

## Article

# Spatial Insights into the Carbon and Environmental Footprint of Mediterranean Wheat: Integrating Life Cycle Assessment and Data Envelopment Analysis for Land-System Climate Resilience

Eleni Adam , Athanasia Mavrommati  and Angelos Patakas 

Department of Food Science and Technology, University of Patras, 30100 Agrinio, Greece;  
amavrom@upatras.gr (A.M.); apatakas@upatras.gr (A.P.)

\* Correspondence: eadam@upatras.gr

## Abstract

Rainfed wheat covers much of the semi-arid Mediterranean, yet its environmental cost is rarely measured at the field scale where management decisions are made. This study assesses the carbon and environmental footprint of rainfed wheat in the Mygdonia Basin, Northern Greece, drawing on a primary dataset of 1385 fields (~976 ha). Life Cycle Assessment (LCA) was coupled with Data Envelopment Analysis (DEA) to link environmental performance with technical efficiency. Carbon footprint ranged from 2030 to 3110 kg CO<sub>2</sub>e ha<sup>-1</sup>, revealing pronounced spatial variability across management systems. Excess nitrogen fertilization emerged as the principal driver of greenhouse gas emissions, acidification, and eutrophication in lowland systems. High-altitude systems showed lower impacts per hectare, an advantage partly offset by higher terrestrial ecotoxicity from increased machinery use. DEA revealed widespread technical inefficiency, most fields scoring between 0.70 and 0.90, with input slacks tracing this to excess nitrogen and seed. The convergence of LCA and DEA findings identifies nitrogen management as the key leverage point for improving environmental and technical performance without compromising productivity. The findings support spatially differentiated interventions under the Common Agricultural Policy, promoting precision nutrient management and conservation-oriented practices to strengthen the resilience of Mediterranean agroecosystems.

**Keywords:** rainfed wheat; life cycle assessment; data envelopment analysis; carbon footprint; eco-efficiency; Mediterranean land systems



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## 1. Introduction

Wheat is the most widely cultivated arable crop in the world, with a total area under cultivation exceeding 240 million hectares [1]. This scale highlights agriculture as the cornerstone of global food security and a primary source of livelihood for millions of rural households [2]. However, the operation of modern agroecosystems entails an extremely high environmental cost. According to the Intergovernmental Panel on Climate Change [3], the primary sector accounts for up to 30% of total anthropogenic greenhouse gas (GHG) emissions, while the global food system contributes approximately one-third of these emissions [4–6].

Consequently, modern agroecosystems confront a fundamental dual challenge: they must maximize productivity to guarantee global food security [7,8] while concurrently achieving a radical mitigation of their environmental footprint [9,10]. Amidst these competing pressures, crop production has exhibited clear signs of stagnation. Historically,

this yield plateau was largely attributed to average yields approaching their biophysical limits [11]. However, recent studies provide a broader perspective, indicating that in intensive, high-yielding environments, such stagnation often stems from suboptimal agronomic management practices [12]. Driven by these management gaps, the continuous push to intensify farming keeps its environmental footprint at unsustainable levels [13]. A significant portion of this ecological burden stems from a deep-rooted dependence on nitrogen inputs and energy-intensive tillage operations [14,15]. Progress is further hindered by a widespread stagnation in Resource Use Efficiency [16–18]. Because these farming systems require sustained input intensification without generating proportional yield gains, the environmental burden associated with each unit of harvested product continues to increase.

Against this backdrop, environmental performance exhibits significant spatial variations dictated by local soil and climate conditions, geographic location, and management practices [19–21]. Although management strategies shape the environmental profile, the interaction between topography and spatial scale is rarely examined systematically [22]. Elevation determines microclimatic conditions, while field size influences landscape heterogeneity [23] and mechanical efficiency requiring the implementation of spatially targeted strategies [24,25]. This spatial heterogeneity reshapes the risks of environmental degradation (e.g., nutrient runoff, depletion of water resources), generating substantial variation in ecological pressures even within the same production zone [19,26].

To assess these dynamics, Life Cycle Assessment (LCA) analyses provide a reliable environmental footprint [27]. However, the combination of LCA and Data Envelopment Analyses (DEA) allows for the evaluation of optimal resource use [28] with broad application [29] based on the principles of linear programming [30,31]. Specifically, the DEA methodology is an internationally recognized tool for identifying “inefficient” farming practices, allowing for the setting of specific targets for reducing inputs without reducing production capacity [32]. Recent studies in Spain have highlighted the importance of environmental efficiency in different wheat cropping systems, emphasizing the differences between dryland and irrigated areas [33]. An input-oriented DEA model allows for optimization by treating yield as the desirable output, while minimising agrochemical and energy consumption as inputs [34–36]. This approach focuses on reducing emissions, thereby preventing the shifting of environmental burden across different impact categories [37–42].

This need is particularly pressing in Mediterranean ecosystems, where intensification has worsened the energy and carbon balance [43]. In these fragile ecosystems, the rational use of fertilizers and fuels [32] emerges as the most critical step toward improving the environmental profile [44]. Furthermore, the shift toward alternative management models reduces emissions [45] and can transform agroecosystems into carbon sinks [46,47].

In the context of Greek agriculture, the DEA methodology has been applied in strategic sectors [48–50]. At the same time, the LCA and DEA framework has been used to assess ecological efficiency in intensive crops, such as rice [38,51,52] and Mediterranean vineyards [37]. Despite this progress, the application of this framework to rainfed agroecosystems remains limited. A systematic examination of how topographic variability interacts with structural scale in dryland wheat systems is still lacking, creating a significant knowledge gap regarding resource optimisation under moisture-constrained conditions, where conventional intensification strategies often fail to account for spatial heterogeneity [32,33].

To bridge this critical gap, the present study focuses on the wider Mygdonia basin, encompassing the Municipalities of Lagadas and Volvi, by analyzing an extensive, primary dataset of 1385 agricultural fields characterized by soil and topographic heterogeneity [53].

This area was selected as a representative case study for Mediterranean rainfed wheat systems, spanning lowland, semi-mountainous and mountainous zones within a single

agroecosystem; the surrounding regional units of Thessaloniki and Kilikis are among Greece's leading wheat producers [54]. While the specific results reflect local conditions, the analytical framework and the observed trade-off between climate performance and terrestrial ecotoxicity across elevation gradients are expected to be transferable to other fragmented, topographically diverse Mediterranean rainfed wheat regions.

Using a multi-criteria LCA framework aligned with ISO 14040/14044 [55,56] and the analytical structure of Goglio et al. [57], the study evaluates carbon footprint, soil acidification, eutrophication and ecotoxicity [58,59]. By identifying nitrogen-related input redundancy through DEA, it translates observed inefficiencies into field-level guidance for farmers on reducing nitrogen application without compromising yield.

Beyond its environmental significance, nitrogen management carries direct economic relevance, as fertilizers represent one of the highest variable costs in cereal production; reducing input redundancy without compromising yield could therefore lower production costs and enhance farm profitability, reinforcing the practical relevance of this research for farmers and policymakers alike.

This spatially explicit LCA–DEA approach supports a shift from uniform to targeted, site-specific management, consistent with Monaco et al. [60] on the importance of local spatial heterogeneity for ecological efficiency and climate neutrality. The findings also carry direct relevance for decision-makers, informing spatially differentiated eco-scheme design under the CAP Strategic Plans 2023–2027 [61]—including targeted nitrogen-management support for lowland systems and terrain-adapted practices for mountainous areas.

Given the pronounced inter-annual rainfall and temperature variability characteristic of Mediterranean climates, the influence of the prevailing meteorological conditions during the study period on the reported footprints is also considered.

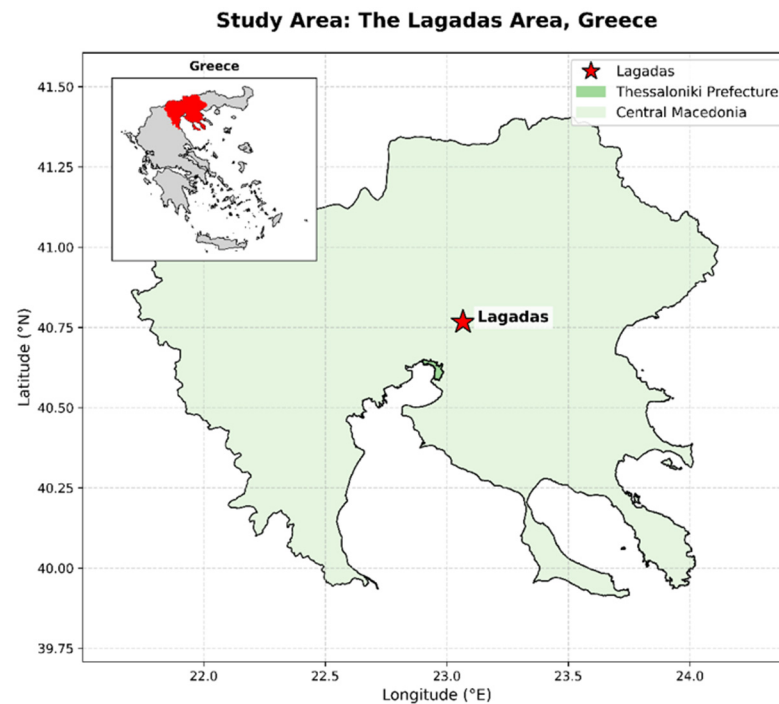
It is hypothesized that environmental performance and technical efficiency vary systematically with topographic zone and field-size class, such that no single typology performs optimally across all indicators. Accordingly, this study quantifies the carbon and environmental footprint of rainfed wheat across contrasting typologies, assesses technical efficiency and input redundancy using DEA, and identifies the management factors offering the greatest potential for simultaneous environmental and technical improvement.

## 2. Materials and Methods

### 2.1. Study Area and Data Collection

The research was conducted throughout the 2024–2025 growing season within the Mygdonia basin, which defines the geographical scope of this study in Northern Greece. The research area is delineated across the main agricultural zones of the Municipality of Lagadas, together with the adjacent cultivated lands extending into the neighbouring Municipality of Volvi. Owing to the spatial and ecological continuity of this agroecosystem, this unified landscape is hereafter referred to as the Lagadas Area (Figure 1). The region represents one of the most important rainfed wheat production zones in Northern Greece and is characterised by a high degree of land fragmentation, predominantly smallholder farming structures, and substantial geomorphological heterogeneity.

The geomorphology of the area extends into lowland, semi-mountainous and mountainous zones, each of which directly affects farming practices, input management and productivity. The Mediterranean climate, with recurring drought periods and high temperature variability, intensifies the vulnerability of these systems to climate change. The region thus constitutes a representative case study for Mediterranean agricultural systems, offering an extensive high-resolution dataset, suitable for LCA applications.



**Figure 1.** Geographical location of the study area in Central Macedonia, Northern Greece.

In total, 1385 agricultural fields were recorded and analyzed, covering approximately 976 ha. Field size ranged from 0.02 to 8.3 ha, reflecting the structural diversity and high degree of land fragmentation characteristic of Mediterranean farming systems. The combined wheat production from all surveyed fields reached 2,764,019 kg, providing a comprehensive primary dataset for the Life Cycle Inventory (LCI) of rainfed wheat cultivation. The unit of analysis was the individual field. Data were collected through structured interviews and standardized field records focusing exclusively on agronomic management practices and input–output flows at the field level. No personal or socio-economic information about farmers was collected. For each field, information was gathered on nitrogen fertilization, seed rates, soil management operations, machinery and fuel use, plant protection products, and final grain yields. All variables referred exclusively to agricultural inputs and outputs associated with the respective field.

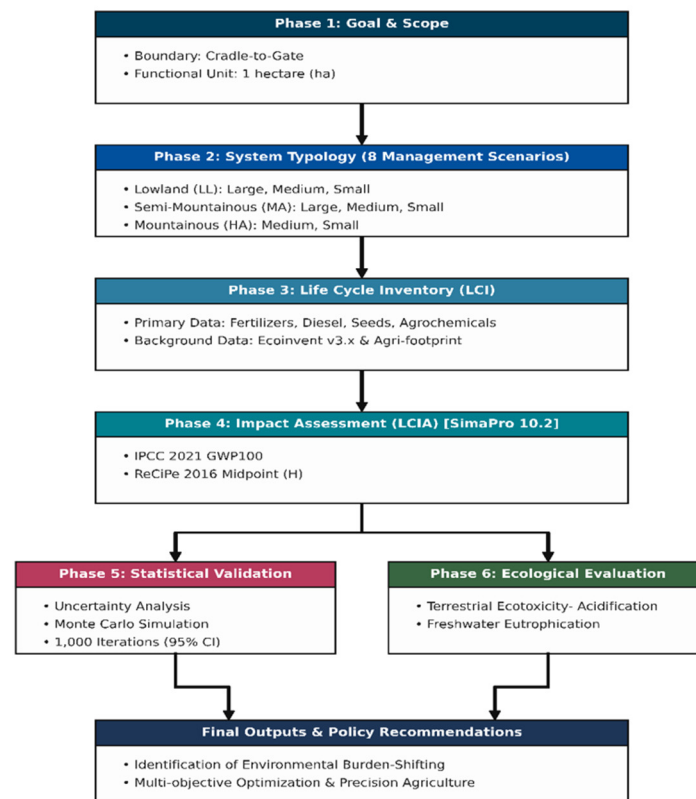
Meteorological conditions during 2025 were characterised using station records from within the study area (Lagadas: 40.70° N, 23.10° E, 87 m). Precipitation (485.2 mm) was close to the station's 16-year mean (497.7 mm, 2009–2024; −2.5%), and the 2025 annual maximum temperature (40.4 °C) fell within the normal range for the same period (37.5–41.9 °C). Mean annual temperature (14.7 °C) was approximately 1.4 °C above the long-term (1970–2000) basin normal (13.27 °C) [62]. The year analyzed was therefore broadly representative rather than climatically atypical.

## 2.2. Life Cycle Assessment Framework

The study applies the Life Cycle Assessment (LCA) methodology to quantitatively assess the carbon footprint and related environmental impacts of wheat cultivation, in accordance with ISO 14040 and ISO 14044 (ISO 2006) [55,56]. The system boundaries were defined as Cradle to Gate, and the functional unit was set at 1 ha, with results expressed in kg CO<sub>2</sub>e ha<sup>−1</sup>. To investigate these mechanisms, eight distinct system typologies were developed, combining elevation zone (lowland, semi-mountainous, mountainous) with farm-size class (small, medium, large). This classification enables the identification of differences in microclimatic conditions, input-use efficiency and the functional organisation

of agroecosystems. Figure 2 schematically presents the multi-criteria methodological framework of the study and the sequence of the individual phases of the LCA.

#### Multi-criteria Life Cycle Assessment (LCA) Framework for Wheat Cultivation



**Figure 2.** A multi-criteria LCA methodological framework for wheat cultivation.

### 2.3. Definition and System Typology

To provide a comprehensive picture of the crop's environmental profile, a matrix of eight (8) distinct functional management typologies was developed. The classification was based on two main axes:

**Geomorphological Factor:** Following the EU delimitation of Areas facing Natural Constraints (ANC), as maintained under Regulation (EU) 2021/2115 (CAP Strategic Plans, 2023–2027) [61], the study zones were divided into:

- Lowland-LL: Areas with high potential for agricultural mechanisation, with inputs being used more intensively.
- Middle Altitude-MA: Areas at intermediate elevations where slope affects farming practices.
- High Altitude-HA: Areas characterised by strong physical and geomorphological constraints.

**Field Size Factor:** The systems were classified as Small (S, <1 ha), Medium (M, 1–3 ha), and Large (L, >3 ha). For the purposes of the present study, this classification was adapted to the field level, with the thresholds reflecting the observed size distribution. The 1-ha threshold aligns with field-size ranges identified in the literature as ecologically and operationally meaningful [23], while the 3-ha threshold reflects the empirical scarcity of larger holdings within the sampled population, consistent with global patterns of field-size distribution [63], as already noted in Table 1.

**Table 1.** Matrix of management systems based on geomorphological zone and field size.

| Geomorphological Zone | Large (>3 ha)<br>n = 6 | Medium (1–3 ha)<br>n = 298 | Small (<1 ha)<br>n = 1081 |
|-----------------------|------------------------|----------------------------|---------------------------|
| Lowland (LL)          | LL-L                   | LL-M                       | LL-S                      |
| Middle Altitude (MA)  | MA-L                   | MA-M                       | MA-S                      |
| High Altitude (HA)    | — *                    | HA-M                       | HA-S                      |

\* Note: The HA-L system was excluded as such agricultural structures are practically non-existent in the study area. It is further noted that the “Large” field-size class is represented by very few fields overall (n = 6, comprising LL-L, n = 1, and MA-L, n = 5), reflecting the genuine scarcity of large-scale holdings in this fragmented Mediterranean landscape.

The combination of the two axes described above resulted in the eight systems under consideration, LL-L, LL-M, LL-S, MA-L, MA-M, MA-S, HA-M, and HA-S, as presented in Table 1. The system involving a large-scale mountainous terrain (HA-L) was excluded from the study, as agricultural structures of this type are practically non-existent in the region’s geography.

#### 2.4. Life Cycle Inventory

The Life Cycle Inventory (LCI) was conducted, and the system boundaries were modeled using SimaPro 10.2 software (PRé Sustainability, Amersfoort, The Netherlands). A hybrid calculation framework was developed that integrates primary field data, secondary inventory databases and exogenous empirical emission models.

Foreground data were compiled for 1385 fields, each treated as an individual decision-making unit (DMU) in the DEA model. Fields fall into eight typologies defined by elevation zone—lowland, semi-mountainous, mountainous and field size, which allows the results to be read spatially.

The background data for the underlying processes (e.g., industrial production of fertilizers and agrochemicals) were obtained from the ecoinvent v3.9.1 database (ecoinvent Association, Zürich, Switzerland) [64] and Agrifootprint 6.3 database (Blonk Consultants, Gouda, The Netherlands) [65].

Direct field emissions were estimated off-model using the Emission Factor Approach (EFA) in accordance with the IPCC [66]. The derived emission fluxes were then incorporated into the LCI. Fertilizer product type was recorded per field for each formulation applied and aggregated into total nutrient units.

Adopting a conservative methodological approach, the model did not account for potential carbon sequestration. This exclusion was intentionally applied to prevent an overestimation of the environmental performance of the systems and to ensure strict comparability of the results. Including carbon sequestration would likely reduce absolute footprint values across typologies, but is not expected to alter their relative ranking, as sequestration potential relates to residue and tillage practices rather than the nitrogen management identified as the dominant driver of differences between systems.

#### 2.5. Life Cycle Impact Assessment-LCIA

The Life Cycle Impact Assessment (LCIA) phase was structured around two methodological pillars. To assess the Global Warming Potential (GWP) and determine the CF, the IPCC 2021 [66] methodology was applied.

This indicator quantifies the cumulative emissions of the main greenhouse gases expressing the total contribution of the dry wheat systems under consideration in kilograms of carbon dioxide equivalent (kg CO<sub>2</sub>-eq) and ensuring methodological alignment with international inventory standards [66]. At the same time, the ReCiPe 2016 Midpoint (H) method was applied to capture the broader environmental profile. The Midpoint level was chosen over Endpoint indicators due to its significantly lower structural uncertainty,

while the hierarchical perspective (Hierarchist-H) was adopted to ensure absolute temporal alignment (100-year horizon) with the IPCC assumptions [59,67].

For the analysis to focus on the main mechanisms of pressure on agroecosystems, three categories of impacts most relevant to the intensity of agricultural inputs were assessed:

- Terrestrial Ecotoxicity (kg 1,4-DCB eq): It reflects the toxicity caused in the soil using plant protection products and the presence of heavy metals, serving as a critical indicator for the conservation of functional biodiversity.
- Terrestrial Acidification (kg SO<sub>2</sub> eq): It is directly linked to emissions of ammonia (NH<sub>3</sub>) from nitrogen-based fertilizers and nitrogen oxides (NO<sub>x</sub>) from the combustion of fossil fuels. Acidification is a fundamental mechanism of soil degradation, particularly in the context of climate change.
- Freshwater Eutrophication (kg P eq): It reflects nutrient losses, with phosphorus (P) as the sole limiting factor, to inland water bodies. This parameter is extremely important in Mediterranean agricultural landscapes, which are subject to intense eutrophication pressure from agricultural runoff.

## 2.6. Data Envelopment Analysis

To evaluate the relative efficiency of the wheat production systems under study, Data Envelopment Analysis (DEA) was employed, a method based on the principles of nonparametric linear programming [30,31]. In this context, each agricultural field was treated as a distinct Decision-Making Unit (DMU), resulting in a total sample of 1385 observations. An input-oriented model was adopted, with crop yield defined as the sole desirable output. This orientation was selected because farmers have greater control over input use than output levels, which are largely influenced by exogenous factors such as climate and soil conditions. The input variables included nitrogen, phosphorus, potassium fertilizers, seeds, herbicides, and diesel fuel consumption.

Given the high degree of land fragmentation and management heterogeneity characterizing the study area, the field was considered the most appropriate analytical unit. This approach allows technical efficiency to be assessed at the level where management decisions are implemented and enables the identification of input-specific inefficiencies across different spatial typologies.

The model estimation assumed Variable Returns to Scale (VRS) [30] to capture differences in returns to scale among farms. In addition, the Slacks-Based Measure (SBM) approach [68] was applied. The VRS specification was selected because the sampled fields differed considerably in size and management intensity, making the assumption of constant returns to scale unrealistic. This approach isolates pure technical inefficiency from scale-related effects and provides a more reliable assessment of resource-use performance.

Unlike conventional radial models, which assume strictly proportional variations, the SBM model allows for non-proportional adjustments. This approach enables the accurate quantification of input slacks and output shortfalls at the field level, providing a reliable representation of individual inefficiencies. Efficiency was assessed relative to a best-practice frontier constructed from the observed data. The resulting technical efficiency scores take values in the closed interval [0, 1], where a score of 1 indicates full technical efficiency. The mathematical models were solved computationally using MaxDEA Pro 8 software (v8.0; Beijing Realworld Software Co., Ltd., Beijing, China).

## 3. Results

### 3.1. Descriptive Statistical Analysis of Raw Data

Table 2 summarizes the descriptive statistics for the full sample ( $n = 1385$ ), showing substantial variability in management. Nitrogen application ranged widely (72.2–152.0 kg ha<sup>-1</sup>;

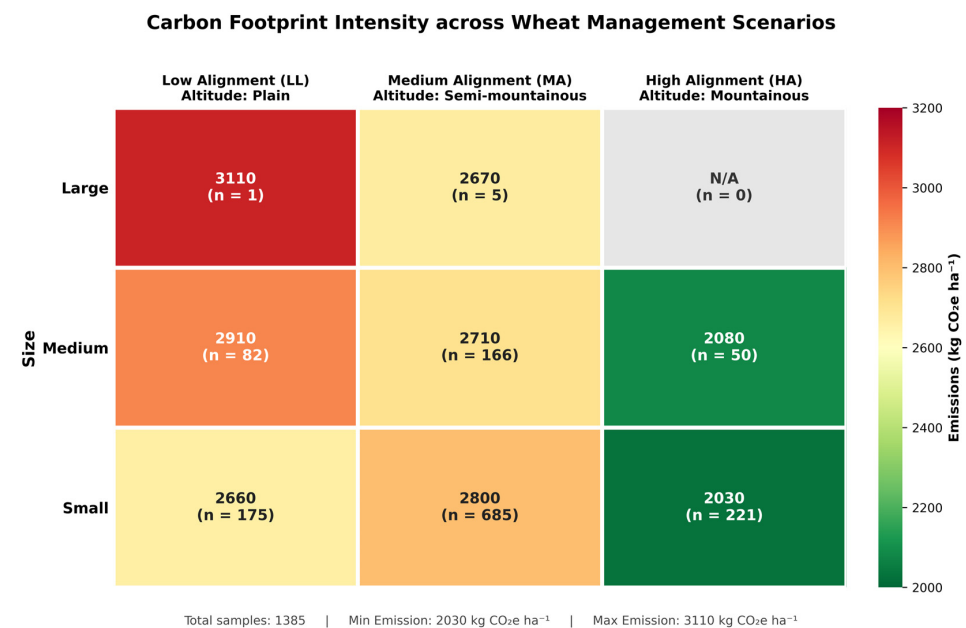
mean 121.0), and potassium showed the greatest relative variability among nutrients (0–33.2 kg ha<sup>−1</sup>). This spread provides a robust basis for the Life Cycle Inventory and for identifying environmental hotspots across contrasting practices.

**Table 2.** Descriptive statistics of the core production inputs and crop yields across spatial typologies (n = 1385).

| Variable (Unit)                   | Mean    | Std    | Min     | Max     |
|-----------------------------------|---------|--------|---------|---------|
| Yield (kg ha <sup>−1</sup> )      | 2827.88 | 606.00 | 1700.00 | 3700.00 |
| Nitrogen (kg ha <sup>−1</sup> )   | 121.00  | 22.00  | 72.20   | 152.00  |
| Phosphorus (kg ha <sup>−1</sup> ) | 14.20   | 3.00   | 8.70    | 19.80   |
| Potassium (kg ha <sup>−1</sup> )  | 14.60   | 14.10  | 0.00    | 33.20   |
| Seeds (kg ha <sup>−1</sup> )      | 186.20  | 12.80  | 168.00  | 225.00  |
| Herbicides (kg ha <sup>−1</sup> ) | 1.68    | 0.17   | 1.35    | 2.00    |
| Diesel Fuel (L ha <sup>−1</sup> ) | 100.20  | 5.10   | 85.00   | 114.00  |

### 3.2. Overall Assessment of the Carbon Footprint by System Typology

The LCIA revealed substantial variation in the carbon footprint across the eight management typologies, ranging from 2030 to 3110 kg CO<sub>2</sub>e ha<sup>−1</sup> (Figure 3).



**Figure 3.** Mean carbon footprint (kg CO<sub>2</sub>e ha<sup>−1</sup>) by wheat management typology.

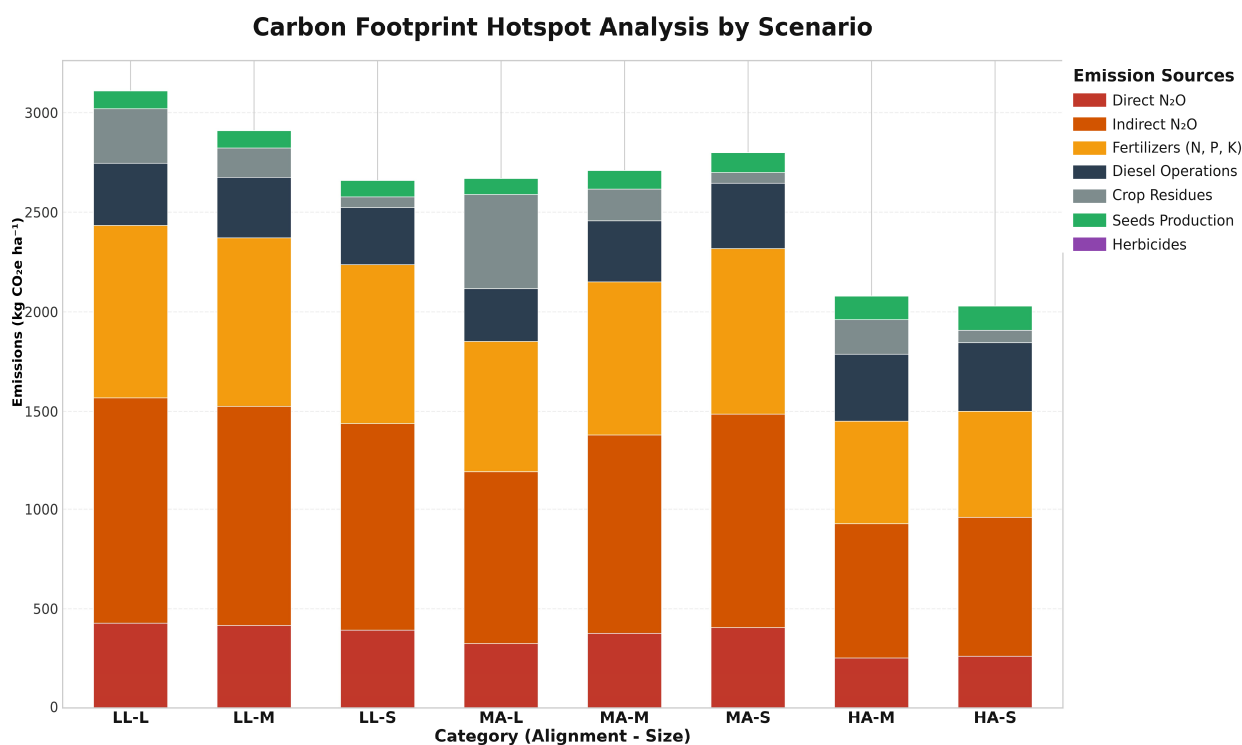
The highest emission levels were observed in large-scale agricultural systems, with the LL-L typology exhibiting the greatest burden (3110 kg CO<sub>2</sub>e ha<sup>−1</sup>). In contrast, the mountainous systems (High Altitude, HA) showed the most favourable environmental performance, with the small-scale typology (HA-S) recording the lowest value (2030 kg CO<sub>2</sub>e ha<sup>−1</sup>), corresponding to a 34.7% reduction relative to LL-L. It should be noted that LL-L is represented by a single field. With respect to field size, a general tendency toward lower carbon footprints was evident in smaller fields within the same elevation zone, except in mid-altitude systems (MA), where differences were minimal.

From a methodological standpoint, the preliminary analysis of the global warming potential [64] revealed the absolute dominance of fossil fuel sources. In contrast, the cumulative contribution of biogenic emissions and land-use change was estimated to be negligible, strictly limited to values < 4.8 kg CO<sub>2</sub> eq ha<sup>−1</sup> (less than 0.2% of the total footprint) for all the functional management typologies. Applying the standard cut-off criteria

of ISO 14040/14044 [55,56], these components were excluded from further assessment as environmentally and statistically insignificant.

### 3.3. Component Analysis and Major Emission Hotspots

A breakdown of the carbon footprint into its individual sources (Figure 4) highlighted the main factors that determine the environmental impact of the crop.



**Figure 4.** Breakdown of the carbon footprint by individual emission sources for the eight management scenarios. The cumulative bars represent the total burden ( $\text{kg CO}_2\text{e ha}^{-1}$ ) per input category, highlighting the dominance of nitrogen emissions (fertilizer production and field  $\text{N}_2\text{O}$  emissions) as the main environmental hotspot, as well as the secondary contributions from mechanical operations, seed production, and herbicides. The contribution of herbicides was negligible across all typologies.

The analysis confirms that nitrogen (N) management is the primary determinant of a crop's carbon footprint, regardless of farm scale or altitude. Indirect nitrous oxide ( $\text{N}_2\text{O}$ ) emissions, primarily attributed to nitrate ( $\text{NO}_3^-$ ) leaching and ammonia ( $\text{NH}_3$ ) volatilization, emerged as the most significant single source of greenhouse gases (GHG). In lowland systems (LL), the intensive application of nitrogen fertilizers led to a peak in indirect emissions, which exceeded  $1040 \text{ kg CO}_2\text{e ha}^{-1}$ . In contrast, the transition to high-altitude systems (HA) in mountainous zones entails a rationalization of nitrogen inputs, which is reflected in a reduction in indirect  $\text{N}_2\text{O}$  emissions by  $\sim 35\text{--}40\%$  ( $676\text{--}698 \text{ kg CO}_2\text{e ha}^{-1}$ ). At the same time, upstream emissions associated with the industrial production of fertilizers (primarily N, but also P and K) emerged as the second critical environmental hotspot. The energy footprint of fertilizer production in the LL scenarios approached  $865 \text{ kg CO}_2\text{e ha}^{-1}$ , while in the HA systems it was significantly reduced ( $521\text{--}540 \text{ kg CO}_2\text{e ha}^{-1}$ ). A notable finding emerges from the analysis of diesel consumption during mechanical cultivation operations. In contrast to agrochemical inputs, which are on a downward trend in mountainous areas, emissions from diesel consumption showed a distinct increase in the HA systems (up to  $344.5 \text{ kg CO}_2\text{e ha}^{-1}$ ) compared to the LL systems (up to  $312.2 \text{ kg CO}_2\text{e ha}^{-1}$ ).

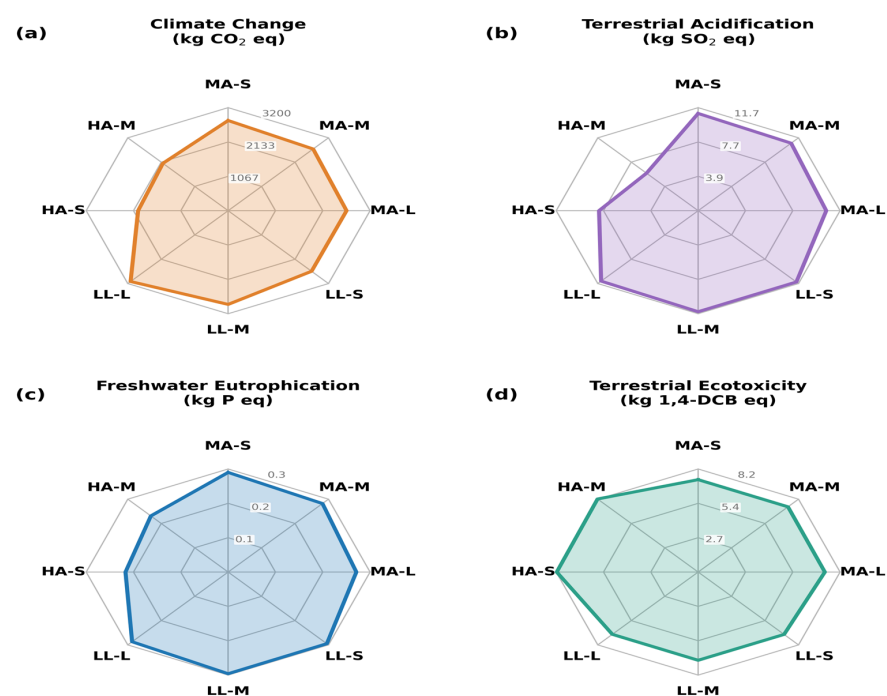
This phenomenon reflects a characteristic techno-environmental trade-off: the extensification of inputs in mountain systems is partially offset by increased traction energy

requirements, which are due to the operation of agricultural tractors on steep slopes and rough terrain. However, as shown in Figure 4, this energy cost is considered negligible, as it is more than offset by the significant reduction in nitrogen emissions, which results in a net reduction in the total carbon footprint of 34.7%.

The remaining emission sources are classified as minor. Emissions from plant residue decomposition showed high variability (53.7–472.8 kg CO<sub>2</sub>e ha<sup>−1</sup>), proportional to the biomass produced and the incorporation practices applied. Upstream emissions from the production of propagation material remained stable (~80–120 kg CO<sub>2</sub>e ha<sup>−1</sup>) across all scenarios, while the footprint of herbicides was deemed negligible (<1 kg CO<sub>2</sub>e ha<sup>−1</sup>), confirming that chemical weed control does not constitute an environmental hotspot in terms of Global Warming Potential.

### 3.4. Characterization Analysis (ReCiPe Midpoint)

The characterization analysis based on the ReCiPe Midpoint method revealed significant differences in the environmental profiles of the eight typologies, revealing a clear phenomenon of environmental burden shifting. As illustrated in the radial plots (Figure 5), the high-altitude systems (HA-S and HA-M) demonstrated the best environmental performance regarding Climate Change (Figure 5a) and Terrestrial Acidification (Figure 5b), recording the lowest emission values (2030 kg CO<sub>2</sub>e ha<sup>−1</sup> and 6.08 kg SO<sub>2</sub>e ha<sup>−1</sup>, respectively). Furthermore, the HA-S system demonstrated the most favorable performance regarding Freshwater Eutrophication (Figure 5c; 0.218 kg P-eq ha<sup>−1</sup>).



**Figure 5.** Comparison of environmental impacts (ReCiPe Midpoint) among the eight management systems: (a) Climate Change (kg CO<sub>2</sub> eq); (b) Terrestrial Acidification (kg SO<sub>2</sub> eq); (c) Freshwater Eutrophication (kg P eq); (d) Terrestrial Ecotoxicity (kg 1,4-DCB eq).

However, the quantitative analysis clarifies the critical trade-off underlying this apparent superiority. Despite the significant reduction in Climate Change (Figure 5a; −34.7%) and Acidification (Figure 5b; −48.0%), the HA-S system exhibits an increased burden on Terrestrial Ecotoxicity (Figure 5d), leading to an expansion of the radial diagram along this axis (+16.5% for HA-S). In contrast, while the lowland systems (LL-M and LL-L) exhibit a milder local toxicological impact (Figure 5d; ~7.01 kg 1,4-DCB-eq ha<sup>−1</sup>), they emerge

as the main contributors to climate degradation (Figure 5a; 3110 kg CO<sub>2</sub>e ha<sup>−1</sup>) and soil acidification (Figure 5b; 11.7 kg SO<sub>2</sub>-eq ha<sup>−1</sup>).

It should be noted that the LL-L typology is represented in the dataset by a single field (>3 ha), reflecting the genuine scarcity of large-scale lowland holdings within the study area's agricultural structure rather than a sampling limitation. The LL-L field has therefore been retained as an observed, real-data case rather than excluded, following established practice in agricultural LCA of distinguishing “typical case” observations—genuine but non-representative single-farm data points, such as the winter wheat datasets identified by Montemayor et al. [69] from data intended to characterize a regional or system-wide average. Accordingly, the corresponding results should be interpreted as illustrative of that specific holding rather than as statistically representative of the lowland-large production type as a whole and are used here to characterize part of the diversity of management systems present in the study area rather than to support generalizable group comparisons. For generalizable conclusions, the reader is referred to the adequately sampled lowland groups (LL-M, n = 82; LL-S, n = 175).

The quantitative assessment of this comparison is summarized in Table 3, which presents the differences in environmental indicators between the baseline system (LL-L) and the optimized scenario (HA-S).

**Table 3.** Comparative assessment of environmental impacts and trade-offs between the baseline (LL-L) and optimized (HA-S) management system typologies, expressed per hectare and per kilogram of product.

| Impact Category           | Unit<br>(ha <sup>−1</sup> ) | LL-L<br>(ha <sup>−1</sup> ) | HA-S<br>(ha <sup>−1</sup> ) | Δ<br>(%) | Unit<br>(kg <sup>−1</sup> ) | LL-L<br>(kg <sup>−1</sup> ) | HA-S<br>(kg <sup>−1</sup> ) | Δ<br>(%) |
|---------------------------|-----------------------------|-----------------------------|-----------------------------|----------|-----------------------------|-----------------------------|-----------------------------|----------|
| Climate change            | kg CO <sub>2</sub> eq       | 3110                        | 2030                        | −34.7    | kg CO <sub>2</sub> eq       | 1.407                       | 0.695                       | −50.6    |
| Terrestrial acidification | kg SO <sub>2</sub> eq       | 11.70                       | 6.08                        | −48.0    | g SO <sub>2</sub> eq        | 5.294                       | 2.082                       | −60.7    |
| Freshwater eutrophication | kg P eq                     | 0.412                       | 0.218                       | −47.1    | g P eq                      | 0.187                       | 0.075                       | −60.0    |
| Terrestrial ecotoxicity   | kg 1,4-DCB eq               | 7.01                        | 8.17                        | +16.5    | g 1,4-DCB eq                | 3.172                       | 2.798                       | −11.8    |

Note: Per-kilogram values were calculated using mean grain yield per typology (LL-L: 2210 kg ha<sup>−1</sup>; HA-S: 2920 kg ha<sup>−1</sup>). Values for acidification, eutrophication, and ecotoxicity are expressed in grams per kilogram of product for readability.

Because LL-L and HA-S differ in mean grain yield (2210 vs. 2920 kg ha<sup>−1</sup>), the comparison was repeated on a per-kilogram basis (Table 3). Climate change, acidification, and eutrophication reductions are larger per kilogram than per hectare, reflecting HA-S's higher yield. Notably, the per-hectare ecotoxicity increase (+16.5%) reverses per kilogram (−11.8%), indicating this trade-off is an artefact of the area-based functional unit. As LL-L is a single field, this comparison should be read alongside the broader typology-level results.

The transition to the HA-S system yields impressive reductions of nearly 50% in Acidification and Eutrophication, confirming the effectiveness of this management strategy.

### 3.5. Uncertainty Analysis and Statistical Evaluation

Uncertainty was assessed through Monte Carlo simulation (1000 iterations; 95% CI) in SimaPro 10.2, revealing considerable variation in the statistical behaviour of the environmental indicators (Table 4) and highlighting both the robustness of the key findings and the inherent stochasticity of Mediterranean agroecosystems. Climate Change and Terrestrial Ecotoxicity showed the highest reliability, with coefficients of variation (CV) consistently below the 10% threshold (6.44–8.00% and 4.15–6.67%, respectively). The complete lack of confidence-interval overlap between lowland (LL) and high-altitude (HA) typologies statistically confirms the study's central trade-off: shifting cultivation to mountainous zones optimizes the climate footprint at the expense of a higher soil toxicological burden.

**Table 4.** Summary of the Monte Carlo uncertainty analysis for the main environmental impact categories, including qualitative uncertainty levels, coefficients of variation (CV), confidence interval overlap, and the corresponding ecological trade-offs across management typologies.

| Parameter         | Climate Change (IPCC 2021) | Climate Change (ReCiPe Midpoint) | Terrestrial Ecotoxicity | Terrestrial Acidification | Freshwater Eutrophication |
|-------------------|----------------------------|----------------------------------|-------------------------|---------------------------|---------------------------|
| Uncertainty Level | Very Low                   | Very Low                         | Minimal                 | Moderate                  | Very High                 |
| CV Range (%)      | 6.44–8.00%                 | 6.34–7.89%                       | 4.15–6.67%              | 17.2–19.6%                | 40.7–46.1%                |
| 95% CI Overlap    | None                       | None                             | None                    | Partial                   | Extensive                 |
| Lowest Impact     | HA-S                       | HA-S                             | LL-L                    | HA-M                      | Inconclusive              |
| Highest Impact    | LL-L                       | LL-L                             | HA-M                    | LL-S/LL-M                 | Inconclusive              |

Note: The HA-L category was excluded due to the absence of such structures in the study area, while the LL-L category was also excluded, as it consists of only one field.

Cross-validation of the climate footprint with the ReCiPe Midpoint (H) method fully confirmed the IPCC 2021 [66] findings ( $CV < 8\%$ ), ensuring that the ranking of management practices is independent of the selected LCIA method. Other indicators showed moderate to high uncertainty: Terrestrial Acidification exhibited moderate variability ( $CV: 17.2\text{--}19.6\%$ ), driven mainly by the stochastic dynamics of  $NH_3$  and  $NO_x$  emissions at field level, while Freshwater Eutrophication showed the highest uncertainty ( $CV > 40\%$ ), with extensive confidence-interval overlap indicating that differences among systems were not statistically significant—highlighting the need for higher-resolution input data in future assessments.

3.6. Efficiency Assessment Using DEA

While the LCA results identified the main environmental hotspots and quantified the environmental burden across spatial typologies, DEA was subsequently applied to evaluate whether the observed input use patterns were technically efficient and to identify opportunities for resource optimization.

The application of the DEA model enabled the estimation of technical efficiency scores for all geomorphological zones and farm size categories under consideration. Furthermore, the analysis of input slacks allowed for the identification of the key parameters contributing to technical inefficiency, indicating the potential margins for reducing inputs while maintaining a constant level of output. These inefficiencies were assessed relative to the efficiency frontier, providing a clear benchmark for optimal resource use. Consequently, the results provide a basis for targeted strategies aimed at optimizing resource use efficiency, enabling the simultaneous reduction in operating costs and mitigation of environmental impacts.

Table 5 presents the distribution of agricultural fields across DEA efficiency score classes by geomorphological zone and field size. A large share of fields is concentrated in the mid-efficiency ranges (0.70–0.90), although an equally substantial proportion remains in lower efficiency classes ( $<0.70$ ), indicating the presence of notable inefficiencies within the system. Small-scale fields show greater dispersion across efficiency classes, with a pronounced concentration in lower efficiency levels, particularly within MA-S systems, where more than half of the observations fall below 0.70. This pattern suggests higher variability and reduced efficiency among smaller farms, likely associated with limitations in resource management and lack of economies of scale. Medium-sized fields exhibit a relatively more balanced distribution, with a stronger presence in higher efficiency classes (0.80–0.999), indicating comparatively better performance relative to small-scale systems. However, a non-negligible number of inefficient units is still observed, particularly in mid-altitude systems (MA-M). Differences across geomorphological zones are also evident. Lowland systems exhibit a more balanced distribution across efficiency classes, whereas mid- and high-altitude systems display greater variability, with both low- and

high-efficiency units observed. This pattern may be attributed to less favorable production conditions and structural constraints in these areas. Overall, the results confirm that both farm size and environmental conditions play a key role in shaping technical efficiency, with larger and more favorably located fields performing closer to the efficiency frontier, while smaller and more constrained systems exhibit greater inefficiency.

**Table 5.** Distribution of agricultural fields across DEA efficiency score classes by geomorphological zone and field size.

| Efficiency Class | <0.60 | 0.60–0.70 | 0.70–0.80 | 0.80–0.90 | 0.90–0.999 | =1 | Total |
|------------------|-------|-----------|-----------|-----------|------------|----|-------|
| LL-M             | 3     | 4         | 10        | 25        | 26         | 14 | 82    |
| LL-S             | 24    | 29        | 27        | 34        | 51         | 10 | 175   |
| MA-L             | 0     | 0         | 1         | 1         | 0          | 3  | 5     |
| MA-M             | 18    | 33        | 33        | 34        | 32         | 16 | 166   |
| MA-S             | 203   | 163       | 154       | 77        | 69         | 19 | 685   |
| HA-M             | 2     | 5         | 16        | 8         | 5          | 14 | 50    |
| HA-S             | 51    | 40        | 71        | 23        | 24         | 12 | 221   |
| Total            | 301   | 274       | 312       | 202       | 207        | 88 | 1384  |

Note: Of the 1385 fields in the dataset, the HA-L category was excluded due to the absence of such structures in the study area, while the LL-L category was also excluded, as it consists of only one field, yielding a total of 1384 fields in this analysis.

Table 6 presents the average slack values for the main production inputs at the field level, disaggregated by geomorphological zone and field-size class. Slack values represent the potential reduction in input use required for each field to reach the efficiency frontier. The results indicate that seeds and nitrogen fertilizer exhibit the highest slack values, identifying them as the principal sources of technical inefficiency in the wheat production systems under study. In contrast, herbicide slack values remain minimal, suggesting that weed-control practices are already close to efficient levels.

**Table 6.** Average slack values of input variables per field by geomorphological zone and field size.

| Geomorphological Zone | Nitrogen | Phosphorus | Potassium | Seed   | Herbicide | Diesel | Total  |
|-----------------------|----------|------------|-----------|--------|-----------|--------|--------|
| LL-M                  | 26.58    | 7.47       | 10.01     | 31.8   | 0.31      | 18.7   | 94.87  |
| LL-S                  | 15.74    | 4.43       | 2.89      | 18.83  | 0.19      | 11.08  | 53.16  |
| MA-L                  | 80.11    | 12.13      | 8.41      | 100.53 | 0.94      | 55.85  | 257.97 |
| MA-M                  | 31.27    | 11.43      | 23.52     | 46.46  | 0.43      | 25.81  | 138.92 |
| MA-S                  | 13.58    | 4.86       | 9.98      | 19.59  | 0.18      | 10.88  | 59.07  |
| HA-M                  | 12.17    | 3.37       | 15.34     | 22.62  | 0.18      | 10.77  | 64.45  |
| HA-S                  | 9.64     | 2.67       | 7.17      | 18.34  | 0.15      | 8.73   | 46.70  |
| Total                 | 189.09   | 46.36      | 77.32     | 258.17 | 2.38      | 141.82 | 715.14 |

Note: The HA-L category was excluded due to the absence of such structures in the study area, while the LL-L category was also excluded, as it consists of only one field.

Lowland systems generally display lower slack values, indicating relatively higher resource use efficiency. Nevertheless, some variability is evident among systems, including relatively high diesel slack values in LL-M fields, suggesting differences in energy-use efficiency. From a spatial perspective, medium-altitude systems (MA) present the highest overall slack values, particularly in the MA-L and MA-M categories, indicating considerable potential for improving efficiency through input reduction. High-altitude systems (HA) also exhibit inefficiencies, primarily associated with seed and nitrogen use, with additional contributions from potassium inputs.

The higher carbon footprint of larger fields reflects greater input intensity per hectare rather than total cultivated area. Slack analysis (Table 6) confirms this: within the middle-altitude zone, nitrogen slack decreased consistently with field size (MA-L: 80.11 kg ha<sup>−1</sup>; MA-M: 31.27; MA-S: 13.58), a pattern also evident, though less pronounced, in the lowland zone (LL-M: 26.58; LL-S: 15.74). The lowland comparison is limited to these two subgroups,

as LL-L ( $n = 1$ ) is excluded from the slack analysis; the pattern is nonetheless well supported across the adequately sampled MA subgroups.

Nitrogen slack, defined as the input reducible without yield loss under the DEA specification, averaged  $16.3 \text{ kg ha}^{-1}$ , or 13.5% of the mean applied rate ( $121.0 \text{ kg ha}^{-1}$ , Table 2), weighted across the sampled population. This indicates that nitrogen application could be reduced to approximately  $105 \text{ kg ha}^{-1}$  without compromising yield.

Overall, the concentration of high slack values in seeds and major macronutrients confirms that technical inefficiency is driven mainly by excessive input use rather than insufficient output levels. These findings suggest that targeted reductions in production inputs and agrochemical use could substantially improve both technical and environmental performance without compromising productivity.

#### 4. Discussion

Quantifying the carbon footprint is central to assessing the climate sustainability of agroecosystems. Across the 1385 fields analysed, the carbon footprint of rainfed wheat ranged from 2030 to  $3110 \text{ kg CO}_2\text{e ha}^{-1}$ , comparable to other dryland systems worldwide; in India, for instance, values of  $1745\text{--}4180 \text{ kg CO}_2\text{e ha}^{-1}$  have been reported depending on management and production conditions [13,24,70]. Much of this variability reflects irrigation and its energy demand: Zhang et al. [17] show that groundwater extraction and fossil-fuel-based electricity can raise the carbon footprint of cereal production by up to 40%.

Recent Mediterranean studies further contextualize these findings. In Thessaly, Greece, rainfed wheat showed consistently low carbon footprints ( $1090 \text{ kg CO}_2\text{e ha}^{-1}$ ) and favourable performance relative to other crops [71,72], while simulated durum-wheat scenarios in southern Italy reported comparable values ( $1190\text{--}1214 \text{ kg CO}_2\text{e ha}^{-1}$ ) [73]. The footprints obtained here ( $2030\text{--}3110 \text{ kg CO}_2\text{e ha}^{-1}$ ) exceed these benchmarks—a gap likely reflecting methodological differences in emission factors (e.g., CoolFarm Tool versus SimaPro/ReCiPe with IPCC Tier 1 field emissions) and the nitrogen input redundancy revealed by the DEA slack analysis, which indicates a tendency toward overapplication in parts of the sampled population.

Similarly, the absence of crop-residue burning, identified as an important greenhouse gas source in intensive Asian systems [13], contributes to the comparatively low emissions observed here. The environmental performance of the Mygdonia Basin is thus consistent with that of other semi-arid systems, including wheat in New Zealand and Mediterranean Italy [74,75], suggesting that rainfed agroecosystems can maintain a relatively favourable climate profile in the absence of energy-intensive irrigation.

Nevertheless, expansion into mountainous environments introduces management constraints and often lowers productivity per unit area. Here the DEA offers complementary insight: technical inefficiency was most evident in lowland (LL) and mid-altitude (MA) systems, where excessive nitrogen and seed inputs generated the highest slack values. Such input redundancy is commonly interpreted as a risk-management strategy, with farmers overapplying inputs to safeguard yields against uncertain conditions [76]; however, it entails diminishing marginal returns and generates both economic and environmental inefficiencies [74,77].

The DEA findings strongly complement the LCA. Nitrogen fertilizer and seed inputs showed the highest slack values across most typologies, revealing substantial scope for input reduction without compromising output. Since the LCA independently identified nitrogen management as the dominant contributor to greenhouse gas emissions, acidification, and eutrophication, the convergence of the two approaches highlights it as the principal leverage point for simultaneously improving environmental and technical performance.

The identified nitrogen slack is more than an efficiency and environmental burden. In dryland cereal systems, excess nitrogen promotes vegetative growth beyond what soil moisture can sustain, increasing transpirational demand and worsening drought stress rather than buffering it [78]. Aligning application with the DEA-derived optimum ( $\sim 105 \text{ kg ha}^{-1}$ ) is therefore expected to reduce this vulnerability, strengthening the capacity of rainfed wheat systems in the Mygdonia basin to withstand the drought and heatwave events characteristic of the Mediterranean climate [79]. Although no cost data were collected, this slack (13.5% of the mean applied rate) implies a proportional reduction in fertilizer expenditure; a full cost–benefit analysis, including precision-agriculture adoption costs, is left for future research.

By contrast, high-altitude (HA) systems exhibited lower input intensity and more conservative resource use. Although they require additional traction energy due to sloping terrain and more demanding field operations, their reduced reliance on nitrogen fertilizers yielded substantially lower carbon footprints. This indicates that their lower environmental burden stems primarily from reduced nitrogen-related emissions rather than lower energy consumption.

Consistent with previous studies [17,70,80], the results confirm that climate intensity in wheat production is largely regulated by nitrogen management and fossil-fuel use. Emissions were highest in lowland systems, where intensive fertilization and straw incorporation raised  $\text{N}_2\text{O}$  emissions and amplified the overall burden [44,81]. Fuel consumption ( $265.1\text{--}344.5 \text{ kg CO}_2\text{e ha}^{-1}$ ) emerged as the second most important source, creating a clear techno-environmental trade-off: in mountainous systems, lower agrochemical inputs were partially offset by the higher fuel requirements of field operations on sloping terrain [82,83].

Moving beyond carbon footprint alone, the ReCiPe Midpoint analysis revealed a pronounced shift in environmental burden among typologies, confirming observations by Laurent et al. [84] and Nemecek et al. [85]. This pattern aligns with a recent SimaPro/ReCiPe assessment of organic durum wheat in Tuscany, which similarly identified eutrophication among the dominant burdens of Mediterranean wheat production [86].

While lowland systems exhibited the highest acidification ( $11.7 \text{ kg SO}_2\text{-eq ha}^{-1}$ ) and eutrophication, high-altitude systems, particularly HA-S, achieved the lowest impacts in these categories ( $6.08 \text{ kg SO}_2\text{-eq ha}^{-1}$  and  $0.218 \text{ kg P-eq ha}^{-1}$ , respectively). These gains, however, came with higher terrestrial ecotoxicity, reaching  $8.17$  versus  $7.01 \text{ kg 1,4-DCB-eq ha}^{-1}$  in lowland systems. These offsetting results underline the value of multi-criteria optimization over single-indicator (carbon) assessment when balancing global climate benefits against local ecological integrity.

This trade-off reflects the spatial heterogeneity of Mediterranean agroecosystems. Although weed management was relatively homogeneous, differences in terrain, machinery use, and hydrological processes shifted environmental pressures among impact categories. Increased mechanical operations on sloping terrain, combined with enhanced runoff, appear to drive the higher ecotoxicological burden in marginal areas; such pressures may accumulate over time, affecting long-term soil quality and ecosystem functioning, in agreement with McAuley et al. [9].

The eight typologies differ not only in environmental performance but in their climate risk exposure. Lowland systems, with the highest nitrogen intensity, are most exposed to yield uncertainty under variable rainfall [78], whereas high-altitude systems face a distinct profile linked to steep terrain, shallow soils, and erosion [87]. This heterogeneity in the type of exposure, not merely its magnitude, is consistent with land-system resilience research linking soil–climate heterogeneity to adaptive capacity [88,89].

Finally, these pressures are intensified by the structural fragmentation typifying Mediterranean farming. Smaller fields ( $<1 \text{ ha}$ ) generally showed greater inefficiencies

and environmental burdens than larger ones (>3 ha), reflecting the absence of economies of scale [13,23]: fragmented, irregularly shaped fields require more machinery manoeuvring, raise fuel consumption per unit area, and reduce input-application precision. Land fragmentation therefore emerges as a critical factor influencing both environmental performance and technical efficiency.

The DEA efficiency gains also carry implications for long-term resilience, not only environmental benefits. Systems near the efficiency frontier depend less on excess inputs to sustain yield, aligning with the robustness and adaptability capacities central to farming-system resilience frameworks [90]. Reducing input redundancy therefore does more than lower carbon and eutrophication burdens: it shrinks the resource base exposed to loss when climate variability disrupts input–yield relationships.

In addition to the small-sample considerations already discussed for LL-L, three further points merit acknowledgement. First, the reported footprints correspond to a single growing season (2024–2025); precipitation was close to the station’s 16-year mean and mean temperature (14.7 °C) about 1.4 °C above the long-term basin normal, yet inter-annual variability could still affect input use and field emissions in ways a single season cannot capture. Second, changes in soil organic carbon were not accounted for; although a common simplification in cradle-to-farm-gate LCA, soil carbon dynamics may act as a meaningful long-term sink or source depending on tillage and residue management. Third, the findings are geographically confined to a single basin; while Mygdonia was selected for its representativeness of Mediterranean rainfed wheat, validation across other regions would strengthen broader applicability. Future research incorporating multi-year data, climate-scenario projections, and differentiated fertilizer-type analysis would help clarify whether these patterns persist across seasons, under changing climate, and over longer horizons.

## 5. Conclusions

This study integrates Life Cycle Assessment and Data Envelopment Analysis within a single, field-level framework. It draws on a primary dataset of 1385 agricultural fields, among the largest of its kind for rainfed wheat systems. The combined approach links environmental performance directly to technical efficiency, identifying nitrogen management as the principal lever for improving both simultaneously.

Beyond its immediate findings, this study carries broader significance for land-system carbon cycle regulation and climate risk response. Reducing nitrogen redundancy lowers direct N<sub>2</sub>O emissions, a major driver of agricultural warming, linking farm-level efficiency gains to land-system carbon cycle regulation. The same efficiency gains reduce dependence on excess inputs whose value becomes uncertain under variable rainfall, strengthening the capacity of these systems to anticipate and absorb climate-related shocks. Rainfed wheat land systems in the Mediterranean therefore represent not only a mitigation opportunity, but a testing ground for climate-resilient agricultural management more broadly.

The findings highlight the inherent climate advantage of Mediterranean rainfed wheat systems, attributing their relatively low carbon footprint to the absence of irrigation requirements and crop-residue burning. However, the multi-criteria assessment revealed a pronounced spatial shift in environmental burden. While agricultural intensification in lowland systems increases acidification and eutrophication through excessive fertilization, farming in marginal and mountainous areas is constrained by higher fuel requirements associated with field operations on sloping terrain, as well as by management practices that contribute to increased terrestrial ecotoxicity.

Land fragmentation further amplifies these pressures by limiting economies of scale and increasing the environmental cost of production. This spatial polarization demonstrates

that uniform mitigation policies are unlikely to be effective, highlighting the need for targeted interventions. In lowland systems, Precision Agriculture (PA) can support the optimization of nitrogen fertilization, with the DEA results indicating that application could be reduced from the current mean of 121.0 kg ha<sup>-1</sup> to approximately 105 kg ha<sup>-1</sup>, a 13.5% reduction, without compromising yield; in sloping environments, minimum tillage and Integrated Pest Management (IPM) can help balance energy requirements and ecotoxicity-related trade-offs.

At the policy level, the Common Agricultural Policy (CAP) should further support collective management schemes and land-consolidation initiatives capable of restoring economies of scale and improving resource-use efficiency, through concrete instruments such as voluntary land-exchange programmes and consolidation subsidies. Eligibility could be based on indicators such as average plot size and the number of scattered holdings per farmer, while nitrogen consumption per hectare could serve as a monitoring indicator to track progress toward the input-reduction potential identified in this study. The LCA–DEA methodology applied here provides a transferable tool for evaluating agricultural systems facing water scarcity and climate stress in other Mediterranean contexts. Future research should incorporate soil carbon dynamics and broader sustainability indicators to further improve the assessment of agroecosystem performance.

Ultimately, sustainable soil management must be considered a cornerstone of agricultural resilience, contributing not only to productivity but also to ecosystem integrity, climate adaptation, and the long-term socioeconomic stability of Mediterranean rural regions.

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