legumes
Winter Barley	Winter barley	no	Cereals
Spring BarleyorSpring barley	Spring barley	no	Cereals
Winter Rape	Winter rapeseed	no	Cereals
Ryevect/Ryevetc/Rye vetch	Rye-vetchmixture	yes	Fodder legumes
Winter Rye	Winter rye	no	Cereals
Tritica	Triticale	no	Cereals
Winter Wheat	Winter wheat	no	Cereals
Swheat	Spring wheat	no	Cereals
Durum	Durumwheat	no	Cereals
Lupin	Lupin	yes	Grain legumes
Soybean	Soybean	yes	Grain legumes
Fababea	Fababean	yes	Grain legumes
Alfalfa	Alfalfa	yes	Fodder legumes
Graclov	Grass/cloverley	yes	Fodder legumes
Grass	Grass ley	no	Classicfodder
Peaoat	Pea-oatmixture	yes	Fodder legumes
Spring Oat	Spring oat	no	Classicfodder
Woat	Winter oat	no	Classicfodder
Oatvect/Oat-vetch/Oatvetc	Oat-vetchmixture	no	Classicfodder
Maize_s/ Silage maize	Maizeforsilage	no	Classicfodder
Maize_g	Maizeforgrain	no	Cereals
Linseed	Linseed	no	Cereals
Potato	Potatoes	no	Cereals
Swedes	Swedes	no	Cereals
Combean	Common bean	yes	Grain legumes
Pea	Peas	yes	Grain legumes
Sunfl	Sunflower	no	Cereals
Clover	Clover	yes	Fodder legumes
Sulla	Sulla	yes	Grain legumes
Swede_Fodder	Fodderswedes	no	Classicfodder

Appendix 8 – Comparison of the results with results on legumes from European MACC studies[34]

	Unit	Pellerin et al, 2013			Moran et. al, 2010	This study, abatement up to 45 Euros/tCO2eq ("Fertilisation")		
		Grain legumes	Fodder legumes	Total legumes	Total legumes	Grain legumes	Fodder legumes	Total legumes
Geographical scope		France			United Kingdom	5 regions in Europe		
Abatement potential	Mt CO_2eq	0.9	0.5	1.4	0.008	-	-	1.244
Total cost	M €	17	-89	-72	94	-	-	-162
Abatement Cost	€/tCO_2eq	19	-185	-52	11,710	-	-	-130
Legumes area introduced	ha	877,681	2,822,500	3,700,181	5,572,683	388,196	597,965	685,551
Abatement potential for legumes	t CO_2eq/ha	1.03	0.18	0.38	0.0014	-	-	2
Cost per legumes area	€/ha	19.4	-31.5	-19.5	17	-	-	-236

[3] MacLeod, M., Moran, D., Eory, V., Rees, R., Barnes, A., Topp, C. F., Ball, B., Hoad, S., Wall, E., McVittie, A., et al. (2010). Developing greenhouse gas marginal abatement cost curves for agricultural emissions from crops and soils in the UK. Agricultural Systems, 103(4), 198–209.

Appendix 9 – Crop-frequency in the rotations (for crop abbreviations see Appendix 6)

Region	Brandenburg					Calabria			S-Muntenia	Eastern Scotland			Västsverige
Site class	LBG 1	LBG2	LBG3	LBG4	LBG5	irrigated highland	irrigated lowland	rainfed	chernozem	Grade 1&2	Grade 3	Grade 4	clay
No. of rot.	345	2724	902	78	9	14	28	905	137	33852	33890	18	44607
alfalfa	215	1203	443	0	0	3	5	0	0	0	0	0	0
clover	0	0	0	0	0	3	0	13	0	0	0	0	0
combean	0	0	0	0	0	0	0	0	35	0	0	0	0
durum	0	0	0	0	0	0	6	227	0	0	0	0	0
fababea	202	729	0	0	0	0	17	440	0	15345	15345	0	2016
graclov	0	126	109	48	0	0	0	0	0	0	20	10	100
grass	0	0	0	0	0	0	0	0	0	0	18	8	100
linseed	0	0	0	0	0	0	0	0	0	0	0	0	22733
lupin	0	0	248	31	3	9	0	0	0	0	0	0	0
maize_g	0	0	0	0	0	0	0	0	90	0	0	0	0
maize_s	277	1839	637	66	0	0	24	0	0	0		0	9629
oatvetc	0	0	0	0	0	0	0	440	0	0	0	0	0
pea	0	909	262	31	0	0	17	440	63	13872	13872	0	19666
peaoat	0	0	0	0	0	0	0	0	0	0	0	0	19667
potato	0	0	0	0	0	14	0	0	0	25098	25098	0	0
ryevetc	0	0	0	0	7	0	0	0	0	0	0	0	0
Spring Barley	0	1172	440	0	0	0	0	0	0	22648	22669	11	21164
seradel	0	0	0	0	3	0	0	0	0	0	0	0	0
Spring Oat	0	1385	480	0	0	0	0	0	0	17261	17282	11	26308
soybean	0	0	0	0	0	0	0	0	35	0	0	0	0
srape	0	0	0	0	0	0	0	0	0	20007	20011	0	14718
sunfl	0	0	0	0	0	0	0	0	28	0	0	0	0
swedes	0	0	0	0	0	0	0	0	0	3141	3143	2	0
swheat	0	0	0	0	0	0	0	0	0	11584	11588	0	18225
tritica	130	986	0	0	0	0	4	307	0	0	0	0	19805
Winter Barley	125	689	0	0	0	0	6	329	79	14117	14121	0	0
woat	0	0	0	0	0	0	4	307	0	11032	11036	4	0
Winter Rape	30	313	80	0	0	9	0	784	131	3414	3418	0	5646
Winter Rye	228	1607	790	78	9	0	0	0	0	0	0	0	19805
WinterWheat	157	825	115	0	0	14	5	310	115	15587	15591	0	22623

The frequency of crops presented in rotations in the different site classes does not reflect the statistical crop proportions of the site class, as the possible rotations are generated to represent all agronomically feasible rotations, rather than a representative set of rotations used in the site classes. However, it gives an overview of the crops appearing at different site classes, and gives an indication of the composition of the rotations. For instance, grass appears in 8 out of 18 rotations in Grade 4 (Eastern Scotland) – the high GHG emissions and low gross margin of this crop influences these eight rotations and subsequently the MAC curve.

WORKING PAPER

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