SUPPORTING INFORMATION

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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1. Model description: FarmLCA

The tool FarmLCA (Meier & Moakes, 2019; Schader et al., 2014) has been developed over the past 10 years and is programmed in Microsoft EXCEL®. Its purpose is to assess the environmental and economic performance of farm products, enterprises and systems. It consists of i) a farm system model, ii) an LCA and iii) an economic assessment. This combined approach enables all farm production activities and flows up to the farm gate to be captured and modelled with increasing detail and accuracy.

A strength of the farm system model is the detailed representation of the livestock and plant production enterprises and their interlinkages. Internal flows, such as cereals or forages from on-farm feed production, are transferred with farm-specific impact values to the livestock enterprise, whilst manure may return from livestock enterprises back to the plant production enterprises via specified allocation from grazing or spreading. These manure flows are specific to the livestock diet and production level on the farm. This context-specific approach allows superior accuracy compared to standard data. The farms livestock herd structure, their nutrient requirements at different life stages, the enteric fermentation and manure management are modelled, as well as plant nutrient requirements and N, P and carbon emissions. Emissions of nitrous oxide (N_2O) are calculated with IPCC (2019) disaggregated emission factors, whilst ammonia emissions from crops are calculated utilising EMEP/EEA (2019) (NH_3 at Tier 2, NO_x at Tier 1) and nitrate losses are estimated using the SQCB method (Faist Emmenegger et al., 2009). Table 1 provides detailed information about the methods used for each type of field emission. In this publication, however, only the plant production module was used, as the focus was on the plot level, not the farm level.

The second feature of the tool is the integrated LCA framework. Inputs and outputs are quantified via the farm system model described above, and background processes derive from the ecoinvent 3.7.1 LCI database (Wernet et al., 2016), which is incorporated as the model's inventory database. This approach allows inputs and outputs to be tailored to the specific circumstances of a farm or region. Impacts can be assessed within the tool through the IMPACT World+ (Midpoint version 1.28) LCIA methodology set (Bulle et al., 2019) with its 18 impact categories or the Ecological Scarcity method 2021 (BAFU, 2021).

The third feature, an economic assessment, is a valuable addition to the tool. When implementing changes or new strategies in food production, the financial implications are a very important factor for farmers. Therefore, a gross margin analysis is performed in the tool to assess the economic performance of different farm production strategies. Cost data for all external inputs (e.g. fertilizer, pesticides, seeds) and for machinery, diesel and labour, as well as prices for selling the farm products, are included in the model and are linked to the same processes used in the LCA.

Table 1. Modelled field emissions.

Production	Module	Field emission	To	Methods	Reference
Plant	Field emissions	Dinitrogen monoxide (N_2O)	Air	IPCC, Tier 2[a]	IPCC (2019)[a]
		Carbon dioxide (CO_2)		IPCC, Tier 1[a]	IPCC (2019)[a]
		Nitrogen oxides (NO_x)		EMEP/EEA, Tier 1c	EMEP/EEA (2019)[c]
		Ammonia (NH_3)		EMEP/EEA, Tier 2[c]	EMEP/EEA (2019)[c]
		Nitrate (NO_3)	Groundwater	SQCB-NO3[d]	Faist (2009)[d]
		Phosphate (PO_4)	Surface water	SALCA-Phosphorus[fg]	Prasuhn (2006)[f], Oberholzer (2006)[g]
			Groundwater		
		Phosphorus (P)	Surface water		
		Cd, Cr, Cu, Hg, Ni, Pb, Zn	Groundwater	SALCA-Heavy metals[h]	Freiermuth (2006)[h]
			Surface water		
			Soil		
Livestock	Rationing	On-farm feeds	Livestock	Yield-driven daily requirements[i]	LfL (2017)[i]
		External feeds			
	Nutrients in FYM	Solid and liquid manures	Storage	Nutrient balance[j]	Richner et al. (2017)[j]
			Field		
	Manure management	Methane (CH_4)	Air	IPCC, Tier 2 & 3[ak]	IPCC (2019)[a], FOEN (2018)[k]
		Dinitrogen monoxide (N_2O), direct		IPCC, Tier 3[ak]	
		Dinitrogen monoxide (N_2O), indirect		IPCC, Tier 3[ak]	
		Ammonia (NH_3)		AGRAMMON[l]	Kupper et al. (2016)[l]
	Enteric fermentation	Methane (CH_4)	Air	IPCC, Tier 2 & 3[ak]	IPCC (2019)[a], FOEN (2018)[k]

a. IPCC: 2019 IPCC Guidelines for National Greenhouse Gas Inventories
b. Meier, M. S., Schader, C., Berner, A., & Gattinger, A. (2012). Modelling N2O emissions from organic fertilisers for LCA inventories.
c. EMEP/EEA, 2019. Air pollutant emission inventory guidebook. Part B: sectoral guidance chapters; Chapter 3.D: Agriculture - Crop production and agricultural soils. 43p.
d. Faist Emmenegger, M., Reinhard, J., Zah, R. : Sustainability Quick Check for Biofuels – intermediate background report. With contributions from T. Ziep, R. Weichbrodt, Prof. Dr. V. Wohlgemuth, FHTW Berlin and A. Roches, R. Freiermuth Knuchel, Dr. G. Gaillard, Agroscope Reckenholz-Tänikon. Dübendorf, 2009.
e. Meier, M. S., Jungbluth, N., Stoessel, F., Schader, C., & Stolze, M. (2014, October). Higher accuracy in N modeling makes a difference. In 9th International Conference LCA of Food (pp. 8-10).
f. Prasuhn V. (2006) Erfassung der PO4-Austräge für die Ökobilanzierung - SALCA-Phosphor. Agroscope FAL Reckenholz, Zürich, 22 S.
g. Oberholzer H.-R., Weisskopf P., Gaillard G., Weiss F. & Freiermuth R. (2006) Methode zur Beurteilung der Wirkungen landwirtschaftlicher Bewirtschaftung auf die Bodenqualität in Ökobilanzen – SALCA-SQ. Agroscope FAL Reckenholz, 98 S.
h. Freiermuth, R. (2006). Modell zur Berechnung der Schwermetallflüsse in der landwirtschaftlichen Ökobilanz. Report Agroscope FAL Reckenholz, 42.
i. LfL (2017). Gruber Tabelle zur Fütterung der Milchkühe, Zuchtrinder, Mastrinder, Schafe, Ziegen, 42. Auflage. Freising: LfL. 100 S.
j. Richner W. & Sinaj S., 2017. Grundlagen für die Düngung landwirtschaftlicher Kulturen in der Schweiz (GRUD 2017). Agrarforschung Schweiz 8 (6). Spezielpublikation, 276 S.
k. FOEN: Switzerland's greenhouse gas inventory 1990–2016, Sub-mission of April 2018 under the United Nations Framework Convention on Climate Change and under the Kyoto Protocol, Tech.rep., Federal Office for the Environment (FOEN), 2018.
l. Kupper T., Bonjour C., Zaucker F., Achermann B., Menzi H., 2010c. Agrammon: An internet based model for the estimation of ammonia emissions. In: Cordovil, C., Ferreira, L., (Eds.). 14th RAMIRAN International Conference. Lisboa Portugal. pp. 334-337.

2. General information on breed characteristics

The winter wheat genotype Nogal has medium tillering and medium-early spike emergence, culminating in early maturation. Originating in France and registered in Spain in 2006, it showcases adaptability to diverse Spanish cultivation conditions, demonstrating moderate to high resistance against multiple fungal diseases. Notable for its moderate height, high yield potential, elevated protein content, and balanced dough strength, Nogal stands out as a versatile and disease-resistant wheat variety, particularly suitable for baking and bread-making applications (Portal Tecnoagricola, 2023).

According to Isterra Hungary (2023) the genotype Cellule has a yield potential ranging from 9-12 t/ha and a hectolitre weight of 80 kg. Its resilience in dry conditions and efficient nitrogen utilization make it adaptable across various climates and soil types. Notably, this variety demonstrates low stem growth, reducing the necessity for additional structural support, and exhibits tolerance to herbicides with Chlorotoluron. It shows outstanding resistance to rust diseases and septoria, enhancing its disease resilience. The grain quality attributes of Cellule, such as protein content >12.5% and gluten content ranging from 26-27%, a Hagberg falling number exceeding 370 seconds, Zeleny sedimentation value between 48-54 ml, and Alveograph W value ranging from 180-220, underscore its medium to strong dough characteristics. Additionally, the balanced resistance versus extensibility ratio (P/L: 1.0-1.5) highlights its potential for bread baking applications.

Mustang displays quick maturity ideal for main season planting. It features an outstanding short canopy, simplifying on-farm management, and embodies a conservative tillering pattern with an erect open canopy. Notably, Mustang demonstrates excellent major gene resistance to Stripe Rust, good resistance to Stem Rust, and moderate resistance to Leaf Rust, along with consistent performance against Yellow Spot and Black Point. Trials have emphasised its adaptability to various climates and soils and potential for high yields, especially under stress conditions (Advanta Seeds Pty Ltd., 2021).

In a 3-year comparative trial among Siberian wheat varieties, Lutescens demonstrated comparatively lower average yields at 2.5 t/ha. In terms of grain quality parameters, Lutescens showcased a lower grain unit (738 – 746 g/l) and varied gluten content, registering ranging from 33.4 to 35.3%. Lutescens consistently met the requirement for strong wheat, with an average flour strength ranging from 318 to 810 a.u.. Additionally, when assessing stability and plasticity, Lutescens displayed stability across the research years, highlighting its consistent yield performance among the tested Siberian wheat varieties (Kazak & Loginov, 2020).

3. Measured data on bread wheat quality

Table 2. Dry matter N and protein content (in %) for the one year of bread wheat cultivation.

		ADJ		REC	
		N	protein	N	protein
Vetch (BY)	Nogal	1.69	10.57	1.84	11.47
	Cellule	1.48	9.27	1.51	9.45
	Mustang	1.56	9.76	1.63	10.19
	Lutescens	1.86	11.65	1.83	11.42
Barley (BY)	Nogal	1.79	11.21	1.66	10.35
	Cellule	1.44	8.99	1.62	10.10
	Mustang	1.77	11.05	1.67	10.46
	Lutescens	1.91	11.93	1.76	10.99
Vetch (RD)	Nogal	1.57	9.79	1.81	11.32
	Cellule	1.38	8.63	1.53	9.57
	Mustang	1.61	10.08	1.86	11.65
	Lutescens	1.91	11.96	2.01	12.59
Rapeseed (RD)	Nogal	1.87	11.67	2.19	13.66
	Cellule	1.56	9.77	1.89	11.79
	Mustang	1.71	10.66	1.92	11.97
	Lutescens	1.91	11.91	2.21	13.84

* The nitrogen content was measured and the protein content was calculated using a protein-to-nitrogen conversion factor of Nx6.25.

4. Statistical analysis

The effects of pre-crop (PC; barley, rapeseed or vetch), nitrogen fertilizer level (N; ADJ, REC) and Genotype (G; Nogal, Cellule, Mustang, Lutescens) and their interactions on dry and fresh yields, were tested using an ANOVA derived from a linear-mixed effects model (Pinheiro and Bates, 2000) in the nlme package of R (R Core Team, 2022). The hierarchical nature of the split-split-plot design was reflected in the random error term that was specified as Rep/PC/G. The normality of residuals of all models was tested using QQ-plots. Post-hoc pair-wise comparisons of genotype means were made using Tukey contrasts in the general linear hypothesis testing (glht) function of the multcomp package in R.

Model structure and R-coding used to generate ANOVA P-values; example for wheat dry matter yields at site “RD”:

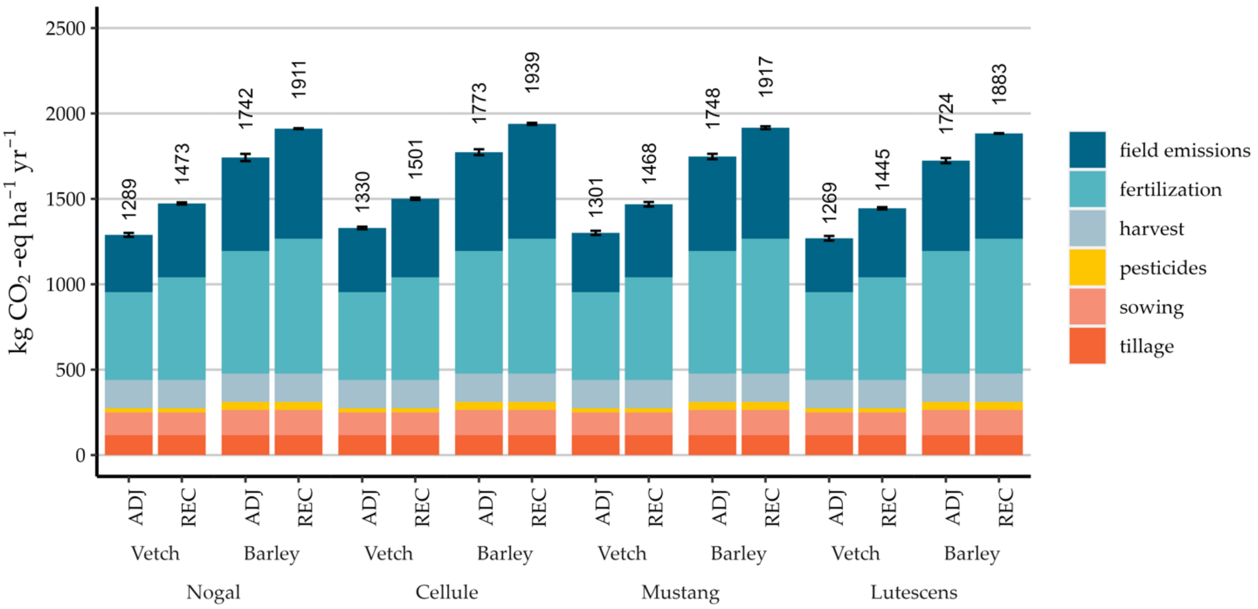
```
model.lme<-lme(DMY~PC*N*G, data=dataRD, random=~1|Rep/PC/G)
```

Table 3. Genotype means and ANOVA P-values for wheat fresh and dry matter yields at the Site BY (top) and Site RD (bottom). Genotype means followed by the same letter in the same column are not significantly different (P < 0.05 using Tukey's HSD test).

Site BY		Dry matter yield kg ha^{-1}		Fresh matter yield kg ha^{-1}	
Pre-crop	Vetch	6,276 ± 1,070		6,911 ± 1,184	
	Barley	5,159 ± 1,233		5,675 ± 1,357	
Nitrogen	ADJ	5,206 ± 1,323		5,731 ± 1,460	
	REC	6,229 ± 1,009		6,856 ± 1,118	
Genotype	Nogal	5,578 ± 1,023	b	6,133 ± 1,130	b
	Cellule	6,992 ± 0,964	a	7,704 ± 1,060	a
	Mustang	5,776 ± 0,930	b	6,358 ± 1,031	b
	Lutescens	4,524 ± 0,847	c	4,978 ± 0,934	c
ANOVA *P-values*	Pre-crop (PC)	0.0102		0.0109	
	Nitrogen (N)	<0.0001		<0.0001	
	Genotype (G)	<0.0001		<0.0001	
	PCxN	0.0015		0.0015	
	PCxG	0.8193		0.8200	
	NxG	0.5976		0.5725	
	PCxNxG	0.6030		0.5637	

Site RD		Dry matter yield kg ha^{-1}		Fresh matter yield kg ha^{-1}	
Pre-crop	Vetch	6,876 ± 1,447		7,658 ± 1,623	
	Rapeseed	6,539 ± 1,335		7,286 ± 1,475	
Nitrogen	ADJ	7,022 ± 1,442		7,831 ± 1,603	
	REC	6,393 ± 1,285		7,113 ± 1,430	
Genotype	Nogal	6,413 ± 1,003	b	7,117 ± 1,117	b
	Cellule	8,589 ± 0,634	a	9,585 ± 0,703	a
	Mustang	6,394 ± 0,801	b	7,115 ± 0,871	b
	Lutescens	5,434 ± 0,617	c	6,071 ± 0,679	c
ANOVA *P-values*	Pre-crop (PC)	0.1131		0.1137	
	Nitrogen (N)	<0.0001		<0.0001	
	Genotype (G)	<0.0001		<0.0001	
	PCxN	0.3646		0.3315	
	PCxG	0.0118		0.0131	
	NxG	0.0008		0.0010	
	PCxNxG	0.2003		0.2116	

5. Results



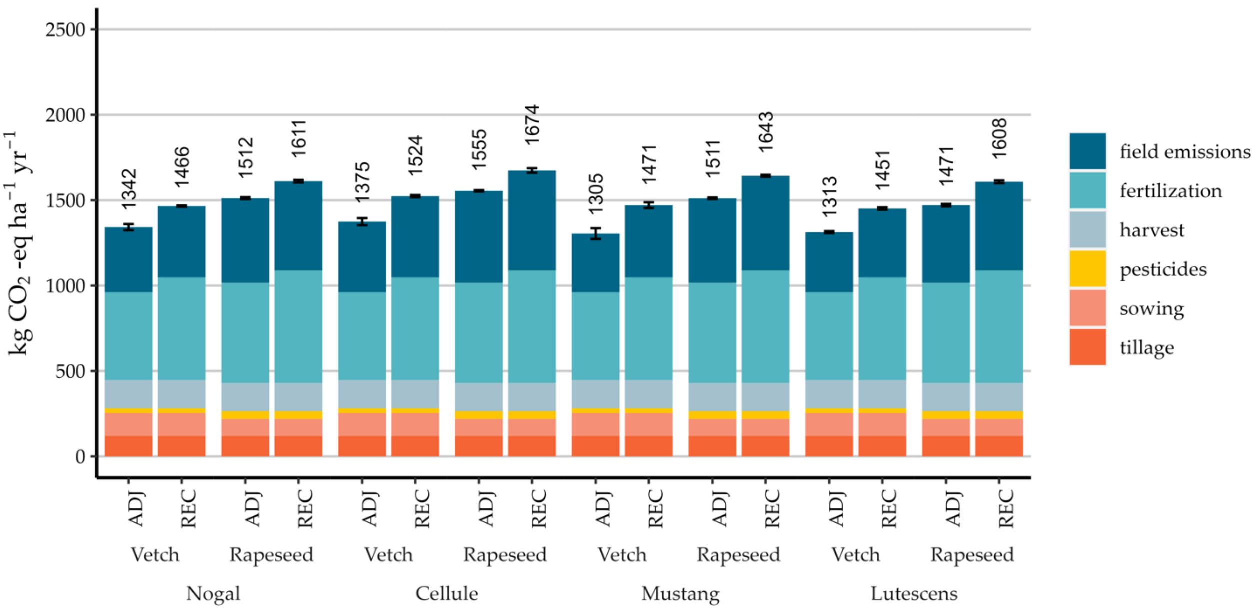


Figure 1: Climate change impact of the vetch-wheat and barley-wheat (Site BY- top) as well as vetch-wheat and rapeseed-wheat rotations (Site RD - bottom), measured in CO_2-eq per hectare per year. "Fertilization" includes the impact of fertilizer production and application by broadcaster; "field emissions" includes the direct and indirect soil emissions from fertilizer application.

Table 4. Results of the two-year rotation with the genotype Nogal per ha and year.

Site BY		legume pre-crop vetch-wheat		non-legume pre-crop barley-wheat	
		ADJ	REC	ADJ	REC
Wheat yield	kg FM	6,175 ± 571	7,316 ± 307	4,650 ± 1,033	6,391 ± 118
Wheat yield	kg DM	5,621 ± 511	6,639 ± 285	4,233 ± 939	5,820 ± 119
Gross margin	EUR	364 ± 43	452 ± 23	332 ± 77	480 ± 9
Revenue	EUR	755 ± 43	863 ± 23	794 ± 77	959 ± 9
Costs	EUR	391 ± 0	411 ± 0	462 ± 0	480 ± 0
Climate change (s)	kg CO_2-eq	1,289 ± 11.47	1,473 ± 6.40	1,742 ± 21.10	1,911 ± 2.67
Fossil energy use	MJ deprived	10,456 ± 0	11,237 ± 0	12,909 ± 0	13,555 ± 0
Marine eutr.	kg N N-lim-eq	15.06 ± 0.28	15.23 ± 0.17	17.22 ± 0.54	17.27 ± 0.06
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	1,464 ± 0	1,485 ± 0

Site RD		legume pre-crop vetch-wheat		non-legume pre-crop rapeseed-wheat	
		ADJ	REC	ADJ	REC
Wheat yield	kg FM	8,480 ± 890	6,607 ± 214	7,529 ± 280	5,851 ± 373
Wheat yield	kg DM	7,638 ± 798	5,959 ± 161	6,781 ± 249	5,273 ± 337
Gross margin	EUR	589 ± 67	390 ± 16	643 ± 21	466 ± 28
Revenue	EUR	974 ± 67	796 ± 16	1,066 ± 21	907 ± 28
Costs	EUR	385 ± 0	406 ± 0	424 ± 0	441 ± 0
Climate change (s)	kg CO_2-eq	1,342 ± 17.94	1,466 ± 3.62	1,512 ± 5.59	1,611 ± 7.56
Fossil energy use	MJ deprived	10,609 ± 0	11,390 ± 0	11,432 ± 0	12,078 ± 0
Marine eutr.	kg N N-lim-eq	14.16 ± 0.42	15.66 ± 0.09	14.93 ± 0.15	16.22 ± 0.22
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

Table 5. Results of the two-year rotation with the genotype Cellule per ha and year.

Site BY		legume pre-crop vetch-wheat		non-legume pre-crop barley-wheat	
		ADJ	REC	ADJ	REC
Wheat yield	kg FM	8,168 ± 352	8,677 ± 356	6,189 ± 0,824	7,782 ± 267
Wheat yield	kg DM	7,415 ± 331	7,872 ± 296	5,615 ± 758	7,068 ± 270
Gross margin	EUR	553 ± 26	581 ± 27	478 ± 62	612 ± 20
Revenue	EUR	944 ± 26	992 ± 27	940 ± 62	1,091 ± 20
Costs	EUR	391 ± 0	411 ± 0	462 ± 0	480 ± 0
Climate change (s)	kg CO_2-eq	1,330 ± 7.44	1,501 ± 6.64	1,773 ± 17.04	1,939 ± 6.07
Fossil energy use	MJ deprived	10,456 ± 0	11,237 ± 0	12,909 ± 0	13,555 ± 0
Marine eutr.	kg N N-lim-eq	14.42 ± 0.17	15.07 ± 0.15	16.87 ± 0.38	16.65 ± 0.14
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	1,464 ± 0	1,485 ± 0

Site RD		legume pre-crop vetch-wheat		non-legume pre-crop rapeseed-wheat	
		ADJ	REC	ADJ	REC
Wheat yield	kg FM	10,146 ± 1,079	9,528 ± 248	9,680 ± 196	8,984 ± 539
Wheat yield	kg DM	9,067 ± 921	8,540 ± 297	8,687 ± 178	8,062 ± 590
Gross margin	EUR	747 ± 81	668 ± 19	847 ± 15	764 ± 40
Revenue	EUR	1,132 ± 81	1,073 ± 19	1,271 ± 15	1,205 ± 40
Costs	EUR	385 ± 0	406 ± 0	424 ± 0	441 ± 0
Climate change (s)	kg CO_2-eq	1,375 ± 20.70	1,524 ± 6.68	1,555 ± 4.01	1,674 ± 13.26
Fossil energy use	MJ deprived	10,609 ± 0	11,390 ± 0	11,432 ± 0	12,078 ± 0
Marine eutr.	kg N N-lim-eq	13.79 ± 0.45	14.70 ± 0.15	14.39 ± 0.09	14.91 ± 0.35
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

Table 6. Results of the two-year rotation with the genotype Mustang per ha and year.

Site BY		legume pre-crop vetch-wheat		non-legume pre-crop barley-wheat	
		ADJ	REC	ADJ	REC
Wheat yield	kg FM	6,766 ± 624	7,057 ± 668	4,936 ± 772	6,673 ± 430
Wheat yield	kg DM	6,135 ± 545	6,419 ± 594	4,487 ± 698	6,065 ± 369
Gross margin	EUR	420 ± 47	427 ± 50	359 ± 58	507 ± 32
Revenue	EUR	811 ± 47	839 ± 50	821 ± 58	986 ± 32
Costs	EUR	391 ± 0	411 ± 0	462 ± 0	480 ± 0
Climate change (s)	kg CO_2-eq	1,301 ± 12.25	1,468 ± 13.34	1,748 ± 15.69	1,917 ± 8.29
Fossil energy use	MJ deprived	10,456 ± 0	11,237 ± 0	12,909 ± 0	13,555 ± 0
Marine eutr.	kg N N-lim-eq	14.96 ± 0.29	15.65 ± 0.32	17.10 ± 0.40	17.11 ± 0.20
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	1,464 ± 0	1,485 ± 0

Site RD		legume pre-crop vetch-wheat		non-legume pre-crop rapeseed-wheat	
		ADJ	REC	ADJ	REC
Wheat yield	kg FM	6,651 ± 1,540	6,880 ± 762	7,504 ± 254	7,425 ± 289
Wheat yield	kg DM	5,958 ± 1,400	6,193 ± 744	6,749 ± 208	6,677 ± 258
Gross margin	EUR	415 ± 115	416 ± 57	641 ± 19	616 ± 22
Revenue	EUR	800 ± 115	822 ± 57	1,064 ± 19	1,057 ± 22
Costs	EUR	385 ± 0	406 ± 0	424 ± 0	441 ± 0
Climate change (s)	kg CO_2-eq	1,305 ± 31.46	1,471 ± 16.71	1,511 ± 4.68	1,643 ± 5.79
Fossil energy use	MJ deprived	10,609 ± 0	11,390 ± 0	11,432 ± 0	12,078 ± 0
Marine eutr.	kg N N-lim-eq	14.98 ± 0.75	15.45 ± 0.44	15.19 ± 0.12	15.70 ± 0.16
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

Table 7. Results of the two-year rotation with the genotype Lutescens per ha and year.

Site BY		legume pre-crop vetch-wheat		non-legume pre-crop barley-wheat	
		ADJ	REC	ADJ	REC
Wheat yield	kg FM	5,204 ± 665	5,928 ± 325	3,759 ± 737	5,022 ± 97
Wheat yield	kg DM	4,729 ± 605	5,380 ± 289	3,414 ± 672	4,572 ± 80
Gross margin	EUR	272 ± 50	320 ± 24	247 ± 55	350 ± 7
Revenue	EUR	663 ± 50	731 ± 24	709 ± 55	829 ± 7
Costs	EUR	391 ± 0	411 ± 0	462 ± 0	480 ± 0
Climate change (s)	kg CO_2-eq	1,269 ± 13.60	1,445 ± 6.50	1,724 ± 15.09	1,883 ± 1.79
Fossil energy use	MJ deprived	10,456 ± 0	11,237 ± 0	12,909 ± 0	13,555 ± 0
Marine eutr.	kg N N-lim-eq	15.37 ± 0.36	15.97 ± 0.17	17.61 ± 0.40	17.84 ± 0.05
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	1,464 ± 0	1,485 ± 0

Site RD		legume pre-crop vetch-wheat		non-legume pre-crop rapeseed-wheat	
		ADJ	REC	ADJ	REC
Wheat yield	kg FM	7,068 ± 259	5,900 ± 307	5,586 ± 292	5,731 ± 475
Wheat yield	kg DM	6,329 ± 262	5,321 ± 316	4,965 ± 313	5,120 ± 357
Gross margin	EUR	455 ± 19	323 ± 23	458 ± 22	455 ± 36
Revenue	EUR	840 ± 19	729 ± 23	882 ± 22	896 ± 36
Costs	EUR	385 ± 0	406 ± 0	424 ± 0	441 ± 0
Climate change (s)	kg CO_2-eq	1,313 ± 5.89	1,451 ± 7.10	1,471 ± 7.03	1,608 ± 8.01
Fossil energy use	MJ deprived	10,609 ± 0	11,390 ± 0	11,432 ± 0	12,078 ± 0
Marine eutr.	kg N N-lim-eq	14.36 ± 0.16	15.79 ± 0.20	15.96 ± 0.19	16.29 ± 0.24
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

Table 8. Results of the two-year rotation with the genotype Nogal per ha and year for the control treatment (MIN).

		Site BY		Site RD	
		vetch-wheat	barley-wheat	vetch-wheat	rapeseed-wheat
Wheat yield	kg FM	7,026 ± 0,475	4,763 ± 0,260	3,881 ± 1,569	5,284 ± 525
Wheat yield	kg DM	6,392 ± 0,433	4,331 ± 0,235	3,480 ± 1,418	4,731 ± 448
Gross margin	EUR	466 ± 36	384 ± 19	173 ± 118	471 ± 39
Revenue	EUR	836 ± 36	805 ± 19	537 ± 118	853 ± 39
Costs	EUR	370 ± 0	421 ± 0	364 ± 0	382 ± 0
Climate change (s)	kg CO2-eq	1,146 ± 9.73	1,423 ± 5.27	1,089 ± 31.87	1,144 ± 10.07
Fossil energy use	MJ deprived	9,678 ± 0	11,350 ± 0	9,831 ± 0	9,873 ± 0
Marine eutr.	kg N N-lim-eq	13.98 ± 0.22	15.47 ± 0.13	15.37 ± 0.76	14.49 ± 0.24
Freshwater eutr.	kg PO4 P-lim-eq	0.2061 ± 0	0.1994 ± 0	0.2067 ± 0	0.1947 ± 0
Freshwater acid.	kg SO2-eq	1.4E-05 ± 0	2.3E-05 ± 0	1.4E-05 ± 0	1.7E-05 ± 0
Water scarcity	m3 world-eq	878 ± 0	1,414 ± 0	878 ± 0	863 ± 0

Table 9. Results of the two-year rotation with the genotype Cellule per ha and year for the control treatment (MIN).

		Site BY		Site RD	
		vetch-wheat	barley-wheat	vetch-wheat	rapeseed-wheat
Wheat yield	kg FM	9,734 ± 324	7,176 ± 150	6,076 ± 357	6,964 ± 526
Wheat yield	kg DM	8,821 ± 261	6,492 ± 131	5,439 ± 316	6,197 ± 451
Gross margin	EUR	723 ± 24	613 ± 11	381 ± 27	631 ± 39
Revenue	EUR	1,093 ± 24	1,034 ± 11	745 ± 27	1,013 ± 39
Costs	EUR	370 ± 0	421 ± 0	364 ± 0	382 ± 0
Climate change (s)	kg CO2-eq	1,201 ± 5.86	1,472 ± 2.94	1,133 ± 7.10	1,177 ± 10.14
Fossil energy use	MJ deprived	9,678 ± 0	11,350 ± 0	9,831 ± 0	9,873 ± 0
Marine eutr.	kg N N-lim-eq	13.04 ± 0.12	14.85 ± 0.06	14.88 ± 0.14	14.19 ± 0.21
Freshwater eutr.	kg PO4 P-lim-eq	0.2061 ± 0	0.1994 ± 0	0.2067 ± 0	0.1947 ± 0
Freshwater acid.	kg SO2-eq	1.4E-05 ± 0	2.3E-05 ± 0	1.4E-05 ± 0	1.7E-05 ± 0
Water scarcity	m3 world-eq	878 ± 0	1,414 ± 0	878 ± 0	863 ± 0

Table 10. Results of the two-year rotation with the genotype Mustang per ha and year for the control treatment (MIN).

		Site BY		Site RD	
		vetch-wheat	barley-wheat	vetch-wheat	rapeseed-wheat
Wheat yield	kg FM	7,245 ± 465	5,076 ± 73	4,307 ± 722	5,504 ± 156
Wheat yield	kg DM	6,572 ± 391	4,608 ± 68	3,862 ± 645	4,919 ± 144
Gross margin	EUR	486 ± 35	414 ± 5	213 ± 54	492 ± 12
Revenue	EUR	856 ± 35	834 ± 5	577 ± 54	874 ± 12
Costs	EUR	370 ± 0	421 ± 0	364 ± 0	382 ± 0
Climate change (s)	kg CO2-eq	1,150 ± 8.79	1,429 ± 1.53	1,097 ± 14.49	1,149 ± 3.24
Fossil energy use	MJ deprived	9,678 ± 0	11,350 ± 0	9,831 ± 0	9,873 ± 0
Marine eutr.	kg N N-lim-eq	13.99 ± 0.19	15.47 ± 0.03	15.43 ± 0.30	14.66 ± 0.07
Freshwater eutr.	kg PO4 P-lim-eq	0.2061 ± 0	0.1994 ± 0	0.2067 ± 0	0.1947 ± 0
Freshwater acid.	kg SO2-eq	1.4E-05 ± 0	2.3E-05 ± 0	1.4E-05 ± 0	1.7E-05 ± 0
Water scarcity	m3 world-eq	878 ± 0	1,414 ± 0	878 ± 0	863 ± 0

Table 11. Results of the two-year rotation with the genotype Lutescens per ha and year for the control treatment (MIN).

		Site BY		Site RD	
		vetch-wheat	barley-wheat	vetch-wheat	rapeseed-wheat
Wheat yield	kg FM	6,063 ± 312	3,855 ± 214	3,057 ± 1,080	4,775 ± 331
Wheat yield	kg DM	5,516 ± 265	3,495 ± 197	2,742 ± 986	4,286 ± 335
Gross margin	EUR	374 ± 23	298 ± 16	94 ± 81	423 ± 25
Revenue	EUR	744 ± 23	718 ± 16	459 ± 81	805 ± 25
Costs	EUR	370 ± 0	421 ± 0	364 ± 0	382 ± 0
Climate change (s)	kg CO2-eq	1,127 ± 5.96	1,404 ± 4.42	1,072 ± 22.16	1,134 ± 7.52
Fossil energy use	MJ deprived	9,678 ± 0	11,350 ± 0	9,831 ± 0	9,873 ± 0
Marine eutr.	kg N N-lim-eq	14.01 ± 0.16	15.78 ± 0.11	15.75 ± 0.53	14.62 ± 0.19
Freshwater eutr.	kg PO4 P-lim-eq	0.2061 ± 0	0.1994 ± 0	0.2067 ± 0	0.1947 ± 0
Freshwater acid.	kg SO2-eq	1.4E-05 ± 0	2.3E-05 ± 0	1.4E-05 ± 0	1.7E-05 ± 0
Water scarcity	m3 world-eq	878 ± 0	1,414 ± 0	878 ± 0	863 ± 0

Table 12. Results for one year of pre-crop cultivation per ha.

		Site BY		Site RD	
		vetch	barley	vetch	rapeseed
Yield	kg FM	1,820	4,500	1,820	2,500
Yield	kg DM	1,602	3,960	1,602	2,200
Gross margin	EUR	-17	249	-17	313
Revenue	EUR	336	704	336	702
Costs	EUR	354	455	354	389
Climate change (s)	kg CO_2-eq	1,181	1,827	1,181	1,237
Fossil energy use	MJ deprived	9,553	12,898	9,553	9,638
Marine eutr.	kg N N-lim-eq	16.95	18.05	16.95	16.62
Freshwater eutr.	kg PO_4 P-lim-eq	0.1799	0.1666	0.1799	0.1560
Freshwater acid.	kg SO_2-eq	1.5E-05	3.4E-05	1.5E-05	2.1E-05
Water scarcity	m^3 world-eq	293	1'366	293	265

Table 13. Results for one year of the bread wheat cultivation per kg.

Site BY		legume pre-crop vetch-wheat		non-legume pre-crop barley-wheat	
		ADJ	REC	ADJ	REC
Wheat yield	kg FM	6,578 ± 1,219	7,245 ± 1,084	4,884 ± 1,177	6,467 ± 1,042
Wheat yield	kg DM	5,975 ± 1,102	6,577 ± 0,979	4,437 ± 1,068	5,882 ± 0,943
Climate change (s)	kg CO_2-eq	0.237 ± 0.04	0.268 ± 0.03	0.376 ± 0.09	0.340 ± 0.05
Fossil energy use	MJ deprived	1.901 ± 0.38	1.964 ± 0.30	2.912 ± 0.78	2.416 ± 0.42
Marine eutr.	kg N N-lim-eq	2.2E-03 ± 5.9E-04	2.1E-03 ± 4.6E-04	3.7E-03 ± 1.2E-03	2.8E-03 ± 6.5E-04
Freshwater eutr.	kg PO_4 P-lim-eq	3.9E-05 ± 7.8E-06	3.6E-05 ± 5.5E-06	5.3E-05 ± 1.4E-05	4.0E-05 ± 6.9E-06
Freshwater acid.	kg SO_2-eq	3.7E-09 ± 7.5E-10	4.9E-09 ± 7.6E-10	7.3E-09 ± 2.0E-09	6.9E-09 ± 1.2E-09
Water scarcity	m^3 world-eq	0.253 ± 0.05	0.237 ± 0.04	0.352 ± 0.09	0.273 ± 0.05

Site RD		legume pre-crop vetch-wheat		non-legume pre-crop rapeseed-wheat	
		ADJ	REC	ADJ	REC
Wheat yield	kg FM	8,086 ± 1,696	7,229 ± 1,474	7,575 ± 1,514	6,998 ± 1,424
Wheat yield	kg DM	7,248 ± 1,515	6,503 ± 1,318	6,795 ± 1,377	6,283 ± 1,284
Climate change (s)	kg CO_2-eq	0.205 ± 0.04	0.273 ± 0.04	0.263 ± 0.05	0.323 ± 0.06
Fossil energy use	MJ deprived	1.609 ± 0.41	2.034 ± 0.38	1.946 ± 0.44	2.311 ± 0.46
Marine eutr.	kg N N-lim-eq	1.6E-03 ± 6.4E-04	2.1E-03 ± 5.4E-04	2.0E-03 ± 6.5E-04	2.4E-03 ± 6.6E-04
Freshwater eutr.	kg PO_4 P-lim-eq	3.2E-05 ± 8.2E-06	3.6E-05 ± 6.8E-06	3.5E-05 ± 7.8E-06	3.8E-05 ± 7.5E-06
Freshwater acid.	kg SO_2-eq	3.1E-09 ± 7.9E-10	5.0E-09 ± 9.5E-10	4.8E-09 ± 1.1E-09	6.6E-09 ± 1.3E-09
Water scarcity	m^3 world-eq	0.209 ± 0.05	0.240 ± 0.05	0.230 ± 0.05	0.255 ± 0.05

6. LCA Sensitivity analysis (Ecological Scarcity Method)

The total eco-points (EP) are the sum of the EP of all 20 impact categories of the Ecological Scarcity Method (BAFU, 2021). In Table 14 we show a small selection of the impact categories that correspond to those used in our primary method, Impact World+: global warming, energy resources, water pollutants, persistent organic pollutants into water and water resources, net balance.

Table 14. Comparison of LCA results using the Ecological Scarcity method 2021. Results of the two-year rotation per ha and year for each genotype at Site BY (top) and Site RD (bottom).

Site BY	legume pre-crop vetch-wheat		non-legume pre-crop barley-wheat	
Nogal	ADJ	REC	ADJ	REC
Total eco-points (million EP)	11.41 ± 0.08	12.19 ± 0.05	12.61 ± 0.16	13.24 ± 0.02
Global warming*	1.18 ± 0.02	1.56 ± 0.01	1.46 ± 0.04	1.80 ± 0.00
Energy resources*	0.11 ± 0.00	0.13 ± 0.00	0.13 ± 0.00	0.16 ± 0.00
Water pollutants* & persistent organic pollutants into water*	2.55 ± 0.10	2.58 ± 0.06	3.08 ± 0.18	3.07 ± 0.02
Water resources, net balance*	0.05 ± 0.00	0.06 ± 0.00	0.06 ± 0.00	0.07 ± 0.00

Site RD	legume pre-crop vetch-wheat		non-legume pre-crop rapeseed-wheat	
Nogal	ADJ	REC	ADJ	REC
Total eco-points (million EP)	4.86 ± 0.06	5.44 ± 0.01	5.36 ± 0.02	5.84 ± 0.03
Global warming*	0.64 ± 0.02	0.77 ± 0.00	0.78 ± 0.01	0.89 ± 0.01
Energy resources*	0.05 ± 0.00	0.07 ± 0.00	0.07 ± 0.00	0.08 ± 0.00
Water pollutants* & persistent organic pollutants into water*	1.12 ± 0.07	1.37 ± 0.02	1.27 ± 0.03	1.48 ± 0.04
Water resources, net balance*	0.02 ± 0.00	0.03 ± 0.00	0.03 ± 0.00	0.04 ± 0.00

* Selection of 5 out of 20 impact categories, whose eco-points are already included in the total eco-points.

Site BY	legume pre-crop vetch-wheat		non-legume pre-crop barley-wheat	
Cellule	ADJ	REC	ADJ	REC
Total eco-points (million EP)	11.25 ± 0.05	12.17 ± 0.04	12.53 ± 0.10	13.07 ± 0.04
Global warming*	1.26 ± 0.01	1.61 ± 0.01	1.52 ± 0.03	1.85 ± 0.01
Energy resources*	0.11 ± 0.00	0.13 ± 0.00	0.13 ± 0.00	0.16 ± 0.00
Water pollutants* & persistent organic pollutants into water*	2.33 ± 0.06	2.53 ± 0.05	2.96 ± 0.13	2.86 ± 0.05
Water resources, net balance*	0.05 ± 0.00	0.06 ± 0.00	0.06 ± 0.00	0.07 ± 0.00

Site RD	legume pre-crop vetch-wheat		non-legume pre-crop rapeseed-wheat	
Cellule	ADJ	REC	ADJ	REC
Total eco-points (million EP)	4.82 ± 0.06	5.32 ± 0.02	5.29 ± 0.01	5.66 ± 0.05
Global warming*	0.66 ± 0.02	0.82 ± 0.01	0.82 ± 0.00	0.95 ± 0.01
Energy resources*	0.05 ± 0.00	0.07 ± 0.00	0.07 ± 0.00	0.08 ± 0.00
Water pollutants* & persistent organic pollutants into water*	1.06 ± 0.08	1.20 ± 0.03	1.18 ± 0.02	1.26 ± 0.06
Water resources, net balance*	0.02 ± 0.00	0.03 ± 0.00	0.03 ± 0.00	0.04 ± 0.00

* Selection of 5 out of 20 impact categories, whose eco-points are already included in the total eco-points.

Site BY	legume pre-crop vetch-wheat		non-legume pre-crop barley-wheat	
Mustang	ADJ	REC	ADJ	REC
Total eco-points (million EP)	11.39 ± 0.08	12.33 ± 0.09	12.57 ± 0.11	13.20 ± 0.06
Global warming*	1.21 ± 0.02	1.55 ± 0.02	1.47 ± 0.03	1.81 ± 0.02
Energy resources*	0.11 ± 0.00	0.13 ± 0.00	0.13 ± 0.00	0.16 ± 0.00
Water pollutants* & persistent organic pollutants into water*	2.52 ± 0.10	2.73 ± 0.11	3.04 ± 0.14	3.02 ± 0.07
Water resources, net balance*	0.05 ± 0.00	0.06 ± 0.00	0.06 ± 0.00	0.07 ± 0.00

Site RD	legume pre-crop vetch-wheat		non-legume pre-crop rapeseed-wheat	
Mustang	ADJ	REC	ADJ	REC
Total eco-points (million EP)	4.98 ± 0.11	5.41 ± 0.06	5.40 ± 0.02	5.77 ± 0.02
Global warming*	0.60 ± 0.03	0.77 ± 0.02	0.78 ± 0.00	0.92 ± 0.01
Energy resources*	0.05 ± 0.00	0.07 ± 0.00	0.07 ± 0.00	0.08 ± 0.00
Water pollutants* & persistent organic pollutants into water*	1.26 ± 0.13	1.33 ± 0.08	1.32 ± 0.02	1.39 ± 0.03
Water resources, net balance*	0.02 ± 0.00	0.03 ± 0.00	0.03 ± 0.00	0.04 ± 0.00

* Selection of 5 out of 20 impact categories, whose eco-points are already included in the total eco-points.

Site BY	legume pre-crop vetch-wheat		non-legume pre-crop barley-wheat	
Lutescens	ADJ	REC	ADJ	REC
Total eco-points (million EP)	11.49 ± 0.10	12.40 ± 0.05	12.71 ± 0.12	13.40 ± 0.01
Global warming*	1.15 ± 0.02	1.51 ± 0.01	1.43 ± 0.03	1.75 ± 0.00
Energy resources*	0.11 ± 0.00	0.13 ± 0.00	0.13 ± 0.00	0.16 ± 0.00
Water pollutants* & persistent organic pollutants into water*	2.66 ± 0.12	2.84 ± 0.06	3.21 ± 0.14	3.27 ± 0.02
Water resources, net balance*	0.05 ± 0.00	0.06 ± 0.00	0.06 ± 0.00	0.07 ± 0.00

Site RD	legume pre-crop vetch-wheat		non-legume pre-crop rapeseed-wheat	
Lutescens	ADJ	REC	ADJ	REC
Total eco-points (million EP)	4.88 ± 0.02	5.45 ± 0.03	5.50 ± 0.03	5.85 ± 0.04
Global warming*	0.61 ± 0.01	0.76 ± 0.01	0.75 ± 0.01	0.89 ± 0.01
Energy resources*	0.05 ± 0.00	0.07 ± 0.00	0.07 ± 0.00	0.08 ± 0.00
Water pollutants* & persistent organic pollutants into water*	1.16 ± 0.03	1.39 ± 0.03	1.45 ± 0.03	1.49 ± 0.04
Water resources, net balance*	0.02 ± 0.00	0.03 ± 0.00	0.03 ± 0.00	0.04 ± 0.00

* Selection of 5 out of 20 impact categories, whose eco-points are already included in the total eco-points.

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