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From metrics to insights: Evaluating cereal farming sustainability in Catalonia using composite index approach

Mahdieh Khezri Nezhad Gharaei[1,2]*, *Bouali Guesmi*[2,3], *Jose Maria Gil Roig*[1,2,4]

[1]*Universitat Politècnica de Catalunya – Barcelona Tech (UPC), Barcelona, Spain*
[2]*Centre de Recerca en Economia i Desenvolupament Agroalimentari UPC-IRTA (CREDA), Castelldefels, Spain*
[3]*University of Carthage, Mograne Higher School of Agriculture, Zaghouan, Mograne, Tunisia*
[4]*Universidad del Bío-Bío, Bío-Bío, Chile*

**Corresponding author: mahdieh.khezrinejadgharaei@upc.edu*

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Abstract: Assessing the agricultural sustainability of farms is challenging, since it involves various aspects that can change over time and differ by location. This paper develops a composite index to evaluate the sustainability of cereal farming in Catalonia, Spain. Using factor analysis, we integrate 21 indicators across economic, environmental, and social dimensions based on the Farm Accountancy Data Network (2016–2021). The results show sustainability scores ranging from 2 to 5, with larger economic s farms outperforming smaller ones by 0.4 points. Five key factors explain the variance in sustainability across farms, with profitability, benefit-cost ratio, and agri-footprint carrying the highest weights. In addition, our empirical findings indicate that subsidy dependence negatively affects the sustainability of farms, while modernisation and environmental management improvements enhance farm performance. This suggests a need for size-specific policy interventions focusing on smallholder management capacity and broader climate adaptation strategies. The methodology could offer a practical tool for monitoring sustainability progress in Mediterranean cereal production systems, and for identifying possible sources of improvements with regard to more sustainable agricultural practices.

Keywords: cereal sector; factor analysis; farm level; indicator integration; sustainable performance

Farm-level sustainability assessment has become increasingly important for both research and policymaking, particularly in regions facing complex agricultural challenges (Arulnathan et al. 2020). Recent methodological approaches have emphasised composite index development as an effective way to evaluate multidimensional sustainability aspects across different farming systems (Latruffe et al. 2016; Tzouramani et al. 2020). As demonstrated by Robling et al. (2023), these approaches acknowledge that data availability often constrains indicator construction, significantly influencing the assessment outcomes at the farm level.

Existing research has applied composite sustainability indices to various Mediterranean farming systems. Gómez-Limón and Sanchez-Fernandez (2010) pioneered this approach for olive farms in Andalusia, while Dantsis et al. (2010) developed frameworks for Greek crop production systems. More recently, Tzouramani et al. (2020) employed factor analysis methods to construct sustainability indices revealing significant performance variations across farm types and ss, findings that align with broader sustainable development goals (de Olde et al. 2017; Balaine et al. 2023).

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Farm-level decisions, including specialisation choices and resource allocation, significantly influence agricultural systems' impacts on society and on the environment (Le Gal et al. 2011; Schader et al. 2016). However, the methodological challenges in measuring these impacts remain considerable, with researchers noting that framework selection and indicator construction strongly influence assessment results (Lynch et al. 2018).

Within the Mediterranean context, cereal farming in Catalonia, northeastern Spain, offers an informative example for examining agricultural sustainability challenges. The region's agricultural sector operates under the European Commission's 2021–2027 Common Agricultural Policy (CAP) reform, which emphasises environmental and climate action alongside social and economic objectives (Cardillo et al. 2023). This policy framework reflects the understanding that sustainability extends beyond productivity, encompassing 'food and nutrition security for all, in such a way that the economic, social and environmental bases to generate food security and nutrition for future generations are not compromised' (United Nations 2015).

This study addresses these challenges by developing a comprehensive composite index for evaluating cereal farming sustainability in Catalonia. Our methodology integrates 21 selected quantitative and qualitative indicators, drawing on farm accounting data. We make three key contributions: *(i)* the provision of a holistic assessment framework that captures sustainability's multidimensional nature while acknowledging data constraints; *(ii)* the employment of factor analysis to derive objective indicator weights, thereby reducing subjective bias; and *(iii)* the combination of simple but basic indicators with more complicated indicators.

Literature review. Sustainable intensification is crucial for addressing global food security challenges without compromising environmental health (Tilman et al. 2011). The literature encompasses three key sustainability dimensionsconomic, environmental, and social. Dong and Hauschild (2017) examined environmental indicators through various frameworks, highlighting such impact categories as climate change, acidification, and biodiversity. In terms of social sustainability, Gaviglio et al. (2016) proposed an integrated approach addressing farm-specific challenges when it comes to measuring social aspects. While various sustainability indices such as the Environmental Performance Index exist, as do frameworks as proposed by Soulé et al. (2021), they often lack examine to a crop farming context. Cereal sustainability is particularly critical for global food security, while sustainable intensification in addressing population growth and resource constraints become increasingly relevant (Perniola et al. 2015). In Catalonia specifically, Page et al. (2019) and Melero et al. (2011) examined soil health and water management, whereas comprehensive sustainability assessments remain limited.

Recent research has increasingly focused on multidimensional assessment. Kremen and Miles (2012) advocated for integrated approaches considering ecological, social, and economic dimensions simultaneously. While Gómez-Limón and Sanchez-Fernandez (2010) developed multiple sustainability indices, few studies have successfully combined all three sustainability pillars into a single composite index. Usubiaga-Liano and Ekins (2024) note growing use of indices in policy discussions, though debate continues about the trade-offs between comprehensiveness and simplification. The development of effective agricultural policies requires identifying critical factors affecting sustainable farming practices. Agricultural scientists acknowledge the importance of sustainable development (Bachev et al. 2017). However, the lack of a standardised assessment methodology poses challenges for policymakers who require clear, interpretable indicators (Bass and Dalal-Clayton 2012).

Despite advances in sustainability measurement, significant research gaps existpecialised methodological frameworks for Mediterranean cereal production are lacking. Most studies fail to capture interactions between sustainability dimensions, and data limitations affecting assessment reliability in cereal farming contexts remain largely unaddressed. Existing metrics often focus primarily on environmental aspects or assess economic, environmental, and social dimensions in isolation (Coppola et al. 2022; Leitgeb et al. 2023), overlooking their synergies and trade-offs. This research adds to the literature by developing a comprehensive composite index (CI) that integrates environmental, economic, and social dimensions into a single framework. The CI synthesises diverse indicators, including resource efficiency, biodiversity impact, economic returns, and social equity, providing a more nuanced assessment of cereal farming sustainability.

MATERIAL AND METHODS

The CI has been used as a valuable tool for policymaking in sustainable development research (Nardo et al. 2005) and as an alternative method for encompassing all individuals' indicators (González-García et al. 2019; Abdar et al. 2022). In this study we define a new CI to assess the sustainability of cereal farms. The following sections describe the steps to construct this CI.

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Selecting individual indicators. Indicator selection follows the pressure-state-response framework (OECD 2008) in terms of considering three criteriaomprehensive dimension coverage, minimal intercorrelation, and computational feasibility. We identified 21 indicators for Catalan cereal farms across economic, social, and environmental dimensions (Table 1). Indicator formulas are detailed in Electronic Supplementary Material (ESM), Table S1.

Economic indicators include profitability (Dillon et al. 2016), factor remuneration (Ryan et al. 2016), economic potential (Sulewski and Kłoczko-Gajewska 2018), and GDP contribution (van Arendonk 2015). Social sustainability is represented by four indicators derived from Kelly et al. (2014) and Ryan et al. (2016), although data limitations restricted additional social metrics. Environmental indicators encompass fertiliser, pesticide, and energy intensity (Dabkiene et al. 2021), greenhouse gas emissions (Verschuuren et al. 2024), eco-conditions (Coluccia et al. 2020), and natural diversification (Ehrmann 2010). Our framework integrates both basic and advanced indicators, including economic potential and agri-footprint indices, for comprehensive sustainability evaluation.

Normalising the individual indicators. Since indicators have different measurement units, they are normalised using the min-max approach in order to maintain consistency in the data (Maimon and Rokach 2010). The scores are then converted to a 1–6 scale where 1 indicates the worst condition (unsustainability) and 6 shows the best outcome (sustainability). The following formulas are used for rescaling the normalised indicators:

Positive indicator: $$Ind_i = 5 \times Ind_{normalisedi} + 1 \quad (1)$$

Negative indicator: $$Ind_i = -5 \times Ind_{normalisedi} + 6 \quad (2)$$

where: Ind_i – each selected indicator for the economic, social and environmental pillars.

Weighting the individual indicators. Weights represent the perceived importance of each indicator, though they may not directly reflect impact on the final index score (Becker et al. 2017). Both subjective and objective weighting methods exist (Xu et al. 2023), with objective methods evaluating criteria through data characteristics, and subjective methods relying on expert judgment. Objective methods consider both index variation and inter-index conflict (Krishnan et al. 2021), while subjective methods compare indicators at different hierarchical levels (Li et al. 2018). While equal weighting has been applied in some study (Caccavale and Giuffrida 2020), weights ultimately remain a value judgment when it comes to deriving composite indices (Nardo et al. 2005). Nonetheless equal weighting can reduce subjectivity (Maggino and Ruviglioni 2011).

This study employs factor analysis to reduce data dimensionality without significant information loss (DeCoster 1998), extracting indicator importance through their interactions while avoiding policy interpolation bias. Two main statistical tests were also conducted. First, the correlation between the 21 selected indicators was checked (Witte and Witte 2019) with results shown in Table S2. In addition, the Kaiser–Mayer–Olkin (KMO) test was also used to examine the sample adequacy and data reliability for creating the CI (Kim and Mueller 1978).

Factor analysis identifies perpendicular factors related to highly correlated indicators, retaining those that explain the most significant variability while discarding less informative ones (Smith 2002). Through rotation, each original indicator is loaded onto one principal factor. The weights are then calculated from factor loadings, which express the ratio of indicator variance explained by the factors (Riedler et al. 2015; Vitunskiene and Dabkiene 2016). Weights are obtained from the following expression:

$$W_i = r_j \left(\frac{l_{ij}^2}{E_j} \right) \quad (3)$$

where: r_j – the proportion of the explained variance of factor j (or the intermediate composite j) in the data; l_{ij} – the factor loading of the i^{th} indicator on factor j; E_j – the variance explained by factor j.

Aggregating the individual indicators. Finally, we employ additive aggregation to construct the CI, using the weighted arithmetic average to sum normalised sub-indicator values (Jain and Mohapatra 2023). This method allows precise index bounds when indicator measurement errors are known (Pollesch and Dale 2015). Aggregation functions vary across the weak-strong sustainability spectrum, from compensatory approaches (arithmetic and geometric means) to non-compensatory ones (Leontief function), each with different substitution elasticities (Rickels et al. 2016). The choice between these methods is crucial for integrating environmental, social,

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Table 1. Indicator description

Dimension	Name	Effect	Description	Reference
Economic	profitability (*PI*)	positive	net income by total revenue	Dillon et al. 2016
	benefit cost (*BC*)	positive	revenue to cost ratio	Kelly et al. 2014
	land productivity (*LDP*)	positive	gross output per hectare	Ryan et al. 2016
	profit ratio (*PR*)	positive	gross profit by net sale	Kelly et al. 2014
	remuneration of factors (*RF*)	negative	labour, land and capital by hectare	Ehrmann 2010
	return to cost (*RTC*)	positive	value added by sustainable value	Sulewski and Kłoczko-Gajewska 2018
	farm contribution to GDP (*FCG*)	positive	value added to agricultural GDP	van Arendonk 2015
	economic potential (*EPI*)[1]	positive	partial indicator based on 8 diagnostic variables	Sulewski and Kłoczko-Gajewska 2018
	modernisation (*MOD*)	positive	capital investment to labour ratio	Kelly et al. 2014
	subsidy ratio (*SUB*)[2]	negative	subsidy per hectare	Ryan et al. 2016
Social	working balance (*WB*)	negative	workload of farmer	Ryan et al. 2016
	risk management (*RMI*)[3]	positive	diversification on activities	Kelly et al. 2014
	rural development (*RD*)	positive	rural development payment per hectare	Kelly et al. 2014
	insurance ratio (*INS*)	positive	insurance per hectare	Kelly et al. 2014
Environmental	agri-footprint (*AFI*)[4]	negative	benchmarking indicator based on 11 variables	Dabkiene et al. 2021
	greenhouse gas emission (*GHG*)	negative	IPCC methodology	Lynch et al. 2018
	eco-efficiency (*EER*)	positive	environmental output to input	Coluccia et al. 2020
	Shannon Weaver (*SH*)[5]	positive	relative number of functional crop groups cultivated in a farm	Ehrmann 2010
	energy ratio (*ER*)	positive	total output by total energy consumption	Ryan et al. 2016
	fertiliser intensity (*FERT*)	negative	fertiliser consumption per hectare	Dabkiene et al. 2021
	pesticide intensity (*PEST*)	negative	crop protection per hectare	Dabkiene et al. 2021

[1]economic potential indicator is computed considering assets, land, labour, production, income, cost, subsidies and their interaction within a benchmarking model; [2]the total subsides used for this indicator include all farm subsidies on crops, including compensatory payments/area payments, set-aside premiums, aid under Article 68 = a CAP measure allowing targeted and sometimes coupled support to specific crops or farm activities. and other coupled support except rural development; [3]the risk management indicator of each farm is calculated according to the income share of all other activities in comparison to cereal farming; [4]the agri-footprinting indicator is computed by taking into account fertiliser, pesticide, water, land and energy usage in addition to GHG production, organic matter, crop diversification, and meadow and forest behaviours within a benchmarking model; [5]the Shannon Weaver indicator is $Hs = -\sum p_i \times \ln p_i$, where: p – crop acreage/total acreage; i – different crop then $SH = Hs/\ln L$; L – number of crops; Source: Authors' own elaboration

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Table 2. Basic descriptive statistics of sample cereal farms

Year	Farm number	Yield (kg/ha)			Farm size (ha)			Net income (EUR)		
		average	min.	max.	average	min.	max.	average	min.	max.
2016	53	6 548	738	18 550	68.3	5.8	308.8	17 628	–39 000	80 516
2017	45	6 703	837	20 000	69.7	7	307.2	17 968	–36 462	82 961
2018	40	6 641	870	21 271	82.2	12.6	306.4	36 576	–59 035	198 161
2019	30	6 233	1 530	18 653	68.1	5.8	306.3	24 284	–15 517	109 752
2020	29	6 473	613	16 940	100.1	5.8	452.6	23 160	–18 551	90 862
2021	37	6 559	371	16 063	85.9	5.8	400.7	36 668	–32 274	212 050
Total	459	6 578	371	21 271	71.7	5.8	452.6	22 396	–59 035	212 050

Source: Authors' own elaboration

and economic dimensions (Usubiaga-Liano and Ekins 2024). The *CI* is calculated as follows:

$$CI = \frac{\sum W_i Ind_i}{\sum W_i} \quad (4)$$

where: W_i – the weight for indicator *i*; Ind_i – the rescaled indicator.

Weights function as substitution rates in additive methods, implying compensatory relationships. The additive approach is suitable given the substantial indicator interactions, allowing both simple and sophisticated indicators to contribute ta comprehensive sustainability assessment.

Data was obtained from the Catalan Farm Accountancy Data Network (FADN) for the period 2016 to 2021 from the Department of Climate Action, Food and Rural Agenda. The data are collected through a standard sample survey carried out every year by each member state of the European Union. Each member state has an official liaison agency that coordinates the collection and processing of the FADN. In Catalonia, this agency is represented by FITXA. FITXA consists of a statistical questionnaire including economic and technical information of a sample of agricultural holdings from all the productive sectors of Catalonia collected by the Department of Climate Action, Food and Rural Agenda (DACC) and protected by the Law 23/98 of Statistics of Catalonia and the 12/89 of the Public Statistics Function. For some indicators more raw data are gathered from FITXA. Table 2 summarises data from a total of 459 observations of cereal farms for the period of analysis. Based on the annual survey used to gather accounting information from farms, the resulting sample data over a period is an unbalanced panel of farms. Our sample farms used an average area ranging from 68 ha to 100 ha to obtain a relatively stable yield that varies between 6 233 and 6 703 kg/ha over six years. Sample farms are focused on the production of barley, wheat, oat, rye, and corn. Although the reported average yield is a weighted average of all five main cereals, the highest maximum yields are predominantly associated with farms concentrating on corn production. As evident in Table 2, average net farm income fluctuates significantly, from EUR 17 628 in 2016 to EUR 36 668 in 2021. However, some farms still show an economic loss.

RESULTS

Table 3 provides summary statistics for the 21 indicators used in the sustainability assessment. The indicators show considerable variability across the sample farms. Some indicators display negative values in their ranges, particularly those related to net farm income, indicating that cereal farming without subsidies or other income-generating activities appears unprofitable.

In terms of ratio-based indicators such as profitability *(PI)* and benefit-cost *(BC)*, the substantial gap between mean and maximum values (0.06 vs. 0.63 for *PI*; 1.19 vs. 2.70 for *BC*) reveals significant performance disparities among farms. This suggests widespread underperformance compared to top-performing operations within the sample.

Indicators measured in euros per hectare show that land productivity *(LDP)* varies dramatically across farms, ranging from EUR 0.30 to EUR 3 157.48 per hectare. Similarly, rural development payments *(RD)* and insurance ratios *(INS)* demonstrate considerable variability, with maximum values many times higher than the mean. Resource use indicators such as fertiliser intensity *(FERT)* and pesticide intensity *(PEST)* show

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Table 3. Summary statistics for the calculated indicators

Indicator	Unit	Mean	SD	Min.	Max.
Profitability (*PI*)	ratio	0.06	0.31	–1.63	0.63
Benefit cost (*BC*)	ratio	1.19	0.43	0.38	2.70
Land productivity (*LDP*)	EUR/ha	715.64	475.46	0.30	3 157.48
Profit ratio (*PR*)	ratio	0.57	0.26	–0.27	1.69
Remuneration of factors (*RF*)	EUR/ha	131.86	154.96	0	913.71
Return to cost (*RTC*)	ratio	1.53	3.70	–4.36	33.68
Farm contribution to GDP (*FCG*)	%	0.7	0.77	0.2	4.5
Economic potential (*EPI*)	ratio	0.26	0.10	0.06	0.64
Modern (*MOD*)	ratio	3.79	20.29	0	273.35
Subsidy ratio (*SUB*)	EUR/ha	252.69	147.42	0	1 073.88
Working balance (*WB*)	%	20	9.6	0	68
Risk management (*RMI*)	ratio	0.10	0.17	0	0.86
Rural development (*RD*)	EUR/ha	18.72	54.32	0	625
Insurance ratio (*INS*)	EUR/ha	33.25	32.02	0	201.03
Agri-footprint (*AFI*)	ratio	0.15	0.09	0.01	0.55
Greenhouse gas emission (*GHG*)	kg CO_2 eq./ha	592.28	573.94	19.86	4 698.64
Eco-efficiency (*EER*)	ratio	2.12	1.76	0.12	11.36
Shannon Weaver (*SH*)	ratio	0.39	0.29	0	0.99
Energy ratio (*ER*)	EUR/ha	26.28	57.65	3.38	539.97
Fertilr intensity (*FERT*)	EUR/ha	132.57	108.42	0	607.83
Pesticide intensity (*PEST*)	EUR/ha	79.63	57.80	0	380

Source: Authors' own elaboration

similar patterns of variability, with some farms applying significantly more inputs than others.

Figure 1 presents the normalised indicator distributions after applying the min-max approach. The normalised values range from 0 to 1, displaying varied distribution patterns across indicators. These scores were subsequently converted to a 1–6 scale to improve interpretability, with one indicating the worst performance (unsustainability) and six representing the best outcome (sustainability).

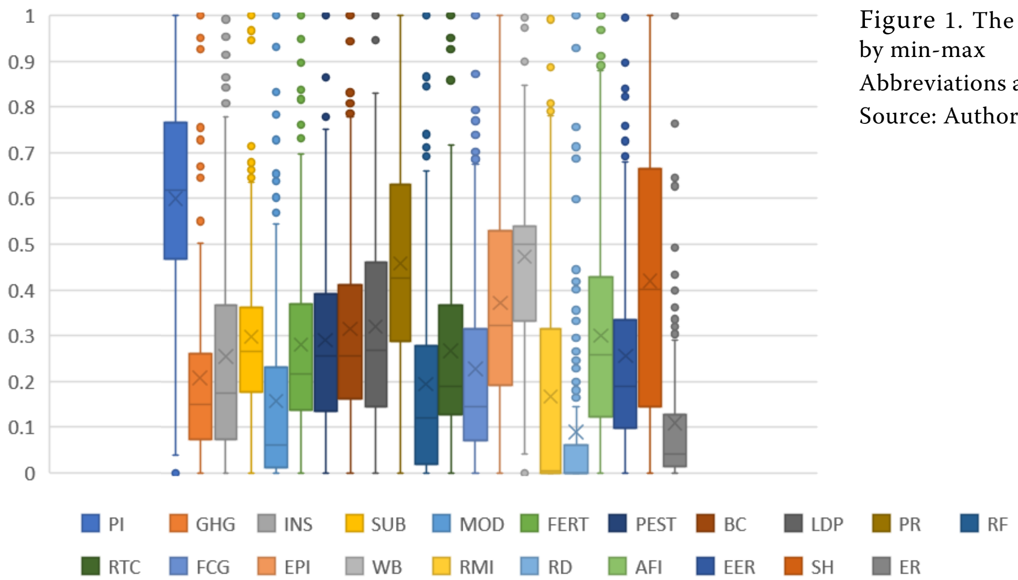

Figure 1. The indicator normalised by min-max
Abbreviations as explained in Table 1
Source: Authors' own elaboration

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Table 4. Total variance explained by the unbalanced indicators set

Factor	Eigenvalue	Difference	Proportion	Cumulative
Factor 1	3.43	0.55	0.31	0.31
Factor 2	2.88	1.02	0.26	0.56
Factor 3	1.86	0.72	0.17	0.73
Factor 4	1.14	0.39	0.10	0.83
Factor 5	0.75	0.16	0.07	0.90

Source: Authors' own elaboration

The factor analysis results are shown in Tables 4 to 6. The methodology incorporates all possible and important individual indicators in an unbalanced indicator set. A balanced set using equal numbers of economic, environmental, and social indicators was also tested as a robustness check, with results shown in Tables S3 to S5. This analysis was limited by the availability of only four social indicators, with three factors fully explaining the data. The KMO test value (0.6) validates the factor analysis application. Results suggest that five factors explain the variance within the indicators, with a cumulative value of 0.90 (Table 4). The weightings for each indicator are extracted solely from their loadings in one factor.

Table 5 presents the rotated factor matrix, revealing the loading of each indicator on the extracted factors. Factor 1 is dominated by economic performance indicators, with profitability *(PI)* and benefit-cost ratio *(BC)* showing the highest loadings at 0.912 and 0.953, respectively. We can observe that Factor 2 is primarily associated with environmental impact indicators, particularly agri-footprint *(AFI)* with a loading of 0.967 and greenhouse gas emissions *(GHG)* at 0.811. When it comes to Factor 3, the latter captures farm modernisation and scale efficiency aspects, with farm contribution to GDP *(FCG)* and economic potential *(EPI)* showing strong loadings of 0.792 and 0.622, respectively. While Factor 4 is characterised by a strong negative loading for subsidy ratio (–0.642), Factor 5 captures the remaining aspects of resource use efficiency.

Table 6 presents the final weights derived from the factor analysis. The three indicators with the highest

Table 5. Rotated factor matrix of the unbalanced set

Indicator	Factor 1	Factor 2	Factor 3	Factor 4
PI	0.912	–0.005	0.040	0.030
BC	0.953	0.012	0.021	0.042
LDP	0.599	–0.445	0.169	0.147
PR	0.434	0.293	0.252	0.667
RF	0.141	0.145	–0.215	–0.126
FCG	0.121	0.011	0.792	0.145
EPI	0.384	0.066	0.622	–0.024
MOD	–0.198	0.173	0.595	–0.035
SUB	0.044	0.205	0.087	–0.642
RTC	–0.038	–0.063	0.066	–0.009
WB	–0.114	0.098	0.109	–0.024
RMI	–0.124	–0.053	0.297	0.076
RD	–0.199	0.083	–0.070	0.140
INS	–0.159	–0.358	–0.001	0.073
AFI	–0.057	0.967	–0.041	–0.021
GHG	0.047	0.811	0.001	0.048
EER	0.292	–0.312	0.080	–0.118
SH	0.004	–0.068	0.173	0.054
ER	0.396	0.125	0.121	0.194
FERT	0.071	0.562	0.294	0.102
PEST	–0.037	0.471	–0.031	0.010

Abbreviations as explained in Table 1.
Source: Authors' own elaboration

Table 6. Final weights of indicators in the unbalanced set

Dimension	Indicator	Weight
Economic	profitability (*PI*)	0.09
	benefit cost (*BC*)	0.09
	land productivity (*LDP*)	0.06
	profit ratio (*PR*)	0.06
	remuneration of factors (*RF*)	0.02
	return to cost (*RTC*)	0.00
	farm contribution to GDP (*FCG*)	0.07
	economic potential (*EPI*)	0.06
	modernisation (*MOD*)	0.06
	subsidy ratio (*SUB*)	0.06
Social	working balance (*WB*)	0.01
	risk management (*RMI*)	0.03
	rural development (*RD*)	0.02
	insurance ratio (*INS*)	0.03
Environmental	agri-footprint (*AFI*)	0.09
	greenhouse gas emission (*GHG*)	0.08
	eco-efficiency (*EER*)	0.03
	Shannon Weaver (*SH*)	0.02
	energy ratio (*ER*)	0.04
	fertiliser intensity (*FERT*)	0.05
	pesticide intensity (*PEST*)	0.04
Total		1

Source: Authors' own elaboration

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weights are profitability *(PI)*, benefit-cost ratio *(BC)*, and agri-footprint *(AFI)*, each with a weight of 0.09. Greenhouse gas emissions *(GHG)* and farm contribution to GDP *(FCG)* follow closely with weights of 0.08 and 0.07, respectively. These weights were used to calculate the composite sustainability index for each farm.

The results are presented in Figures 2 to 4 for the unbalanced set of indicators. The same results for balanced set

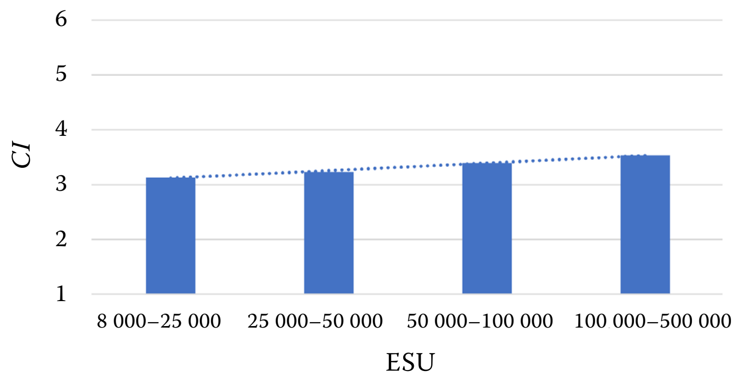

Figure 2. Average composite index *(CI)* for different economic sizes of farms
ESU – Economic size of holding expressed in 1000 euro of standard output.
Source: Authors' own elaboration

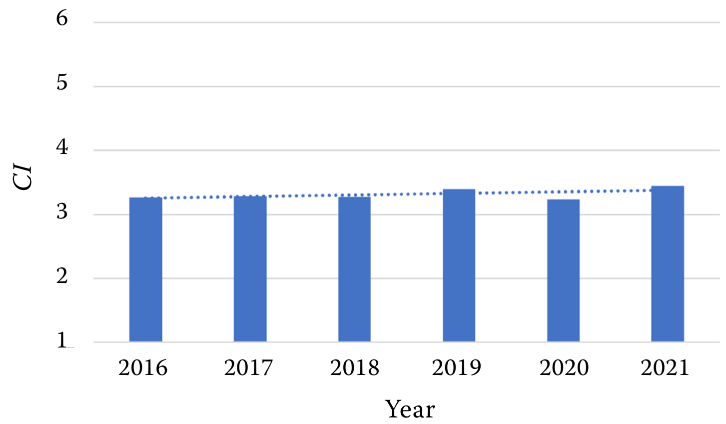

Figure 3. Average composite index *(CI)* over time
Source: Authors' own elaboration

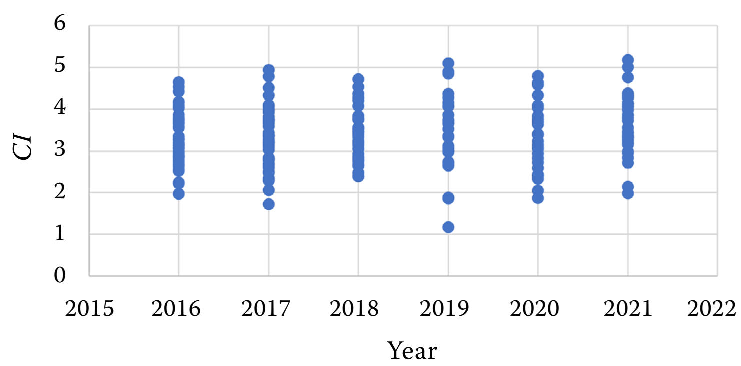

Figure 4. Distribution of farms composite index *(CI)* during sample time
Source: Authors' own elaboration

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are in Figures S1 to S3. The *CI* for the sample farms ranged from 2 to 5 on a 1–6 scale. Figure 2 shows the average *CI* values across different economic size categories. Farms of a larger economic size consistently achieved higher sustainability scores, though the difference between the smallest and largest categories is approximately 0.4 unit of the scale.

Figures 3 and 4 illustrate the temporal patterns in sustainability performance. Figure 3 shows the average *CI* values across the study period (2016–2021). While no consistent linear trend emerged, the results indicate some progress toward improved sustainability over time, with higher average *CI* values in the later years. Notable exceptions include a slight decrease in average *CI* scores in 2018 and a more pronounced decline in 2020.

Furthermore, to prevent bias in average interpretation, the distribution of *CI* over time in Figure 4 confirms the presence of sustainable farms. In the first year, the *CI* distribution ranges between 2 and 4, but over time, this distribution improves, and in the last year, it is between 3 and 5. Farms with *CI*s between 0 and 2 face sustainability challenges, and in our sample, only a few farms encountered such issues in 2019. The most prevalent *CI* range in the current sample is between 3 and 4, suggesting an acceptable level of sustainability. However, considering the average results of the individual indicators, even slight improvements in the financial management of farms could lead to a significant increase in the *CI*. Using a balanced indicator set showed similar trends across economic ss (Figure S1) and years (Figure S2), though with generally lower sustainability scores. Farm scores mostly ranged between 3 and 4 (Figure S3), averaging 0.5 units lower than the unbalanced set, suggesting a trade-off when equal the number of economic, environmental, and social indicators.

As a comparative reference point, similar studies such as that of Volkov et al. (2022), which analysed agricultural sustainability across six European countries from 2004–2017, found sustainability indices ranging from 0.4 to 0.6 on a normalised scale. When converted to comparable units, these values are similar to, or slightly lower than, our findings for Catalonian cereal farms.

DISCUSSION

Our factor analysis identified five key determinants of sustainability in Catalonian cereal farmingconomic performance (31% of variance), environmental impact management (26%), farm modernisation (17%), subsidy dependence (10%), and resource efficiency (7%). The *CI* ranged from 2 to 5 across farms, with larger operations outperforming smaller ones by 0.4 points. Temporal analysis revealed modest sustainability improvements over 2016–2021, with a notable decline in 2020 during COVID-19 and drought conditions.

The predominance of economic factors aligns with Gómez-Limón and Sanchez-Fernandez's (2010) findings that economic viability forms the foundation of agricultural sustainability in Mediterranean systems. The high loadings for profitability (0.912) and benefit-cost ratio (0.953) confirm financial viability as the primary sustainability driver, supporting Sulewski and Kłoczko-Gajewska's (2018) assertion that economic stability enables environmental improvements.

Notably, the negative loading of the subsidy ratio (–0.642) suggests that over-reliance on external support may undermine long-term sustainability, contrasting with traditional policy assumptions, but aligning with emerging research by Volkov et al. (2022). The positive loading of modernisation (0.595) suggests that technological investment offers a more effective sustainability pathway than subsidies alone.

The size-related sustainability advantage likely reflects economies of scale in technology adoption rather than any inherent advantages of larger operations. Similar patterns have been documented by Balaine et al. (2023) and Robling et al. (2023) across European contexts. However, this should not diminish the importance of small farms, which provide 75% of global agricultural production (Palacios and Ruiz-Vanoye 2018). Rather, it highlights the need for targeted support addressing the specific barriers which smaller operations face.

The 2020 sustainability decline demonstrates vulnerability to both acute (pandemic) and chronic (climate) stressors, aligning with Lynch et al. (2018) concept of agricultural resilience requiring adaptability to multiple challenges. While the 2021 recovery suggests moderate adaptive capacity, these disruptions highlight the need for enhanced resilience given projected climate change impacts in Mediterranean regions (Perniola et al. 2015).

Our methodological approach using unbalanced indicator sets has limitations. While factor analysis helps derive weights objectively, the FADN data structure provides limited social and environmental indicators compared to economic ones. Additionally, farm-level indicators may not fully capture landscape-level environmental processes, creating a scale mismatch between measurement and ecological processes (Schader et al. 2016). Policy implications include transitioning from direct subsidies toward incentivising specific sustainability improvements, aligning with the EU's

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2021–2027 CAP reform (Cardillo et al. 2023). Differentiated approaches are needed to further investigate the development of advanced environmental management tools for larger farms, and management capacity development for smaller operations. The vulnerability revealed in 2020 highlights the need for enhanced climate adaptation strategies through water-efficient technologies and diversified production systems.

CONCLUSION

This study measures the multidimensional sustainability of cereal farming in Catalonia. Our findings show that while some farms excel in terms of specific indicators, the overall composite index ranges from 2 to 5, demonstrating the value of integrated assessment approaches. The average sustainability index increases with farm economic s, confirming that smaller farms may require targeted policy interventions to improve their performance through enhanced management capacity, technological adoption, and speciald support programs.

In addition, the results reveal sustainability fluctuations over time, with notable declines in 2020. The 2020 decline reflects the combined impacts of COVID-19 disruptions and drought conditions, highlighting farming systems' vulnerability to both acute shocks and environmental stressors. Climate change also presents an ongoing threat to cereal production, suggesting that precision agriculture and farm modern investments including fertilr use, pesticide application, and energy efficiency could significantly improve key sustainability indicators.

The primary limitations of this analysis include insufficient social and environmental information in the FADN data structure, resulting in more emphasis on economic performance indicators. This data constraint underscores the need for more comprehensive sustainability metrics across all dimensions. Another limitation is the gap between farm-level environmental assessment and broader ecological impacts. Environmental elements such as water quality and landscape connectivity cannot be fully captured through farm-boundary indicators alone. Future research could benefit from approaches that connect farm-level metrics with landscape or regional-scale sustainability assessment. Furthermore, future study might expand indicators to include more robust social and environmental metrics, conduct longitudinal studies over longer periods, and compare different regions. Most critically, linking farm-level metrics with landscape-scale assessments would help bridge the gap between individual farm performance and broader ecological outcomes, potentially revealing synergies and trade-offs invisible at a single scale of analysis.

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