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Legume-based crop rotations as a strategy to mitigate fluctuations in fertilizer prices? A case study on bread wheat genotypes in northern Spain using life cycle and economic assessment

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ABSTRACT

Today's agricultural production is heavily dependent on synthetic nitrogen (N) fertilizer. Its energy-intensive production and use are associated with a number of environmental burdens, such as global warming and marine eutrophication. Furthermore, fertilizer prices are subject to high volatility and have been rising steadily for years. One strategy to reduce the dependence on synthetic N fertilizer is to include legumes in the crop rotation, but it is important that this practice is economically viable to be adopted by farmers. Through gross margin analysis and life cycle assessment (LCA), we quantified the economic and environmental impacts of introducing grain legumes into rainfed bread wheat rotations in northern Spain. The analysis covered the full two-year sequences of barley-wheat, rapeseed-wheat and vetch-wheat. We further investigated the effect of four different bread wheat genotypes on the environmental and economic performance. In this case study, replacing synthetic N fertilizer with legume-fixed N in a two-year cropping rotation decreased most of the analysed environmental impacts. Modelled greenhouse gas emissions were 24 % lower for vetch-wheat compared to barley-wheat and 11 % lower compared to rapeseed-wheat. Despite higher wheat yield, the vetch-wheat rotation had an 18 % lower gross margin than the rapeseed rotation and a 1 % higher gross margin than the barley rotation. The sensitivity analysis showed that only when fertilizer and wheat grain prices were more than doubled, that the legume rotation became more profitable than the other rotations. Consequently, farmers would require a financial incentive to include legumes in crop rotations and reduce environmental impacts.

1. Introduction

On a global scale, the agricultural sector is a significant contributor to anthropogenic global warming. Driven by population and economic growth, greenhouse gas (GHG) emissions from agriculture are projected to increase further (Mohammed et al., 2019). Developing mitigation strategies is crucial, but it is equally important that these practices are economically viable and adopted by farmers. One strategy is to reduce the use of synthetic nitrogen (N) fertilizer, as it causes emissions of carbon dioxide (CO_2) via the energy-intensive production process and of nitrous oxide (N_2O) via application (Smith et al., 2008). However, climate change is not the only risk, as N fertilizer flows exceed the so-called planetary boundaries (Steffen et al., 2015). Synthetic N fertilizer application is also a major source of ammonia (NH_3) emissions that have significant environmental impacts such as eutrophication and acidification (Xu et al., 2019), and may cause surface and ground-water pollution by nitrates (Quemada et al., 2013). Improving the efficiency and/or reducing synthetic N fertilizer inputs would therefore, potentially reduce both pre-farm CO_2 emissions from fertilizer production and on-farm emissions from the application (e.g. N_2O, NH_3, NO_3).

Several studies across different climate zones indicate that incorporating grain legumes into crop rotations can decrease N fertilizer

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requirements during both the legume production year and in the subsequent year, reducing the environmental impact of these production systems (Barton et al., 2014; Brock et al., 2016; Costa et al., 2021; MacWilliam et al., 2014). However, it is crucial that the subsequent crop efficiently uses the N introduced into the soil by the atmospheric biological fixation of the legumes (Quemada et al., 2020). In this context, genetic variation in the ability to use this legacy N is the focus of studies on bread wheat in Egypt and central Spain. Noureldin et al. (2013) found genotypic differences in N uptake and utilization efficiency under different N fertilizer levels. The same applies to Raya-Sereno et al. (2023) who compared genotypes with a different root architecture and their response to varying N fertilizer levels and pre-crops. However, these studies were purely agronomic, and most studies that focus on environmental impacts did not include different genotypes in their assessment. Using a life cycle assessment (LCA) approach, we explored the potential of combining reduced N fertilizer inputs using a legume pre-crop and genetic diversity to improve N uptake and utilization efficiency.

The strategy of reducing synthetic N fertilizer inputs is attractive not only from an environmental point of view but also to reduce costs and exposure to price fluctuations for the farmer. Fertilizer prices are subject to high fluctuations and have been rising steadily for years. High energy prices, strong demand and limited supply, caused the price of urea ammonium nitrate (UAN) to increase fivefold between January 2021 and March 2022 (Hebebrand and Laborde, 2022; Trading Economics, 2022). As a result, we included an economic evaluation in this study and performed a sensitivity analysis with varying fertilizer and grain prices, given the high price uncertainty. In addition, we repeated the sensitivity analysis with a premium and discount for the grain protein content in order to take a qualitative aspect into account. A protein premium or discount is common for bread wheat, but varies greatly depending on the region.

The specific objective of this study was to quantify the economic and environmental impacts of introducing grain legumes into rainfed bread wheat rotations in northern Spain. The analysis covered the 2-year sequences of barley-wheat, rapeseed-wheat and vetch-wheat. Using gross margin analysis and LCA, we aimed to answer the following research questions for this study: (i) Does incorporating legumes into a crop rotation cost-effectively reduce the environmental impact of bread wheat production through reduced N fertilizer input? (ii) Are legume-based crop rotations a viable mitigation strategy for fluctuations in fertilizer prices? (iii) Does the choice of bread wheat genotype affect the environmental and economic performance?

2. Material and methods

2.1. Case study

The two on-farm trials were part of a European H2020 project (SolACE) that explored the potential for improved varieties and agronomic interventions to improve crop production under water and nutrient stressed conditions. The trials were conducted under field conditions in the 2020 harvest year in Northern Spain in Viñalta (42°01’N, 04°55’W, 772 m a.s.l.) and Villamuera de la Cueza (42°25’, 04°69’, 829 m a.s.l), hereinafter referred to as Site BY and Site RD respectively (“BY” and “RD” represent the pre-crops barley and rapeseed). According to Köppen (1923), the climate of the area is classified as warm-summer Mediterranean climate (Csb). The mean annual temperature is 12 °C, and the mean annual rainfall is 440 mm (based on 1985–2015 data). The study year was slightly drier than normal with mean rainfall of 391 mm at Villamuera and 341 mm at Viñalta. The mean annual temperatures were slightly cooler: 10 °C at Villamuera and 11 °C at Viñalta. Precipitation occurs mainly in autumn and spring. The soil is mapped as a Cambic Calcisol (World Reference Base for Soil Resources, 2014) with a sandy clay loam topsoil for the two sites.

We conducted a split-split-plot experiment with 96 plots (1.8 m x 12.8 m each plot; replicated four times) at each site, considering pre-crop as the main factor, wheat genotypes as the subplot and N fertilization as the sub-subplot. Four bread wheat (*Triticum aestivum L.*) genotypes were included based on their level of drought-tolerance. Touzy et al. (2019) tested 210 European genotypes in four water stress scenarios and grouped them according to their susceptibility to water stress. We selected genotypes from all clusters: Mustang as drought-tolerant; Cellule as intermediate; and Nogal and Lutescens as susceptible to water stress (more information on the genotype characteristics is provided in the supplementary material, chapter 2).

Prior to the trial, in the 2018 harvest season, barley was grown at Viñalta (Site BY) and rapeseed at Villamuera (Site RD). Afterwards, each field was divided into 4 replicate blocks, each with one-half planted to a legume and one-half planted to a non-legume. The legume pre-crop species vetch (*Vicia sativa L.*) used as grain was cultivated at both sites; whilst non-legume species were barley (*Hordeum vulgare L.*) at Site BY and rapeseed (*Brassica napus L.*) at Site RD. Vetch was sown in November 2018, rapeseed in October 2018 and barley in January 2019. All pre-crops were harvested in early summer 2019, with the residues being incorporated into the soil. The 8 main plots at each site were then divided into a series of genotype subplots. The selected wheat genotypes were sown on the same date, at the end of October or the beginning of November 2019, at a rate of 160 kg ha^{-1}. At tillering, wheat plots were split into three N fertilization sub-subplots, a control treatment and two treatments with different fertilizer rates. Therefore, an interaction of N and pre-crop was created for each genotype.

Nitrogen fertilizer was split into two applications and broadcast on wheat plots at two growth stages (GS) (Meier, 1997): at tillering (GS22) and at stem elongation (GS36–37). Each sub-subplot received a conventional fertilizer; ammonium nitrate sulphate (26 % N), at one of the two rates; adjusted (ADJ) or recommended (REC) rate (Table 1). The REC rate (110.5 kg N ha^{-1}) was calculated based on the N requirements of wheat for an expected yield of 3700 kg ha^{-1} with the decision support system FertiliCalc (Villalobos et al., 2020). As the fertilizer rates were adjusted according to the soil inorganic N content (Nmin) in the upper 0.6 m before the first N application, the REC treatments for wheat plots with a legume pre-crop received 32.5 kg N ha^{-1} less fertilizer than the ones without a legume pre-crop. The ADJ rate for wheat plots with a legume pre-crop was half the REC rate (39 kg N ha^{-1}), and the ADJ rate of the wheat plots without a legume pre-crop was equal to the REC rate for wheat plots with a legume pre-crop. The ADJ rate was set to reflect typical farmer adjustments to the N fertiliser rate based on soil analysis that indicates improved N availability. The control sub-subplots (MIN) did not receive any N input. Given that the MIN treatment is not representative of common practice, its results are exclusively presented in the supplementary material (Tables 8–11).

Based on soil tests, phosphorus and potassium fertilizers were applied at a consistent rate before wheat sowing to ensure adequate P and K availability. Plant protection products (including herbicides and fungicides) were applied according to common farm practice (Table 1). An experimental combine undertook harvest in late July or early August 2020, and the wheat grain yield (GY, kg ha^{-1}) was recorded. A grain sub-sample was taken for laboratory analysis, where the grain N concentration (GNC, %N) (see supplementary material, Table 2) and moisture content (%) were measured. Straw was left on the field as a residue.

2.2. Life cycle assessment

We used a cradle-to-farm gate LCA approach to quantify and compare the environmental impacts of selected genotype, pre-crop species and fertilizer input combinations associated with bread wheat production. Upstream production of farm inputs (e.g. seed, fertilizer) and their use in the field (e.g. operation of machines) were included within the system boundary. They were organised into the following process groups: tillage, sowing, fertilization, plant protection, harvest

Table 1
Inventory of inputs for the cultivation of 1 hectare bread wheat in Spain as part of this study.

		Site BY				Site RD			
		leg. pre-crop wheat		non-leg. pre-crop wheat		leg. pre-crop wheat		non-leg. pre-crop wheat	
		ADJ	REC	ADJ	REC	ADJ	REC	ADJ	REC
N	kg ha^{-1}	**39**	**78**	**78**	**110.5**	**39**	**78**	**78**	**110.5**
P_2O_5	kg ha^{-1}	36	36	36	36	36	36	36	36
K_2O	kg ha^{-1}	60	60	60	60	60	60	60	60
Fertilizing	passes ha^{-1}	2	2	2	2	2	2	2	2
Pesticides[1]	kg a.i. ha^{-1}	0.93	0.93	0.93	0.93	0.43	0.43	0.43	0.43
Pesticide application	passes ha^{-1}	2	2	2	2	3	3	3	3
Seeds	kg ha^{-1}	160	160	160	160	160	160	160	160
Tillage[2]	passes ha^{-1}	2	2	2	2	2	2	2	2

1 Site BY: Tribenuron-methyl 0.56 kg a.i. ha^{-1}, Metsulfuron-methyl 0.28 kg a.i. ha^{-1}, Triazol 0.09 kg a.i. ha^{-1}
Site RD: Fluazifop-P-butyl 0.19 kg a.i. ha^{-1}, Mesotrione 0.15 kg a.i. ha^{-1}, Triazol 0.09 kg a.i. ha^{-1}.
[2] Site BY: 1 x chisel, 1 x cultivator; Site RD: 1 x disc harrow, 1 x cultivator.

Table 2
Results of the environmental and economic assessment of the two-year rotations at Site BY (top) and Site RD (bottom) per hectare and year.

Site BY		legume pre-crop/vetch-wheat						non-legume pre-crop/barley-wheat					
		ADJ			REC			ADJ			REC		
Wheat yield	kg FM	6578	±	1219	7245	±	1084	4884	±	1177	6467	±	1042
Wheat yield	kg DM	5975	±	1102	6577	±	979	4437	±	1068	5882	±	943
Gross margin	EUR	402	±	91	445	±	81	354	±	88	487	±	78
Revenue	EUR	793	±	91	856	±	81	816	±	88	966	±	78
Costs	EUR	391	±	0	411	±	0	462	±	0	480	±	0
Climate change (s)	kg CO_2-eq	1297	±	24.76	1472	±	21.99	1747	±	23.99	1913	±	21.18
Fossil energy use	MJ deprived	10456	±	0	11237	±	0	12909	±	0	13555	±	0
Marine eutr.	kg N N-lim-eq	14.95	±	0.44	15.48	±	0.41	17.20	±	0.48	17.22	±	0.46
Freshwater eutr.	kg PO_4 P-lim-eq	0.2066	±	0	0.2072	±	0	0.2005	±	0	0.2010	±	0
Freshwater acid.	kg SO_2-eq	1.9E-05	±	0	2.4E-05	±	0	3.3E-05	±	0	3.7E-05	±	0
Water scarcity	m^3 world-eq	903	±	0	928	±	0	1464	±	0	1485	±	0
Site RD		legume pre-crop/vetch-wheat						non-legume pre-crop/rapeseed-wheat					
		ADJ			REC			ADJ			REC		
Wheat yield	kg FM	8086	±	1696	7229	±	1474	7575	±	1514	6998	±	1424
Wheat yield	kg DM	7248	±	1515	6503	±	1’318	6795	±	1377	6283	±	1’284
Gross margin	EUR	551	±	127	449	±	111	647	±	114	575	±	107
Revenue	EUR	936	±	127	855	±	111	1071	±	114	1016	±	107
Costs	EUR	385	±	0	406	±	0	424	±	0	441	±	0
Climate change (s)	kg CO_2-eq	1334	±	34.04	1478	±	29.61	1512	±	30.94	1634	±	28.85
Fossil energy use	MJ deprived	10609	±	0	11390	±	0	11432	±	0	12078	±	0
Marine eutr.	kg N N-lim-eq	14.32	±	0.63	15.40	±	0.49	15.12	±	0.60	15.78	±	0.61
Freshwater eutr.	kg PO_4 P-lim-eq	0.2072	±	0	0.2078	±	0	0.1958	±	0	0.1963	±	0
Freshwater acid.	kg SO_2-eq	1.9E-05	±	0	2.4E-05	±	0	2.7E-05	±	0	3.1E-05	±	0
Water scarcity	m^3 world-eq	902	±	0	927	±	0	913	±	0	934	±	0

and field emissions. A summary of the inventory data collected is presented in Table 1. For this study, we assumed that storage and grain drying takes place outside the farm gate at the processing stage as the focus was at the field level. Background data for externally sourced inputs, e.g. the impacts of the production of fertilizers and pesticides, were included using the ecoinvent 3.7.1 LCI database. As vetch seeds were not available in the database, we used fava bean seeds instead. No co-product allocation was required, as the straw was incorporated into the soil as part of tillage for the following crop.

We assessed the collected data through the tool FarmLCA (Meier and Moakes, 2019; Schader et al., 2014). The model uses an LCA framework and is supported by biophysical systems modelling. It utilizes a modular approach to model farm systems and their emissions on an annual basis. The quantity of crop residue was not measured but calculated based on the IPCC 2019 Tier 2 guidelines, which estimate above and below ground residues from the wheat grain yield. Emissions of nitrous oxide (N_2O) were calculated with IPCC (2019) disaggregated emission factors, whilst ammonia emissions from crops were calculated utilising EMEP/EEA (2019) (NH_3 at Tier 2, NO_x at Tier 1) and nitrate losses were estimated using the SQCB method (Faist Emmenegger et al., 2009). A full description of the model and a table of methods used to estimate each field emission type is included in the supplementary material, chapter 1. The ecoinvent 3.7.1 LCI database (Wernet et al., 2016) is incorporated as the model's inventory database. We selected six system-relevant midpoint impact categories, which are part of the IMPACT World+ (Midpoint version 1.28) LCIA methodology set (Bulle et al., 2019): The Global Warming Potential (GWP) (over a 100-year timeframe) reflected in the impact category climate change shorter-term, fossil energy use, marine and freshwater eutrophication, freshwater acidification, and water scarcity. To address the uncertainty related to the LCA method, we presented the results based on a second method, namely the Ecological Scarcity 2021 (BAFU, 2021), in the sensitivity analysis.

2.3. Economic assessment

A gross margin analysis was conducted to determine the economic viability of each treatment on a per hectare basis. The economic assessment complemented the environmental assessment, using the same input data in parallel. Revenue for by-products, such as straw, were not accounted for, as it was left on the field as a residue and not sold. Unless otherwise stated, the revenue and cost data per unit of input or output was based on the agricultural statistics of the Spanish Ministry of Agriculture (Gobierno de España, 2023) for the years 2019 and 2020. Prices for mineral fertilizers were calculated based on their nutrient value (N, P, K) consistent with the ecoinvent LCI database (1.06; 0.9; 0.62 EUR/kg nutrient). The costs for machinery operations and pesticides are based on the dataset incorporated into the FarmLCA tool. Machinery costs derive from KTBL (Kuratorium für Technik und Bauwesen in der Landwirtschaft e.V, 2020), as it is the most comprehensive, reliable and suitable dataset for assessing farm systems across Europe. Whilst specific to Germany, processes and data are relevant to commercial agriculture within the EU. Machinery costs included depreciation, interests for the capital invested in the machine, storage, insurance, fees, repairs and maintenance. Other costs associated with the use of a machine were the diesel and labour costs, which depend on the working time. Wages were adapted to Spanish market conditions in 2019 and 2020 and based on (Gobierno de España, 2023). Pesticide costs have been calculated based on the online shop myAgrar (AgrarOnline GmbH, 2020). All plant protection products containing the active ingredient (a.i.) of interest were screened, and the average price was calculated considering the different proportions of the a.i. in the products. Land costs, such as taxes or rent, were not accounted for.

2.4. Functional units

For the LCA of a single year of bread wheat production, we selected a functional unit based on land management (per hectare) and on production-output (per kg). However, as the pre-crops are composed of species with varying compositions (protein, etc.), the results for the two years of crop rotation (pre-crop and bread wheat) are presented only as per hectare results following Nemecek et al. (2015). The per kg results for the one year of wheat cultivation can be found in the supplementary material (Table 12), but since they do not provide any additional information on the 2-year crop rotation, the results are not discussed in this study. The per hectare results for the crop rotation were calculated by summing the environmental impacts and gross margin of the year of pre-crop cultivation and the subsequent bread wheat cultivation and then dividing it by the number of years of the crop rotation (two). The gross margin is expressed in Euro per hectare and year (EUR ha^{-1} yr^{-1}).

3. Results

Wheat grown after a legume, in this case, vetch, resulted in 18 % higher yield than wheat grown after barley. In the ADJ treatments, the legume rotation received a lower N input (39 vs. 78 kg N ha^{-1}), but wheat yield was still 26 % higher on average than wheat following barley. In the REC treatments (78 vs. 110.5 kg N ha^{-1}) it was, on average, 11 % higher than wheat grown after barley.

The wheat yield after vetch compared to rapeseed was, on average, 6 % (ADJ) and 3 % (REC) higher. Moreover, yields differed strongly between genotypes, ranging from 4 % to 22 % higher yield for the legume-wheat rotation.

Table 2 summarises the agronomic, economic and environmental indicator results for the trials, to allow for further discussion. The results are presented for the two-year rotations per hectare and year.

3.1. Environmental impact under reduced fertilizer input

In this study, the introduction of a legume in the crop rotation and the associated reduction in N fertilizer use generally led to lower environmental impacts per hectare for most of the analysed impact categories. The GHG emissions of the vetch-wheat rotation were 24 % lower than those of the barley-wheat rotation and 11 % lower than those of the rapeseed-wheat rotation (see Fig. 1a).

The differences between the two types of rotations are mainly due to (i) the impact of pre-crop cultivation with different inputs and agricultural practices, (ii) the impact of fertilizer production (pre-farm) influenced by the different N fertilizer rates in the year of wheat cultivation and (iii) the field emissions (e.g. N_2O), which are mainly influenced by the rate of N fertilizer applied (on-farm) and the quantity of residues from wheat cultivation.

The results for most of the other impact categories were in line with this trend of lower impacts. The per hectare impacts on marine eutrophication (BY: −12 %; RD: −4 %) freshwater acidification (BY: −39 %; RD: −26 %), water scarcity (BY: −38 %; RD: −1 %) and energy use (BY: −18 %; RD: −6 %) were lower for all treatments in the vetch-wheat rotation. Only the impacts on freshwater eutrophication deviate from these results. More P_2O_5 fertilizer was used in vetch cultivation compared to rapeseed and barley, which resulted in a 3 % (BY) and 6 % (RD) higher impact on freshwater eutrophication for the legume-wheat rotation.

3.2. Economic viability of legume-based cropping rotations

The economic results indicated that the vetch-wheat rotation was less profitable than the rapeseed-wheat rotation, but similarly profitable to the barley-wheat rotation. The lower N fertilizer use in the legume-wheat rotations saved about 8 % of the total costs in the year of wheat cultivation. In addition, the costs of growing vetch as a pre-crop were 9 % lower than for rapeseed and 22 % lower than for barley. However, revenue for vetch was 52 % lower, which resulted in a negative gross margin in the year of pre-crop cultivation. In the year of wheat cultivation, the revenue for the vetch-wheat rotation at Site BY was 18 % higher, but the negative gross margin from the pre-crop year reduced the total gross margin, resulting in only 1 % higher gross margin considering both years. At Site RD, the difference in revenue in the second year of the rotation was 5 % higher for the vetch-wheat rotation compared to rapeseed-wheat. As a result, the overall gross margin for the two-year sequence was 18 % lower for the vetch-wheat compared to the rapeseed-wheat rotation.

3.3. Sensitivity analysis

In order to address uncertainties associated with the results of the environmental analysis, we employed a secondary LCA method, namely the Ecological Scarcity method (BAFU, 2021). The method uses "eco-factors" to assign weights to the impact categories, based on the distance to predefined targets. The greater the eco-factor, expressed in eco-points (EP), the higher the environmental impact. The EP of all 20 impact categories add up to the total EP. Table 3 shows the total EP and the EP of the impact category global warming, which is comparable to climate change in the Impact World+ method. More detailed results with the Ecological Scarcity method can be found in the supplementary material (Table 14).

Despite variations in numerical values due to differing units, the analysis reveals consistent outcomes across both methods, underscoring the robustness of our findings amidst uncertainty.

Farm-level economics varied considerably depending on location and pre-crop species. In addition, fertilizer and grain prices have been very volatile in recent years. The price of UAN increased by up to 455 % between 2020 and 2023 (Trading Economics, 2022). The price of wheat increased by up to 139 % (finanzen.net GmbH, 2023). We conducted a sensitivity analysis of the gross margin at different fertilizer and wheat prices. However, such scenarios would also potentially cause an increase in barley, rapeseed and vetch prices due to higher production costs and

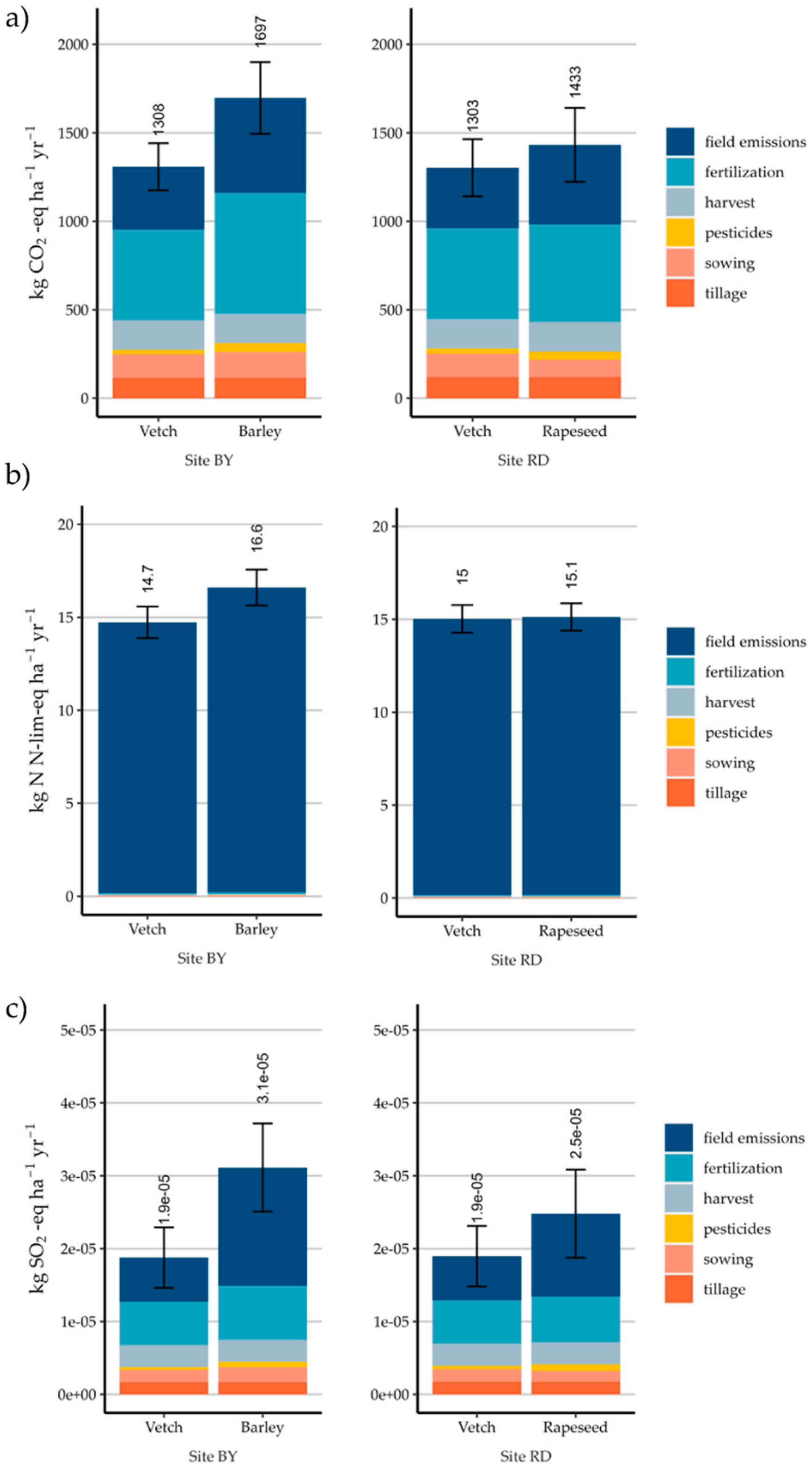

Fig. 1. Impact on a) climate change, measured in CO_2-eq per hectare and year, b) marine eutrophication, measured in kg N N-lim-eq per hectare and year, and c) freshwater acidification, measured in kg SO_2-eq per hectare and year, of the vetch-wheat and barley-wheat (Site BY) as well as vetch-wheat and rapeseed-wheat rotations (Site RD). "Fertilization" includes the impact of fertilizer production and application by broadcaster; "field emissions" includes the direct and indirect soil emissions from fertilizer application.

Table 3
Sensitivity analysis of the environmental results using a second LCA method. Results reflect the two-year rotation at Site BY (top) and Site RD (bottom) per ha and year.

Site BY		Ecological Scarcity method 2021						Impact World+		
		total eco-points million EP			global warming million EP			climate change (s) kg CO_2-eq		
Pre-crop	Vetch	11.83	±	0.07	1.38	±	0.02	1385	±	23.37
	Barley	12.92	±	0.08	1.64	±	0.02	1830	±	22.59
Nitrogen	ADJ	11.99	±	0.10	1.33	±	0.03	1522	±	24.37
	REC	12.75	±	0.05	1.68	±	0.01	1692	±	21.59
Genotype	Nogal	12.36	±	0.08	1.50	±	0.02	1604	±	10.41
	Cellule	12.26	±	0.06	1.56	±	0.02	1636	±	9.30
	Mustang	12.37	±	0.09	1.51	±	0.02	1608	±	12.39
	Lutescens	12.50	±	0.07	1.46	±	0.02	1580	±	9.25
Site RD		Ecological Scarcity method 2021						Impact World+		
		total eco-points million EP			global warming million EP			climate change (s) kg CO_2-eq		
Pre-crop	Vetch	5.14	±	0.05	0.70	±	0.01	1406	±	31.82
	Rapeseed	5.58	±	0.03	0.85	±	0.01	1573	±	29.90
Nitrogen	ADJ	5.14	±	0.04	0.71	±	0.01	1423	±	32.49
	REC	5.59	±	0.03	0.85	±	0.01	1556	±	29.23
Genotype	Nogal	5.37	±	0.03	0.77	±	0.01	1483	±	8.68
	Cellule	5.27	±	0.04	0.81	±	0.01	1532	±	11.16
	Mustang	5.39	±	0.05	0.77	±	0.01	1482	±	14.66
	Lutescens	5.42	±	0.03	0.75	±	0.01	1461	±	7.01

alternative use in feedstuffs. In nine scenarios, we increased the N-fertilizer price by 250 % and 500 % and the wheat grain price by 100 % and 200 %. The difference in gross margin between the legume-wheat rotation and the corresponding rotation without legumes is shown aggregated over all genotypes in Fig. 2.

The results of the sensitivity analysis confirmed the robustness of the results, as the trends remained mostly the same considering the strong price increases. After increasing the N fertilizer price by a factor of three and a half, the result changed only marginally. The vetch-wheat became more profitable than the barley-wheat rotation (Fig. 2). However, even after increasing the N fertilizer price by a factor of six, the legume-wheat rotation was still financially less attractive than the rapeseed-wheat rotation, although the difference in gross margin decreased. An increase in wheat grain price favoured the higher yielding rotations, which were the legume-wheat rotations (except genotype Mustang at Site RD, supplementary material Table 6). The difference in gross margin shrank but was still higher for the rapeseed-wheat rotations. An increase of both N and wheat prices in different variations made the legume-wheat rotation also slightly more profitable than the rapeseed-wheat rotation.

When it comes to the economic result, grain yield is a very decisive variable. Therefore, during the last decades cultivar breeding has focused on boosting yield. But not only quantity, also the quality is important for selling bread wheat, which is associated with processing attributes, such as the grain protein content (Geyer et al., 2022). However, several studies have demonstrated an inverse relationship between grain yield and grain protein content (e.g. Oury and Godin, 2007; Laidig et al., 2017). Commonly, for bread wheat a premium is paid for a high protein content, but if it is too low and not suitable for baking, it can only be sold at a lower price for use as feed. In this study, no price premium or discount was applied, but to reflect this common practice, we have included a 21 % (40 EUR/t) premium for a protein content >12 % and a 10 % (19 EUR/t) discount for a protein content <10 % in the sensitivity analysis. As prices and ranges can vary widely, we have decided to base the analysis on values that are common in the region. We repeated the sensitivity analysis, including the protein premium/discount and the results changed slightly (Fig. 3). Protein content tended to be higher for wheat grown after barley and rapeseed than after vetch. In contrast to Fig. 2, in the baseline scenario and with a 3.5-fold increase in the price of

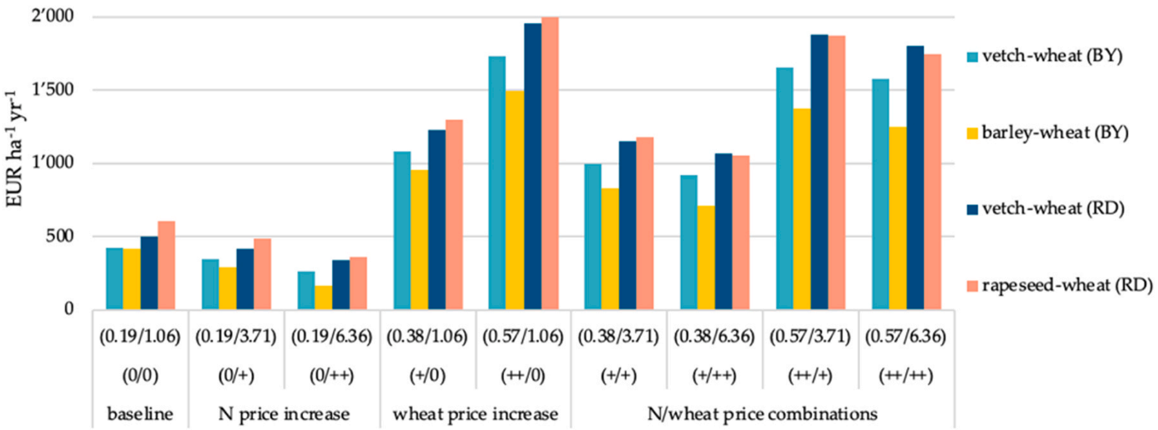

Fig. 2. Price scenarios for the sensitivity of the gross margin in EUR per hectare and year for each site. Average gross margin across all genotypes and fertilization levels (ADJ & REC). Price scenarios refer to the units (EUR per kg wheat/EUR per kg N).

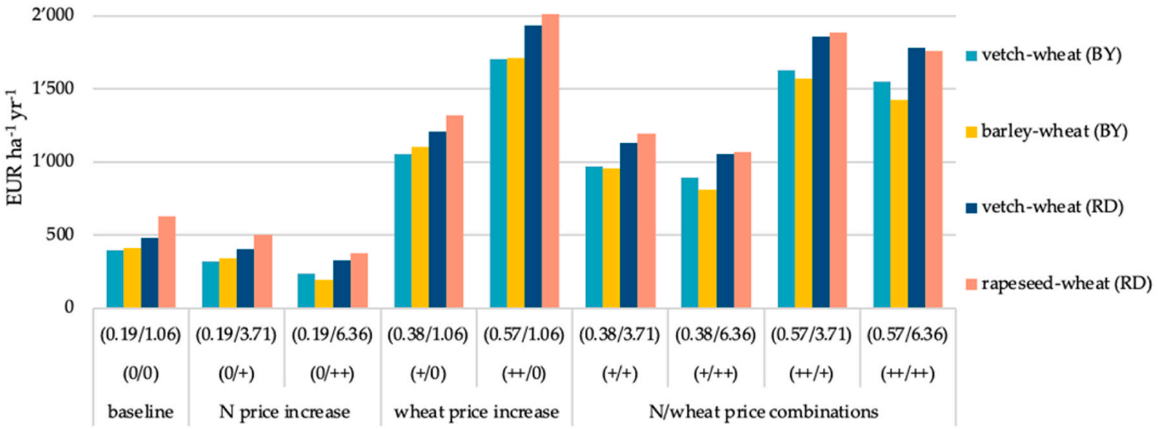

Fig. 3. Price scenarios including a protein premium/discount for the sensitivity of the gross margin in EUR per hectare and year for each site. Average gross margin across all genotypes and fertilization levels (ADJ & REC). Price scenarios refer to the units (EUR per kg wheat/EUR per kg N).

N fertilizer, the barley-wheat rotation had a higher gross margin than the vetch-wheat rotation. The same was observed when the wheat grain price increased. However, in the scenarios with a combination of both prices the vetch-wheat rotations were more profitable than barley-wheat. Only if the wheat grain price increased by a factor of three and the N fertilizer price increased by a factor of six, vetch-wheat outperformed rapeseed-wheat.

3.4. *Differences in genotypes*

The results remained consistent across most indicators for all genotypes. Variations were observed exclusively in indicators directly or indirectly influenced by yield, such as gross margin, impact on climate change and on marine eutrophication. Cellule had a 45 % higher gross margin than Lutescens, considering the two-year rotation. The drought-resistant genotype Mustang had a 24 % higher gross margin than Lutescens and 2 % higher gross margin than Nogal, which are classified as susceptible to water stress. On a per hectare basis for the two-year rotation, the highest-yielding genotype Cellule had a 4 % higher impact for climate change than the lowest-yielding genotype Lutescens. The impact is greater for the genotypes with higher yields, mainly because the estimated amount of crop residues is greater and their decomposition leads to higher N_2O emissions. Regarding marine eutrophication, higher yield leads to higher N uptake and, thus, lower nitrate leaching. Cellule had a 7 % lower impact on marine eutrophication per hectare than Lutescens on a two-year basis.

As Cellule was the highest-yielding genotype, its protein content was on average the lowest of the four genotypes. Its protein content was below 12 % in all treatments and mostly even below 10 %. The above results are presented without a protein premium/discount, but Fig. 4 illustrates the effects if the protein content were taken into account. On average, wheat grain of the Cellule genotype would have to be sold as feed, but it would still be the genotype with the highest gross margin due to its high yield. Lutescens, on the other hand, had a comparatively high protein content and would have received a premium at site RD, but would continue to be the genotype with the lowest gross margin.

4. Discussion

4.1. *Environmental impact of legumes in crop rotations*

Replacing synthetic N fertilizer with legumes that can fix N, as part of a two-year cropping rotation, decreased the modelled impact on climate change and marine eutrophication. In the present study, 32.5 (REC) and 39 (ADJ) kg N ha^{-1} in the form of ammonium nitrate sulphate fertilizer were saved when legumes were included in the crop rotation, leading to a reduction in emissions and energy consumption associated with the production, transport and use of fertilizer.

Using vetch before wheat resulted in average energy ($MJ_{deprived}$ ha^{-1} yr^{-1}) savings of 18 % compared to the barley-wheat rotation and 6 %

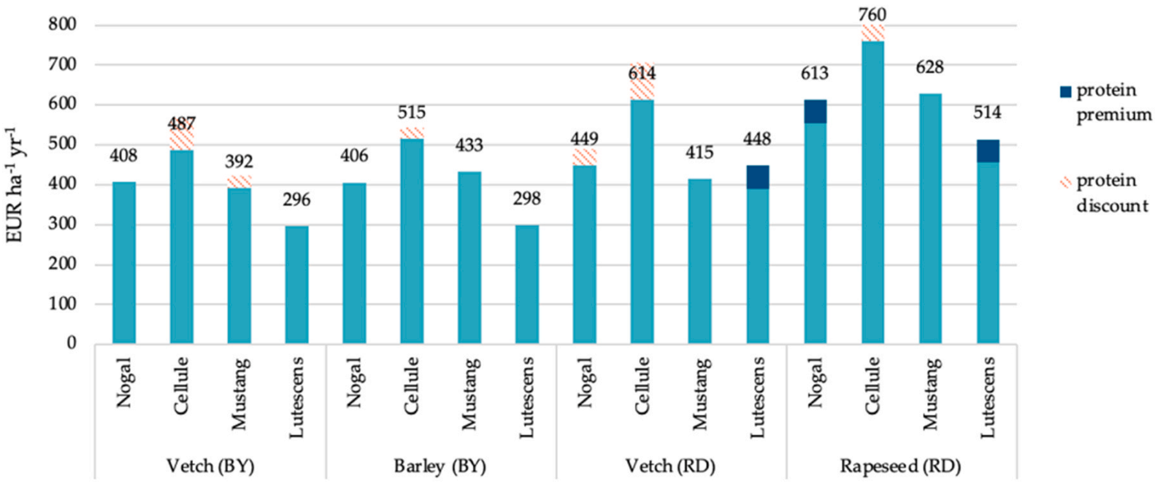

Fig. 4. Comparison of genotypes under consideration of a protein premium/discount in the gross margin in EUR per hectare and year for each site. Average gross margin across both fertilization levels (ADJ & REC). Protein premium of 40 EUR/t wheat grain if grain protein content >12 % and 19 EUR/t discount if <10 %.

compared to rapeseed-wheat. This result is comparable to that of a study by Nemecek et al. (2008), in which N fertilizer input was reduced by 23 kg ha^{-1}, which resulted in fossil fuel savings of 14 % by replacing wheat with peas in one year of a five-year crop rotation.

For the two-year sequence, greenhouse gas emissions were 24 % lower for vetch-wheat (total 1385 kg CO_2-eq ha^{-1} yr^{-1}) compared to the barley-wheat rotation (total 1830 kg CO_2-eq ha^{-1} yr^{-1}) at Site BY, and 11 % lower for vetch-wheat (total 1406 kg CO_2-eq ha^{-1} yr^{-1}) compared to rapeseed-wheat (total 1573 kg CO_2-eq ha^{-1} yr^{-1}) at Site RD. The total quantity of CO_2-eq ha^{-1} emitted for one year of wheat cultivation varies quite strongly when comparing other studies on wheat production (e.g. from 364 kg CO_2-eq ha^{-1} in Barton et al., 2014 to 3720 kg CO_2-eq ha^{-1} in Naudin et al., 2014). Differences in yield and field emissions can be due to the location, such as the experiment in Barton et al., 2014 took place in Australia with differences in climate, precipitation and soil properties. Furthermore, different methods may be used to estimate field emissions, and background data for e.g. fertilizer production may come from different databases or database versions. Moreover, different types of fertilizer and the energy mix of its producing country can lead to differences in impacts. Or simply the amount of fertilizer applied. In Naudin et al., 2014, 190 kg ha^{-1} of ammonium nitrate was used, so depending on the database, fertilizer production and transport can already lead to more than 1600 kg CO_2-eq ha^{-1}.

Nevertheless, our observation of a proportional reduction in emissions due to substitution by legumes and the associated reduction in N fertilizer use is in line with the results of other studies. In Nemecek et al. (2008), N fertilizer was reduced by 23 kg N ha^{-1} when wheat was replaced by peas in the rotation, resulting in 11 % lower CO_2-eq ha^{-1}. The lentil and dry pea rotations in MacWilliam et al. (2014) reduced the effects on global warming by 17–22 % and the introduction of lupin pre-crops reduced greenhouse gas emissions by 30 %.

In this study, an average of 159 kg CO_2-eq ha^{-1} can be attributed to the production and transport of the additional fertilizer used in the barley and rapeseed-wheat rotation in the year of wheat production. The other main contributor to the impact on climate change is field emissions, which were reduced by an average of 102 kg CO_2-eq ha^{-1} in the legume rotations. Field emissions in this case mainly reflect nitrogen oxides (N_2O), whose global warming potential is about 300 times higher than that of CO_2. Nitrogen oxide emissions are caused by losses from the N fertilizer input and through the decomposition of crop residues. As a result, the higher yielding treatments, which were mainly the legume-wheat rotations, had higher N_2O emissions, due to a greater estimated quantity of crop residue, but overall lower emissions, due to lower fertilizer inputs.

Apart from these aspects, emissions from legume crops may well be higher due to greater N levels within the field residues, and this is reflected in the IPCC 2019 Tier 2 methodology adopted here. Biological nitrogen fixation is not included as a direct source of N_2O because of the lack of evidence of significant emissions arising from the fixation process itself. Rochette and Janzen (2005) concluded that the N_2O emissions induced by the growth of legume crops may be estimated solely as a function of the above-ground and below-ground N inputs from crop residue. For this assessment, soil organic changes were not considered, therefore, the release of N by mineralisation of soil organic matter as a result of a change of land use or management is not included.

Freshwater acidification was lower for the vetch-wheat rotation compared to both barley-wheat and rapeseed-wheat, (39 % and 26 %, respectively). It was mainly caused by ammonia volatilization. Especially in alkaline soils, ammonium (NH_4^+), which was part of the N fertilizer used in this study, can be converted into ammonia gas (NH_3) and emitted into the atmosphere. It can travel long distances and is deposited in soils and waterways via rain, altering their acidity, which can harm species (Bulle et al., 2019). However, this risk is much higher for fertilizers containing urea (Brentrup et al., 2001). According to Peoples et al. (1995a, as cited in Crews and Peoples, 2004), legume pre-crops could reduce the risk of ammonia volatilization during crop residue deposition but at the same time, potentially result in higher denitrification losses of N_2O (Hansen et al., 2021; Sanz-Cobena et al., 2014). Nevertheless, the increase in N_2O emissions caused mainly by legume residue decomposition is compensated by the reduction in direct and indirect emissions associated with N fertilizer savings (Guardia et al., 2019).

Regardless of the source of N, a higher yield is associated with greater biomass that takes up more N. As a result, less nitrate is available for leaching into groundwater, rivers and subsequently, coastal marine ecosystems where it can cause eutrophication. Reducing the N input in the first place can reduce this risk of marine eutrophication. In this study, part of the synthetic N fertilizer was replaced by legume pre-crops, but also legumes can promote nitrate leaching before the subsequent crop can take it up. Only few studies provide insights into this topic and uncertainties are high (Crews and Peoples, 2004; Masoni et al., 2015). In the underlying model of this study, nitrate emissions are calculated based on the SQCB tool (Mireille Faist Emmenegger et al., 2009). Overall, the use of the pre-crop vetch before wheat resulted in a 12 % lower impact on marine eutrophication compared to the barley-wheat rotation but only a 4 % lower impact compared to the rapeseed-wheat rotation. In this study, the two years of the rotation were modelled separately, and the impacts were then summed. Therefore, most of the nitrate provided by the legume pre-crop was modelled as lost when residues were incorporated into the soil, whereas some of it would likely be taken up by the wheat crop following the legumes. As a result, the reduction in the impact on marine eutrophication from the introduction of legume pre-crops estimated in this study may be even greater than we have reported.

The impact on water scarcity was 38 % (BY) and 1 % (RD) lower for the vetch-wheat rotation. In the ecoinvent LCI database, the impact on water scarcity was much greater for barley seed than for fava bean seed used to model vetch, which was unavailable in the database. We chose fava bean seed, as their cultivation is quite similar to vetch, however, fava bean seed in the database are not specific to Spain and have a higher yield than vetch in this study. As a result, the impact per kg is lower and therefore might be slightly underestimated. However, for most impact categories the contribution of seed to the overall impact is between 0 % and 20 %. Only water scarcity is largely driven by the seed and in the case of the barley seed from the database, mainly caused by irrigation. If the vetch grown to produce the seed used in our trial were rainfed, we would expect the fava bean seed to be a good proxy, but if they were irrigated, the result would be quite different.

Freshwater eutrophication was the only impact category where the impact of the vetch-wheat rotation was slightly higher (3 % BY; 6 % RD), due to the larger quantity of P_2O_5 fertilizer used in the vetch cultivation in this study.

This study highlights the positive role legumes can play in reducing reliance on synthetic N fertilizer and the problems of assessing multi-year cropping rotations due to differing products (e.g. protein content). It remains difficult to assess the true productivity of a crop rotation without using alternative functional units, which may not be comparable to mainstream studies. Furthermore, modelling of nitrogen transfer between crop years is challenging within an LCA focus when most assessments are on an annual basis. Therefore, emissions from lost nutrients, and especially crops such as legumes can be overestimated.

The results of this study are limited to two trials in northern Spain with different non-legume pre-crops in one year. A different climate or weather during the growing season can strongly influence the performance of different crops. Consequently, our results are specific to the assessed year (2020), and the conclusions drawn should not be generalised beyond this context. Nevertheless, most researchers reported that a precedent legume crop increases the performance of subsequent cereals compared to non-legume crops (Angus et al., 2015; Gan et al., 2015). Though, whilst the response to N fertilization of the subsequent wheat will greatly depend on the N supply from the pre-crop (Cernay et al., 2018), the N supply might be low if the pre-crop growth is limited.

On-farm trials such as this case study offer numerous benefits for agricultural research. They provide a real-world setting that allows researchers to evaluate the performance of agricultural practices under authentic conditions. As the research takes place on the farmers' own fields and on topics that are relevant to them, farmers are more interested, motivated and more likely to adopt the practices later on (Kyveryga, 2019). On-farm trials foster collaboration between researchers and farmers, promote hybridisation of knowledge and ensure that the results are both scientifically sound and applicable to the farming community (Lacoste et al., 2022). However, on-farm trials are also associated with risks. Indeed, we were unable to use the data from 2021 because the fertilization plan was not adhered to. Nevertheless, our results are consistent with those of other studies and provide an insight into the topic from an environmental and economic perspective.

4.2. Economic viability of legume-based crop rotations

From an economic perspective, partial substitution of synthetic N fertilizer with legume-fixed N in the year of wheat cultivation led on average to (i) lower N fertilizer costs of about 8 % of total costs; (ii) higher revenues of 18 % (BY) and 5 % (RD) due to higher yields; and (iii) a 32 % (BY) and 11 % (RD) higher gross margin. Thus, in the year of wheat cultivation, it tends to be more profitable to use legumes as pre-crops (see also Nemecek et al., 2015). However, several studies have shown that the cultivation of a legume in the preceding year is less profitable for the farmer when subsidies are not accounted for (e.g. Brock et al., 2016; Preissel et al., 2015). There may be differences depending on the choice of legume pre-crop. This study was limited to a single legume pre-crop, vetch, whose grains were sold as fodder. The costs for cultivating vetch were 22 % lower than for barley and 9 % lower compared to rapeseed. However, the revenue of vetch was 52 % lower than barley and rapeseed. As a result, the gross margin for cultivating vetch was negative and positive for the other pre-crops. Thus, taking into account the results of the two-year crop rotation lead on average to a lower gross margin of −18 % for vetch-wheat compared to rapeseed-wheat and 1 % higher gross margin compared to barley-wheat.

In the context of this case study, we can conclude that using a legume pre-crop before bread wheat results in a lower environmental impact but its profitability is strongly dependent on the pre-crop species. While the wheat-rotation with vetch was similarly profitable to barley, it could not compete with rapeseed when assessing the two years of crop rotation. Therefore, farmers would require some form of financial incentive to change rotations and reduce environmental impacts. This is in line with the results from Barton et al. (2014), who compared a lupin-wheat with a wheat-wheat crop rotation. In their study, an incentive of 93$ per tonne of carbon dioxide equivalents reduced would be required to promote the inclusion of legumes in the crop rotation.

The results of this study are limited to the pre-crops vetch, barley and rapeseed. The fact that the difference between the results of the two non-legume pre-crops, barley and rapeseed, in this study was quite substantial shows that not only the choice of legume pre-crop, but also the counterfactual can strongly influence the result. In addition, the cultivation of the same crop in the year preceding the non-legume pre-crops may resulted in a potential side-effect on agronomic outcomes due to increased disease pressure. Further research in this field with other legume and non-legume pre-crops over a longer period of time could be of great benefit to the literature. The agronomic effect of different break-crops on the wheat yield has been investigated in many studies. Kirkegaard et al. (2008) and Angus et al. (2015) showed that rapeseed is superior to other break crops in terms of more efficient N recovery, high levels of residual N and suppression of cereal pathogens. Wheat following barley, on the other hand, was similar to wheat following wheat, thus missing the break-crop benefits.

A limitation of this study is that a small part of the economic data (machinery and pesticide costs) originated from a German cost database implemented in our model. Although these values may vary for Spain, absolute values of the parameters were not crucial to the analysis, but rather their relative values were important for comparing the treatments. The key variables for the analysis were gathered from Spanish databases. Furthermore, the sensitivity analysis with varying fertilizer and wheat grain prices showed that only a very strong increase in the N fertilizer price (+500 %) and the wheat price (+100 %) made the legume-wheat rotation more profitable in direct comparison to the rapeseed-wheat rotation. An increase in the wheat grain price or N fertilizer price alone did not change the overall result. Hence, from an economic perspective, legumes outperform most alternative crops only in the face of very strong price fluctuations.

If a premium (>12 %) or discount (<10 %) for the grain protein content is taken into account, a 500 % increase in the N fertiliser price and a 200 % increase in the grain price are needed to make the vetch-wheat rotation more profitable than rapeseed-wheat. The vetch-wheat rotations tend to have a lower protein content than the rapeseed and barley-wheat rotations. This is in line with the well-documented inverse relationship of protein content and yield, since the vetch-wheat rotations in this study had a higher grain yield.

4.3. Effect of different bread wheat genotypes

The results showed an effect of genotype only on variables influenced by yield. The high-yielding genotype Cellule was identified as moderately drought-tolerant in a panel of 210 European genotypes (Touzy et al., 2019). The low-yielding genotype Lutescens, on the other hand, was identified as susceptible to water stress. Li et al., (2019) associated tolerance to drought with a greater rooting depth. Genotypes with more developed root systems can access more soil resources, such as N and water, and increase or stabilize yield and N use efficiency under low-input conditions (Lassaletta et al., 2023). The deep roots of the genotype Mustang were identified by Odone et al. (2023). Additionally, Touzy et al. (2019) categorized Mustang as drought-tolerant, which is further supporting the association between deep roots and its ability to withstand drought conditions.

The two-year gross margin of the highest yielding genotype Cellule was 45 % higher than that of the lowest yielding genotype Lutescens. However, Cellule had the lowest grain protein content of all four genotypes tested, so that on average a protein discount would be incurred, while Lutescens would receive a protein premium. Despite this, the Cellule genotype would still have the highest gross margin due to its high yield and Lutescens the lowest. This indicates that yield tends to be more important than protein content when it comes to overall profitability.

When analysing the environmental impact of the second year of wheat cultivation on a per hectare basis, the higher yielding genotypes had higher N_2O emissions (climate change) due to the greater amount of decomposing crop residues, but less nitrate leaching (marine eutrophication) due to greater nitrogen offtake.

This study is limited by the inclusion of four genotypes selected to represent the varying degrees of drought tolerance. While this selection provides valuable insight, it does not capture the full range of genetic diversity within the wider wheat population, highlighting the importance of considering additional genotypes in future studies.

5. Conclusion

In this case study, the introduction of legumes into the crop rotation, to replace part of the synthetic N fertilizer, decreased most environmental impacts per hectare when assessing the two years of crop rotation. However, in comparison to the pre-crop rapeseed the trade-off was lower profitability for the farmer, as the cost savings from reduced fertilizer use could not compensate for the poor economic outcome of legume cultivation. Only with very strongly increased fertilizer and grain prices, the legume pre-crop vetch did slightly outperform rapeseed. This highlights the importance of exploring financial incentives to encourage farmers to include legumes in their crop rotations, especially as reducing synthetic fertilizers by 20 % by 2030 is an objective of the European Green Deal Farm to Fork strategy. Crop rotations with legumes could also play a key role for human consumption as part of the so-called "planetary healthy" diet recommended by the EAT-Lancet Commission.

The choice of bread wheat genotype had a strong effect on the economic performance in this study. The moderately drought-tolerant genotype Cellule generated the highest gross margin, even if a discount was applied due to its low grain protein content. The genotype Mustang, which is classified as drought-tolerant and deep-rooted, ranked second after Cellule. The evidence for whether genotypes with deep or powerful root systems are better suited to reduced fertilizer conditions with legume pre-crops remains unclear. Therefore, further studies with a larger range of genotypes and conditions over a longer period of time are needed to confirm whether such root traits consistently make a significant difference.

CRediT authorship contribution statement

Mareike Weiner: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Conceptualization. **Simon Moakes:** Writing – review & editing, Validation, Methodology, Formal analysis, Conceptualization. **María Dolores Raya-Sereno:** Writing – review & editing, Investigation, Conceptualization. **Julia Cooper:** Writing – review & editing, Supervision.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Mareike Weiner reports financial support was provided by Horizon Europe.

Data availability

Data will be available online (European Commission website) in the near future

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.eja.2024.127267.

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