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Enhancing the Sustainability of Apple Farming Utilizing Climate-Smart Agricultural (CSA) Practices

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Abstract

The main scope of the present study is to assess the environmental and economic outcomes of applying distinct Climate-Smart Agricultural (CSA) practices in apple cultivation. Thus, four different CSA practices, including organic farming, cover crops, floral bands, and grazing, were selected, and their environmental and economic performance was evaluated and compared to that of a conventional apple orchard system (baseline). Specifically, Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) methodologies were applied to assess the environmental and economic sustainability of the studied systems, respectively. Among the studied practices, grazing exhibited the best environmental performance among the modeled scenarios (approximately 25% decrease in greenhouse gas emissions compared to the baseline under the assumed conditions), followed by organic farming that significantly decreased eutrophication- and ecotoxicity-related impacts. Similarly, organic farming and grazing exhibited the best economic performance in the concept of the present study, with the total profit per hectare rising to approximately 5300 € and 4300 €, respectively, compared to the value of 3700 € of the conventional apple orchard. The results suggest that the implementation of CSA practices has the potential to improve the environmental and economic performance of apple orchards under the modeled conditions.

Keywords: Climate-Smart Agricultural; apple farming; life cycle assessment; life cycle costing; sustainability

1. Introduction

The adoption of more sustainable, resilient, and efficient technologies and methods is of great importance in all industrial sectors, including the agricultural one, due to the growing need to tackle climate change effects, the necessity for climate-neutral production systems, and the scarcity of natural raw resources [1,2]. In this context, the inclusion and adoption of Climate-Smart Agriculture (CSA) practices emerge as a very promising approach that simultaneously aims to boost production, promote adaptability to climate change, and decrease the environmental impacts related to agricultural activities [3,4]. Apples can be characterized on a global scale as very important fruits, which are essential to the agricultural economy and consumer diets, since they are linked with numerous health benefits, including heart and digestive issues, and the management of blood sugar [5–7]. However, traditional apple-farming practices are often associated with substantial consumption

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of fossil fuels in agricultural machinery and application of considerable quantities of fertilizers or other chemical agents, which contribute to increased greenhouse gas emissions, water pollution, and other adverse environmental burdens [8,9]. Consequently, studying and implementing alternative, sustainable practices for apple production has become increasingly important. Among the most appealing CSA practices of apple cultivation are organic farming, cover crops, floral bands, and grazing.

Organic farming focuses on environmentally friendly methods, supports biodiversity, preserves natural resources, assures high standards of animal welfare, and addresses consumers' desires for products and crops cultivated using natural resources and approaches [10,11]. Essential practices in organic agriculture include extensive crop rotation to maximize on-site resources, tight restrictions on synthetic chemical agents, exclusion of genetically modified organisms (GMOs), and a strong emphasis on local, sustainable farming methods [12]. Cover crops are deliberately cultivated species of plants, like grasses, legumes, or flowering varieties, which are utilized to improve soil quality, act helpfully to beneficial insects, and monitor weeds [13,14]. In orchard systems, the inclusion of cover crops assists in retaining moisture, minimizing erosion, and improving nutrient cycling by incorporating organic matter and nitrogen into the soil [15]. When maintained by mowing or mulching, cover crops help with natural pest management and decrease dependence on chemical treatments and other synthetic agents [13,14]. Floral bands can be considered as a cost-effective and efficient way to reduce pesticide reliance in apple cultivation systems [16]. Floral bands are planted in non-cultivated areas, such as field edges or sprinkler zones, which attract beneficial insects that naturally help control pests [16,17]. In cases where they are planted in the cultivated zone, they occupy about 2% of the crop area, with their main advantage being their minimal maintenance requirements [17]. Finally, grazing involves the utilization of livestock, such as sheep or goats, to control apple scab and reduce pesticide use [18]. Through the consumption of unpicked fruit and leaf litter, sheep constitute environments that are less favorable to apple scab pathogens and pest larvae, while at the same time improving nutrient cycling via manure deposition [19,20]. This low-input method enhances soil quality, promotes biodiversity, and provides farmers with added economic and social advantages without the need for heavy dependence on machinery or chemicals [19].

The utilization of the aforementioned CSA practices can demonstrate considerable potential to significantly improve the overall environmental sustainability and improve the economic performance of agricultural processes [21]. Nonetheless, a detailed evaluation of the environmental and economic outcomes and impacts of CSA practices is essential to emphasize and pinpoint their advantages. Life Cycle Assessment (LCA) is a respected methodology for evaluating the environmental effects of product systems during their entire life cycle, from raw material extraction to the end of life of the final products [22]. LCA can highlight critical areas in resource consumption, emissions, and waste production, and offer various recommendations for enhancing the overall environmental performance of the studied product system [23,24]. On the other hand, Life Cycle Costing (LCC) is a method that considers all expenses related to the product system, encompassing investment, operational, and end-of-life costs, hence revealing any potential financial pressures and serving as an effective approach to enhance the economic efficiency of the system [25].

The main scope of this study was to assess the environmental and economic outcomes of applying four distinct CSA practices (organic farming, cover crops, floral bands, and grazing) in an apple cultivation system, and compare the results to a traditional-production apple orchard (hereafter referred to as the "baseline" scenario). Despite various studies exploring the potential of CSA, few of them have conducted a quantitative evaluation of the environmental and economic results in real-world farming conditions. The present study, by employing LCA and LCC in an apple orchard, aims to provide data-driven insights on how CSA practices can enhance the environmental and economic sustainability of agricultural systems. The present study focuses primarily on the environmental and economic dimensions of CSA practices, while the adaptation component is considered indirectly through practices that improve soil quality, reduce input dependency, and enhance system resilience. It should be noted that the adaptation pillar is not quantitatively assessed in this work, and therefore, the use of the CSA concept is applied in a focused and operational manner, rather than as a full evaluation of all three pillars.

2. Materials and Methods

LCA analysis was performed following the guidelines established in the ISO 14040 series (ISO 14040 and 14044:2006) [26,27]. ReCiPe 2016 (Hierarchist) was selected as the impact assessment methodology that transforms life cycle inventory data into a set of environmental impact indicators using characterization factors. LCA analysis was carried out using SimaPro Craft software (version 10.3) developed by PRé Sustainability, located in Amersfoort, The Netherlands.

LCC analysis was carried out with Microsoft Excel (v15.0) and included the identification of all the economic flows related to the studied product system. For the present work, only operating expenditures (OPEX) were considered, and capital expenditures (CAPEX) were excluded, since the application of the studied CSAs does not include the acquisition of new equipment.

2.1. Goal and Scope

The primary goal of the present study is to assess the environmental and economic performance of applying different CSA practices in apple production and compare their performance with a typical apple production system. Therefore, the environmental performance of a conventional apple production system was evaluated, and subsequently, four different scenarios were also assessed, with each one covering the performance of the studied CSA practices.

2.2. Functional Unit

The selected functional unit for the present study is 1 ha of cultivated land for all studied scenarios. Additionally, for the LCA analysis, results are also expressed per ton of apples to allow for a thorough comparison of the studied CSA practices.

2.3. System Boundaries

The objective of the study is to compare the application of the CSA practices with conventional apple farming over a single harvesting cycle. To this aim, a cradle-to-gate approach was adopted, focusing solely on processes occurring within the farm, and the boundaries of the system encompass all the stages from the soil preparation of the apple orchard to the harvesting of the apples. It should be noted that the system boundaries do not include capital expenditures (CAPEX) or the orchard establishment phase (e.g., planting, infrastructure installation, and long-term investments). These stages may contribute significantly to the overall environmental and economic performance when assessed over the full life cycle of perennial crops such as apple orchards. Therefore, the present results should be interpreted as a comparative assessment of operational practices (OPEX) within a single production cycle, rather than a full life cycle evaluation. This limitation should be considered when interpreting the magnitude of the reported differences among scenarios.

Moreover, the analysis focuses on a single production cycle, which represents a simplification for perennial systems such as apple orchards. Long-term processes, including soil carbon dynamics, biodiversity evolution, and infrastructure-related impacts, are not captured. While this approach allows for a consistent comparison of operational practices, it may not fully reflect long-term system behavior. Future studies could incorporate multi-year modeling to better account for temporal dynamics and cumulative effects.

2.4. Data Requirements

For the LCA analysis, data were collected by distributing questionnaires to relevant stakeholders, along with data from reliable databases like Ecoinvent, Agri-footprint, and Agribalyse, which encompass the geographical region of the European Union 28 (EU-28). The gathered information pertains to the growing season of 2023–2024. The present research was performed in the context of the BEATLES project (HORIZON EUROPE—Grant id: 101060645). Data are specified for the activities of 1 Use Case in Spain, where different CSA practices in apple production have been evaluated. Data were collected through structured questionnaires from project partners located in Spain, who were responsible for communicating with farmers who applied the studied CSA practices. The questionnaire was designed to capture detailed information regarding the input use (i.e., fertilizers, pesticides, diesel, and water), the orchard-management practices and the application of CSA practices, and the yields and production outcomes. The respondents included farmers, technical advisors, and project partners with direct knowledge of orchard-management practices. In total, responses were obtained from 8 respondents, representing 4 farms, which constitute the primary empirical basis of the analysis. The collected data were used to construct the Life Cycle Inventory (LCI) and support assumptions regarding input reductions and management changes. The quality of the responses was ensured through cross-validation with project partners and comparison with literature and database values (Ecoinvent, Agri-footprint, and Agribalyse). As a result, the dataset reflects a hybrid approach in which primary data are complemented by modeled and aggregated information, and the results should be interpreted accordingly as scenario-based rather than purely empirical outcomes. All GDPR procedures were followed, and the quality of the obtained data followed the directions of the Project's Management Handbook and the directives of the European Union.

2.5. Assumptions and Limitations

In all studied scenarios, the collected data correspond to farms located in Navarra, Spain, that produce Golden variety apples. In all studied systems, the data collected referred to 1 ha of cultivated land. The CSA practices were selected based on their potential contribution to reduction in emissions and inputs, improved soil quality and system resilience, and economic performance. However, their classification as CSA practices should be interpreted within this context-specific framework.

2.5.1. Baseline

Baseline is representative of a conventional apple orchard, possessing an irrigation system.

2.5.2. Organic Farming

The collected data correspond to a model organic apple orchard with an irrigation system.

2.5.3. Cover Crops

The collected data correspond to an apple orchard with an irrigation system that applies cover crops. The reduction in the usage of nitrogen fertilizers was calculated based on the available nitrogen from the cover crop to the soil, according to the USDA (Equation (1)), assuming 3% N content in the cover crop [28]:

$$\text{PAN (Plant-Available Nitrogen) (kg/ha)} = \text{Dry biomass (kg/ha)}\ \%\ \text{N} \times 0.4 \qquad (1)$$

Additionally, this study assumes a 20% reduction in pesticides, phosphorus, and potassium fertilizer usage due to the benefits of cover cropping indicated in the literature [29]. However, to take into account the potential variability in the decrease in pesticide and chemical fertilizer usage, two additional scenarios were evaluated with 10% and 30% in pesticide, phosphorus, and potassium fertilizer use, respectively.

2.5.4. Floral Bands

The collected data correspond to an apple orchard with an irrigation system that applies floral bands. The present study assumes a 20% reduction in pesticide usage due to the benefits of floral bands. However, to take into account the potential variability in the decrease in pesticide application, two additional scenarios were evaluated with 10% and 30% in pesticide application, respectively.

2.5.5. Grazing

The collected data correspond to an apple orchard with an irrigation system that combines grazing. Data were collected referring to 1 ha of cultivated land. The grazing is done by sheep from neighboring farms, which are supplied free of charge. The present study assumes a 20% reduction in pesticide usage due to the benefits of grazing. Additionally, a 30% reduction in diesel burned in agricultural machinery is assumed, while the manure of sheep during grazing is considered as a natural fertilization process that could replace the need for synthetic fertilizers application, with a 30% replacement rate being considered. However, to take into account the potential variability in the decrease in pesticide application, two additional scenarios were evaluated with 10% and 30% in pesticide application, respectively.

In the present modeling framework, manure and grazing services are assumed to be provided by neighboring farms without direct economic cost. However, from an environmental perspective, these inputs are not burden-free. In this study, manure is treated as a residual output (waste stream) from livestock production, and therefore, no upstream burdens are allocated to it. This assumption follows a system-expansion perspective but may underestimate the environmental impacts associated with manure production and livestock systems. Alternative allocation approaches (e.g., economic or mass allocation) could lead to different results and should be explored in future work.

2.6. Life Cycle Inventory (LCI)

The Life Cycle Inventory (LCI), created using data collected via interviews with involved stakeholders and supplemented with related literature sources, is presented in Table 1. The estimation of the initial emission-distribution fractions of the applied chemical agents (fungicides, herbicides, insecticides, and phytoregulators) was based on emission modeling for pesticides provided in the literature [30]. Fertilizer emissions in air, soil, and water were estimated using the IPCC guidelines [31]. Specifically, nitrogen-related emissions (N_2O and NH_3) were estimated using IPCC emission factors and were directly linked to the type and quantity of applied fertilizers.

Table 1. Life cycle inventory (LCI) of studied scenarios (2023–2024 period).

Parameter	Baseline (BL)	Organic Farming (OF)	Cover Crops (CC)	Floral Bands (FB)	Grazing (GR)
Inputs					
Land use (ha)	1	1	1	0.98	1
Cover crops application (ha)	-	-	0.8	-	-
Floral application (ha)	-	-	-	0.02	-
Inorganic phosphorous fertilizer (kg)	44	-	35.2	44	30.8
Inorganic potassium fertilizer (kg)	376	-	300.8	376	263.2
Inorganic nitrogen fertilizer (kg)	101	-	70.7	101	70.7
Organic phosphorous fertilizer (kg)	-	24.28	-	-	30.3
Organic potassium fertilizer (kg)	-	121.4	-	-	112.8
Organic nitrogen fertilizer (kg)	-	181.5	-	-	13.2
Herbicides (kg)	1.83	-	1.845	1.845	1.845
Insecticides (kg)	0.38	-	0.255	0.255	0.255
Fungicides (kg)	2.88	-	1.68	1.68	1.68
Calcium (kg)	3	3	3	3	3
Boron (kg)	-	0.48	-	-	-
Paraffin (kg)	5.58	5.58	5.58	5.58	5.58
Water (m^3)	6360	6360	6360	6360	6360
Diesel (kWh) *	8250	12,540	8250	8250	5775
Outputs					
Apples (tn)	35	30	35	35	35
Emissions to air					
Emissions from fungicides (kg)	0.23	-	0.17	0.17	0.17
Emissions from insecticides (kg)	0.031	-	0.024	0.024	0.024
Emissions from herbicides (kg)	0.37	-	0.27	0.27	0.27
Dinitrogen monoxide (kg)	1.59	2.86	1.16	1.59	1.59
Ammonia (kg)	12.26	22.11	8.95	12.26	12.26
Emissions to water					
Emissions from fungicides (kg)	0.0002	-	0.000145	0.000145	0.000145
Emissions from insecticides (kg)	0.0000285	-	0.00002085	0.00002085	0.00002085
Emissions from herbicides (kg)	0.00044	-	0.000321	0.000321	0.000321
Phosphate (kg)	3.08	1.7	2.245	3.08	3.08
Nitrate (kg)	44.73	80.64	32.66	44.73	44.73
Emissions to soil					
Emissions from fungicides (kg)	0.69	-	0.54	0.54	0.54
Emissions from insecticides (kg)	0.06	-	0.025	0.025	0.025
Emissions from herbicides (kg)	1.39	-	1.015	1.015	1.015
Nitrate (kg)	30.3	54.63	22.12	30.3	30.3

* 1 kWh of diesel corresponds to 0.38 L.

It should be emphasized that several values presented in Table 1 are based on assumptions and scenario modeling, particularly regarding reductions in agrochemical inputs and diesel use. These assumptions were derived from literature sources and expert judgment and are intended to represent plausible implementation pathways of CSA practices rather than exact field measurements. Furthermore, some assumptions, such as the availability of manure from neighboring farms or the absence of associated costs for grazing animals, are context-specific and may not be representative of all production systems. As a result, the findings should be interpreted with caution, and their applicability to other regions or farming systems may be limited. Future work should aim to validate these assumptions with broader empirical datasets and uncertainty analysis.

To ensure consistency between the methodological assumptions and the inventory data presented in Table 1, each modeled reduction (e.g., in fertilizers, pesticides, and diesel use) was directly translated into corresponding changes in input flows and emissions. For example, reductions in pesticide application were reflected proportionally in emissions to air, water, and soil, while reductions in synthetic fertilizers were linked to corresponding changes in nitrogen- and phosphorus-related emissions based on IPCC guidelines.

3. Results and Discussion

3.1. LCA Results

LCA results of the baseline scenario, along with each of the different studied CSA practices in selected midpoint impact categories, are presented in Figure 1. Additionally, it is important to note that the observed differences among scenarios are strongly influenced by the assumptions embedded in the modeling framework, particularly regarding input reductions, substitution of synthetic fertilizers, and diesel use. Therefore, the reported environmental advantages should be interpreted as scenario-dependent outcomes, rather than universally applicable results.

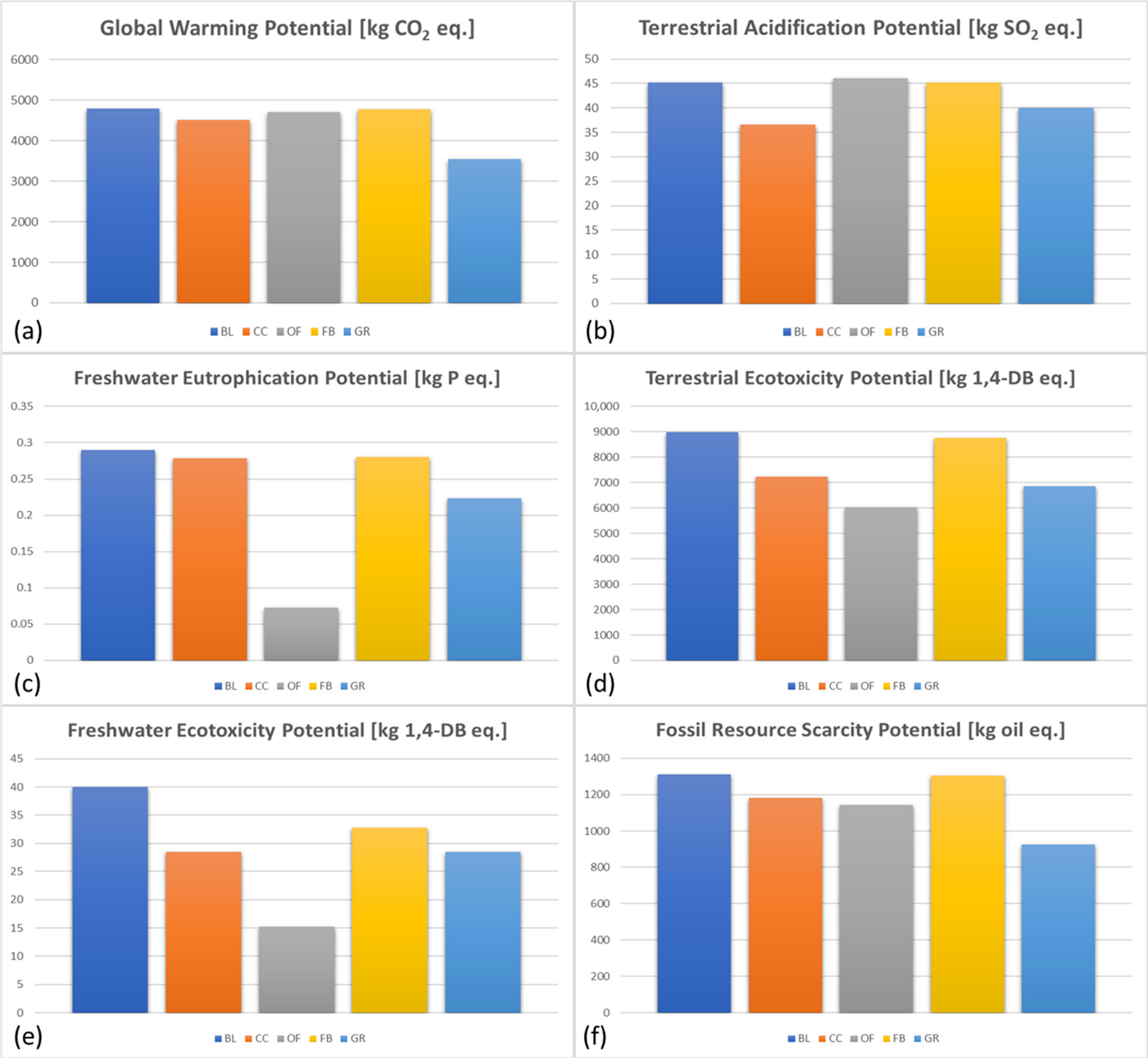

Figure 1. Environmental impact of the baseline (BL), cover crops (CC), organic farming (OF), floral bands (FB), and grazing (GR) on (**a**) global warming potential (kg CO_2 eq.), (**b**) terrestrial acidification potential (kg SO_2 eq.), (**c**) freshwater eutrophication potential (kg P eq.), (**d**) terrestrial ecotoxicity potential (kg 1,4-DB eq.), (**e**) freshwater ecotoxicity potential (kg 1,4-DB eq.), and (**f**) fossil resource scarcity potential (kg oil eq.).

The LCA results of the baseline scenario and the four different analyzed CSA practices presented distinct variations in environmental performance among the chosen midpoint impact categories. The environmental results varied depending on the particular management practices used in each case and the degree to which synthetic inputs, diesel usage, and field emissions were minimized or altered.

Regarding the global warming potential, the baseline scenario exhibited a value of 4798.3 kg CO_2 equivalent per hectare of cultivated land. The organic farming CSA led to a minimal decrease in greenhouse gas emissions, with the corresponding value being 4702.3 kg CO_2 eq., which constitutes an estimated improvement of 2% compared to the baseline system. Although organic systems generally necessitate extra mechanical actions for controlling weeds and pests, the removal of synthetic fertilizers and pesticides balances out the heightened diesel consumption [32]. Cover crops were beneficial as well, bringing GWP value down to 4510.4 kg CO_2 eq., highlighting the combined impacts of decreased chemical fertilizer usage and potential improvements in soil properties, as suggested in the literature [33]. Grazing yielded the greatest improvement in terms of greenhouse gas emissions, lowering GWP to 3550.7 kg CO_2 eq., representing a decline of more than 25% from the conventional product system, which is mainly attributed to decreased diesel usage, lower fertilizer requirements, and the nutrient recycling role of grazing animals [19,34]. Finally, floral bands exhibited a slight decrease, with a GWP value close to the baseline at 4774.3 kg CO_2 eq., since the usage of fertilizers did not differ compared to the baseline scenario, and only a decrease in the usage of chemical agents, such as pesticides and herbicides, was obtained. It should be noted that soil carbon sequestration effects were not explicitly modeled in this study. Therefore, any potential contribution of CSA practices to long-term carbon storage is not quantified and should not be overinterpreted.

The outcomes for terrestrial acidification potential presented a distinct trend. The value of the conventional apple orchard system was 45.16 kg SO_2 equivalent per hectare. Organic farming slightly raised acidification potential to 46.06 kg SO_2 eq., which can be attributed to the elevated ammonia (NH_3) emissions linked to the application of manure fertilizers [35]. Cover crops greatly lowered acidification-related effects, decreasing emissions to 36.58 kg SO_2 eq., owing to decreased nitrogen fertilizer application and improved nutrient retention in soils. Grazing led to a minor decrease, lowering impacts to 39.97 kg SO_2 eq., primarily due to reduced use of synthetic fertilizers and less machinery operation. Floral bands, on the other hand, demonstrated acidification levels that were similar to the baseline system, since only the use of pesticides varied in this specific CSA practice.

Significant variations were also noted in the freshwater eutrophication potential indicator, which is heavily affected by phosphorus losses and runoffs. The corresponding value of the baseline system was 0.29 kg P eq. per hectare. Organic farming saw the most significant enhancement, lowering eutrophication to 0.0725 kg P eq., leading to a decrease of about 75%. This demonstrates the benefits of removing phosphorus-rich synthetic fertilizers and improving nutrient recycling linked to organic fertilization [36]. Similarly, the application of cover crops decreased eutrophication, reaching a value of 0.2784 kg P eq. by decreasing phosphorus runoff and enhancing soil structure. Grazing resulted in even greater decreases (0.2233 kg P eq.) due to reduced synthetic fertilizer application and natural nutrient recycling. Floral bands exhibited only slight variations from the baseline (0.2799 kg P eq.), since this practice mainly affects pesticide application rather than nutrient control.

The decline in pesticide application within CSA practices significantly impacted the terrestrial ecotoxicity. The baseline scenario exhibited the greatest value at 8981.3 kg 1,4-DB eq per hectare, owing to its dependence on synthetic pesticides and the resulting emissions due to their application [37]. Organic farming lowered terrestrial ecotoxicity to 6017.5 kg 1,4-DB eq., indicating a decrease of about 33%. Cover crops lowered values to 7229.9 kg 1,4-DB eq., whereas grazing produced 6825.8 kg 1,4-DB eq. Finally, the application of floral bands demonstrated a slight enhancement, reducing terrestrial ecotoxicity to 8756.8 kg 1,4-DB eq. These findings highlight that a decrease in the usage and application of pesticides can lead to lower ecotoxic effects, particularly in situations where synthetic inputs are significantly reduced or substituted.

Patterns for freshwater ecotoxicity potential closely resembled those of terrestrial ecotoxicity. The baseline recorded 39.95 kg 1,4-DB eq., while organic farming significantly reduced this impact to 15.18 kg 1,4-DB eq. due to the removal of synthetic pesticides and fungicides. Cover crops and grazing both resulted in moderate decreases (28.56 kg 1,4-DB eq. for both systems), indicating reduced pesticide reliance. Floral bands led to a slight reduction to 32.76 kg 1,4-DB eq., in line with its modest pesticide reduction expectations. These findings emphasize the significance of reducing or replacing pesticides to enhance the health of freshwater ecosystems, and they showcase the ecological advantages of approaches that encourage natural pest management methods [37].

Finally, the scarcity of fossil resources demonstrated enhancements across all studied CSA practices. The baseline scenario exhibited a value of 1313.0 kg oil eq. Organic farming did not raise fossil resource consumption, and instead, it exhibited a decrease to 1142.3 kg oil eq., demonstrating the avoided use of synthetic fertilizers and pesticides, which require significant energy and fossil fuel consumption during their production stages [38]. Cover crops decreased fossil resource scarcity to 1181.7 kg oil eq., with floral bands achieving a similar reduction at 1306.5 kg oil eq. The CSA of grazing exhibited the most significant decrease in this specific environmental indicator, with the value being 925.7 kg oil eq., which translates to an approximately 30% decrease compared to the conventional apple orchard, due to reduced dependence on machinery, fertilizers, and outside chemical inputs.

In order for the outcomes of the CSA practices to be thoroughly compared, the results of the LCA analysis were also evaluated per ton of cultivated apples. Overall, the general trends remain broadly consistent with the hectare-based results; however, some differences emerge due to variations in yield among the systems. Specifically, for global warming potential, the baseline system records 137.09 kg CO_2 eq. per ton. Among the CSA practices, grazing achieves the lowest value (101.45 kg CO_2 eq.), confirming its strong mitigation potential even when normalized per unit of product. Cover crops also reduce emissions (128.87 kg CO_2 eq.), while floral bands remain very close to the baseline (136.41 kg CO_2 eq.). In contrast, organic farming exhibits a higher GWP (156.74 kg CO_2 eq.), indicating that lower productivity offsets the emission reductions achieved per hectare.

Regarding terrestrial acidification potential, the baseline value is 1.29 kg SO_2 eq. per ton. Organic farming presents the highest impact (1.54 kg SO_2 eq.), likely due to ammonia emissions from organic fertilizers. Grazing (1.08 kg SO_2 eq.) shows the lowest value, followed by cover crops (1.05 kg SO_2 eq.), while floral bands (1.29 kg SO_2 eq.) remain similar to the baseline.

For freshwater eutrophication potential, the baseline reaches 0.00829 kg P eq. per ton. Organic farming achieves the greatest reduction (0.00242 kg P eq.), confirming its effectiveness in limiting phosphorus-related emissions. Cover crops (0.00795 kg P eq.), grazing (0.00638 kg P eq.), and floral bands (0.00800 kg P eq.) also show improvements, although to a lesser extent.

In terms of terrestrial ecotoxicity potential, the baseline system exhibits 256.61 kg 1,4-DB eq. per ton. All CSA practices reduce this impact, with grazing (195.79 kg 1,4-DB eq.) and organic farming (200.58 kg 1,4-DB eq.) showing the largest improvements. Cover crops (206.57 kg 1,4-DB eq.) and floral bands (250.19 kg 1,4-DB eq.) provide smaller reductions.

A similar trend is observed for freshwater ecotoxicity, where the baseline records 1.14 kg 1,4-DB eq. per ton. Organic farming achieves the lowest value (0.506 kg 1,4-DB eq.), followed by grazing (0.816 kg 1,4-DB eq.) and cover crops (0.816 kg 1,4-DB eq.). Floral bands (0.936 kg 1,4-DB eq.) show only a moderate decrease.

Finally, for fossil resource scarcity, the baseline system has a value of 37.51 kg oil eq. per ton. Grazing again demonstrates the best performance (26.45 kg oil eq.), followed by cover crops (33.76 kg oil eq.) and organic farming (38.08 kg oil eq.), while floral bands (37.33 kg oil eq.) remain nearly unchanged compared to the baseline.

The findings of the LCA analysis indicate that CSA practices can significantly improve the environmental performance of apple orchard systems; however, the extent and nature of the impacts vary depending on the nature of the selected practice. Organic agriculture significantly decreases eutrophication and ecotoxicity, while it slightly raises terrestrial acidification. Cover crops offer balanced enhancements in various areas, especially in terms of acidification and ecotoxicity. Floral bands offer slight advantages, primarily in environmental metrics that are impacted by the application of pesticides. Finally, grazing provides the widest environmental benefits, especially in decreasing GWP, eutrophication, and scarcity of fossil resources. The obtained results emphasize the need to choose CSA practices based on the unique environmental priorities of each farm and suggest that integrating various practices might improve the overall sustainability outcomes of apple orchards.

3.2. LCC Results

A comparative LCC analysis was conducted for the different studied scenarios. Farm-specific factors like management techniques, market prices, and access to subsidies can all have a substantial impact on actual costs, yields, and revenues. Therefore, the LCC results can offer indicative insights into the economic implications of the different CSA practices, based on the interpreted results. Annual operating costs, annual revenues, and any subsidies provided were taken into account. The life cycle costs that are taken into account are only those related to one production cycle, as only the apple's growth and harvesting are included within the boundaries of the studied systems. Other stages, such as orchard establishment, are excluded, and any equipment used is considered to have been depreciated, with only its maintenance costs considered. A single production cycle was chosen to ensure a direct and consistent comparison between organic and conventional farming under the same conditions. This approach aligns with the cradle-to-gate system boundaries and minimizes uncertainties associated with multi-year projections.

LCC results of the baseline scenario and of the different studied CSA practices in the present work are presented in Table 2 and Figure 2.

Table 2. LCC results of the baseline and the different studied CSA practices for the period 2023–2024.

Cost Category (€/ha)		**Baseline (BL)**	**Cover Crops (CC)**	**Organic Farming (OF)**	**Floral Bands (FB)**	**Grazing (GR)**
Expenses	Energy	908	908	1379	908	635
	Water	532	532	532	532	532
	Fertilizers	526	423	-	526	372
	Manure transportation	-	-	60	-	-
	Plant-protection products	741	596	90	596	596
	Equipment maintenance	1447	1447	1893	1447	1447
	Labor	5081	5081	4653	5081	5081
	Other (taxes, admin, etc.)	2248	2248	2248	2248	2248
	Total	11,482	11,235	10,855	11,337	10,911
	Change over BL	-	−2.2%	−5.5%	−1.3%	−5%
Revenues	Apples	15,050	15,050	15,480	15,050	15,050
	Subsidies [39,40]	170	270	696	210	199
	Total	15,220	15,320	16,176	15,260	15,249
	Change over BL	-	+0.66%	+6.28%	+0.26%	+0.19%
Profit		3738	4086	5320	3923	4338

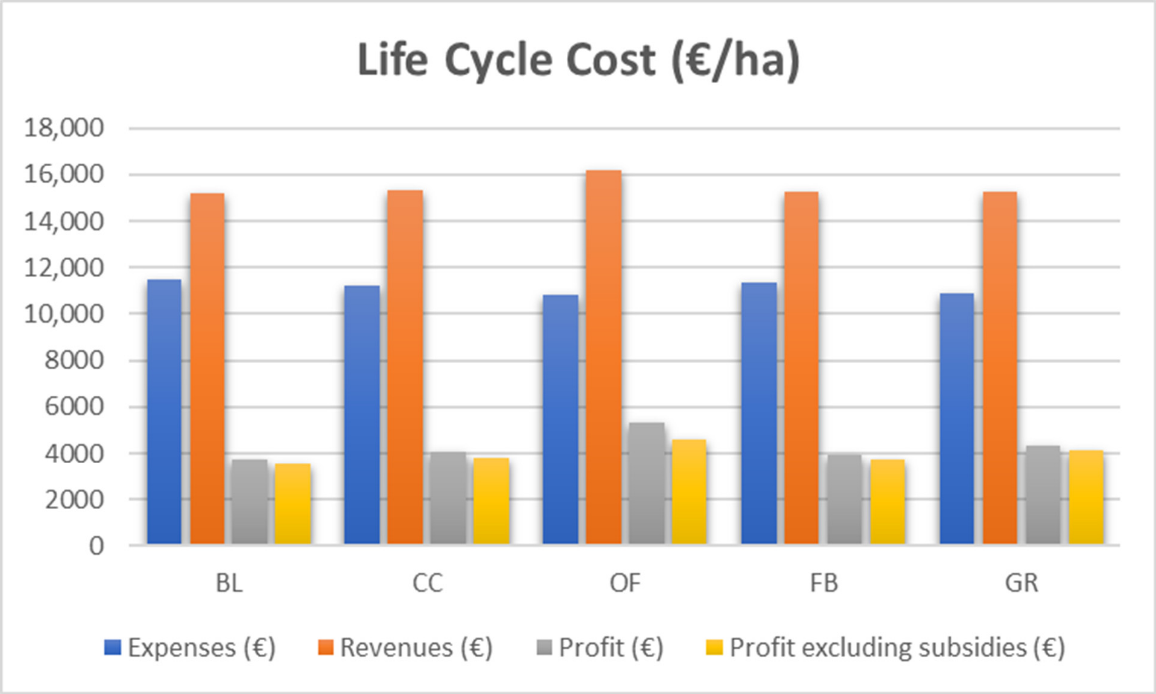

Figure 2. Economic performance of the baseline (BL), cover crops (CC), organic farming (OF), floral bands (FB), and grazing (GR).

The integration of agri-environmental management practices, supported by public funding, is a key element of organic production in Navarra, with a 2.5% allocation of the region's Strategic Plan public expenditure (695.5 €/ha) [39]. This investment supports the long-term sustainability of organic farming practices, contributing to both environmental and agricultural benefits. In the organic farming CA practice, due to their increased added value, apples are sold at a price 20% higher than that of conventional cultivated apples. Synthetic plant-protection products are not applied in this CSA practice; hence, their cost is not included, and synthetic fertilizers are replaced by an equivalent amount of manure from neighboring farms that is supplied free of charge, with only the transportation cost being included. The need for more intensive techniques for weed and pest management leads to increased total cost of diesel. In the studied product system, the cost of diesel use appears to have increased by 52% compared to the baseline scenario, due to the more extensive use of agricultural machinery required in organic farming. The cost of pesticides and other synthetic plant-protection products is eliminated. Similarly, the cost of synthetic fertilizers is net zero, due to their replacement by manure; manure is provided for free by neighbor farms, thus only the cost of its transportation is taken into account. For these reasons, the total costs are calculated up to around 10,800 € per ha per year, decreased by 5% compared to the baseline scenario. The increased by 20% market value of the final product, despite the reduced yield per cultivated hectare, along with the subsidy provided, increases the revenues of the modeled farm per ha per year by 6%. The above contribute to a profit increase of about 46%, leading to a total profit of 5320 € per ha per year in the organic farming scenario, providing promising insights to the farmers for the adoption of organic farming practices.

The reduced use of pesticides in the cover crops CSA led to a subsequent reduction in the cost of plant-protection products. The extra subsidy provided for the application of cover crops was 100 €/ha [39,40]. The cost for the planting and management of cover crops is estimated to be quite low (seed cost, sowing, and management costs) and was considered negligible. The findings imply that the application of cover crops can be carried out under the modeled conditions with little additional financial strain on the farmer. On the contrary, cover crops can contribute to pest management and fertilization, limiting the expenditures of pesticides and fertilizers, respectively. According to the studied CSA practice, an apple orchard using cover crops could generate up to €15,320 in revenue, including any applicable subsidies. The total cost, assuming no additional capital expenditures, is estimated to be €11,235. Under the specified assumptions, this leads to a projected profit margin of €4086 per hectare annually, which represents a 9.5% increase over the baseline scenario.

The reduced use of pesticides in the floral band CSA practices led to a subsequent reduction in the cost of plant-protection products. An additional subsidy of 40 €/ha was considered for the adoption of floral bands [39,40]. The costs for the planting and management of floral bands were estimated to be quite low (seed cost, sowing, and management costs) and were considered negligible. The application of floral bands seems to be a reasonably inexpensive tactic under the modeled circumstances, possibly doable for farmers without putting them under a lot of financial strain. Floral bands may help control pests and lower the costs associated with pesticides, in addition to their possible environmental advantages. Assuming no further capital investment is needed, total costs are estimated to be 11,337 €. Revenues, including subsidies, could reach about 15,260 €/ha in this scenario. Under the specified assumptions, this translates to an estimated annual profit of 3923 €/ha, or a 5% increase over the baseline scenario.

Finally, the reduced use of pesticides in the grazing CSA was assumed to result in lower expenditures for plant-protection products. An extra subsidy of 29 €/ha was included to account for policy support for grazing practices [39,40]. In the modeled scenario, grazing was carried out by sheep from neighboring farms, which are supplied free of charge. The practice was also associated with a 30% reduction in diesel use due to decreased reliance on fuel-intensive machinery. The replacement of synthetic fertilizers by manure was assumed to reduce their total cost by 30%, depending on the scenario studied. Similarly, the cost of pesticides was estimated to be reduced by 20%. Under these modeled conditions, grazing appeared to be a potentially cost-effective strategy that could support organic fertilization, pest control, soil fertility, and biodiversity. The estimated revenues could reach up to 15,250 € per ha per year, along with the subsidies provided, while the total costs were expected to be 10,911 €, assuming no additional CAPEX required. In comparison to the baseline scenario, this translates to a potential profit margin of 16%, or 4338 €/ha annually.

As mentioned in Table 2 and in the discussion of the LCC results, it is evident that subsidies can play an important role in the economic performance of each studied system. Therefore, Figure 2 also exhibits the profit of each system without taking into consideration the subsidies related to each agricultural practice. Based on the results, it is evident that all CSA practices present a better economic performance compared to the conventional apple orchard, even when subsidies are excluded. Specifically, organic farming CSA is the most economically sustainable practice, followed by grazing and cover crops. These observations further solidify the economic benefits of implementing CSA practices, indicating that they can be economically competitive and viable against conventional production systems without the need to heavily rely on external subsidies.

The economic results are highly dependent on local conditions, including product prices (e.g., organic apple premiums), availability and cost of manure, access to livestock for grazing, and subsidy schemes. Additionally, the exclusion of CAPEX and implementation costs may lead to an overestimation of economic benefits for certain practices. Furthermore, several cost components were simplified or excluded in the present analysis, including implementation costs (e.g., seeding of cover crops, establishment of floral bands), opportunity costs of land use, and potential coordination or infrastructure requirements for grazing (e.g., fencing). These simplifications may lead to an underestimation of the total costs associated with certain CSA practices. In addition, apple price assumptions (including a 20% premium for organic products) and subsidy levels are based on current regional conditions and may vary significantly across markets and over time. Therefore, the LCC results should be interpreted as context-specific and indicative rather than broadly generalizable.

3.3. Cover Crop CSA Sensitivity Analysis

Figures 3 and 4 present the results of the sensitivity analysis of the cover crop CSA in the environmental and economic performance of the system, respectively.

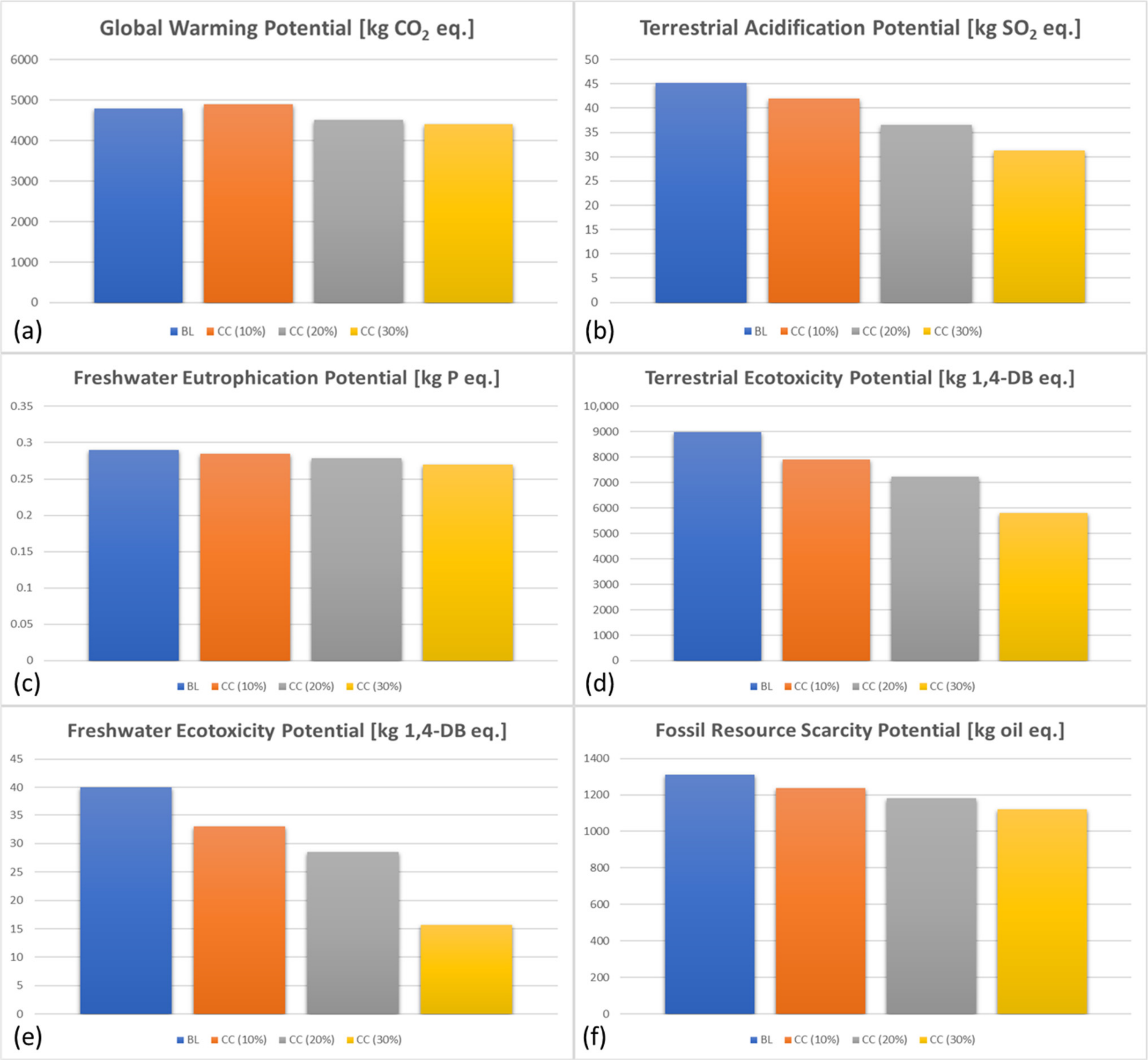

Figure 3. Environmental impact of the baseline (BL) and the different scenarios of pesticide and fertilizer use in cover crops (CC) on (**a**) global warming potential (kg CO_2 eq.), (**b**) terrestrial acidification potential (kg SO_2 eq.), (**c**) freshwater eutrophication potential (kg P eq.), (**d**) terrestrial ecotoxicity potential (kg 1,4-DB eq.), (**e**) freshwater ecotoxicity potential (kg 1,4-DB eq.), and (**f**) fossil resource scarcity potential (kg oil eq.).

The sensitivity analysis for the cover crop CSA practice took into account variations in pesticide and fertilizer reductions of 10%, 20%, and 30% relative to the conventional apple orchard system. The increase in the reduction levels led to consistent environmental improvements across most impact categories. Global warming potential decreased from 4894 kg CO_2 eq. (10%) to 4405 kg CO_2 eq. (30%), while terrestrial acidification declined from 42.0 to 31.2 kg SO_2 eq. Additionally, freshwater eutrophication and ecotoxicity indicators also decreased progressively, reflecting lower nutrient losses and reduced pesticide emissions. Finally, fossil resource scarcity was reduced by approximately 15% at the highest reduction level compared to the conventional apple cultivation farm.

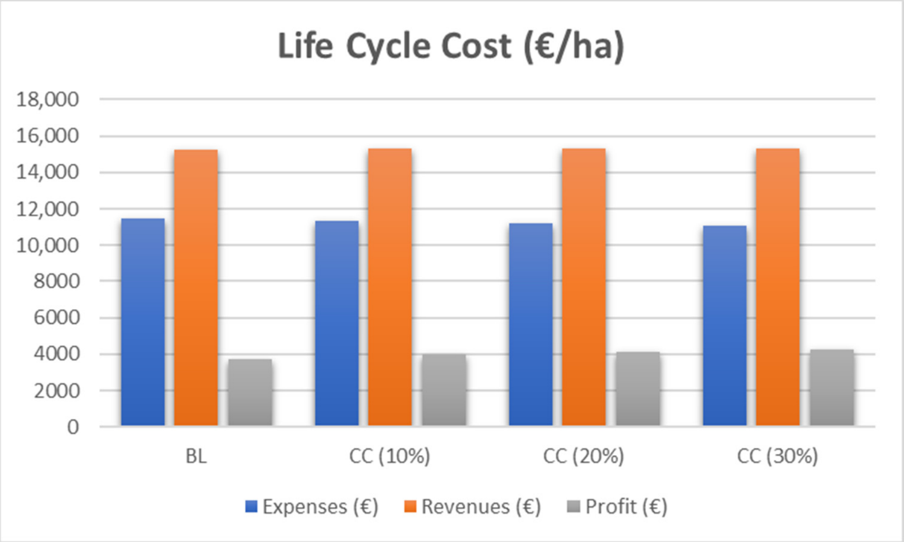

Figure 4. Economic performance of the baseline (BL) and the different scenarios of pesticide and fertilizer use in cover crops (CC).

From an economic perspective, higher input reductions slightly improved profitability. Total costs decreased from 11,356 €/ha to 11,103 €/ha, while revenues remained constant, resulting in a slight increase in profit from 3964 €/ha to 4217 €/ha. Overall, the results indicate that the environmental and economic benefits of cover crops are robust and increase gradually with higher reductions in agrochemical inputs.

3.4. Floral Band CSA Sensitivity Analysis

Figures 5 and 6 present the results of the sensitivity analysis in the floral band CSA in the environmental and economic performance of the system, respectively.

The sensitivity analysis for the floral band CSA practice centered around pesticide reduction scenarios of 10%, 20%, and 30%, with environmental improvements being consistent but modest. Global warming potential showed only a slight decrease, reaching 4750 kg CO_2 eq. at the 30% reduction level, while terrestrial acidification remained unchanged, as fertilizer inputs were not affected. Freshwater eutrophication and ecotoxicity indicators declined gradually with increasing pesticide reduction, with freshwater ecotoxicity decreasing by nearly 30% at the highest reduction level.

Economic impacts were limited, reflecting the low cost and narrow scope of the practice. Total expenses decreased marginally from 11,429 €/ha to 11,324 €/ha, leading to a slight profit increase from 3830 €/ha to 3936 €/ha. These findings suggest that floral bands provide low-risk environmental gains, mainly related to reduced pesticide use, with minimal influence on overall economic performance.

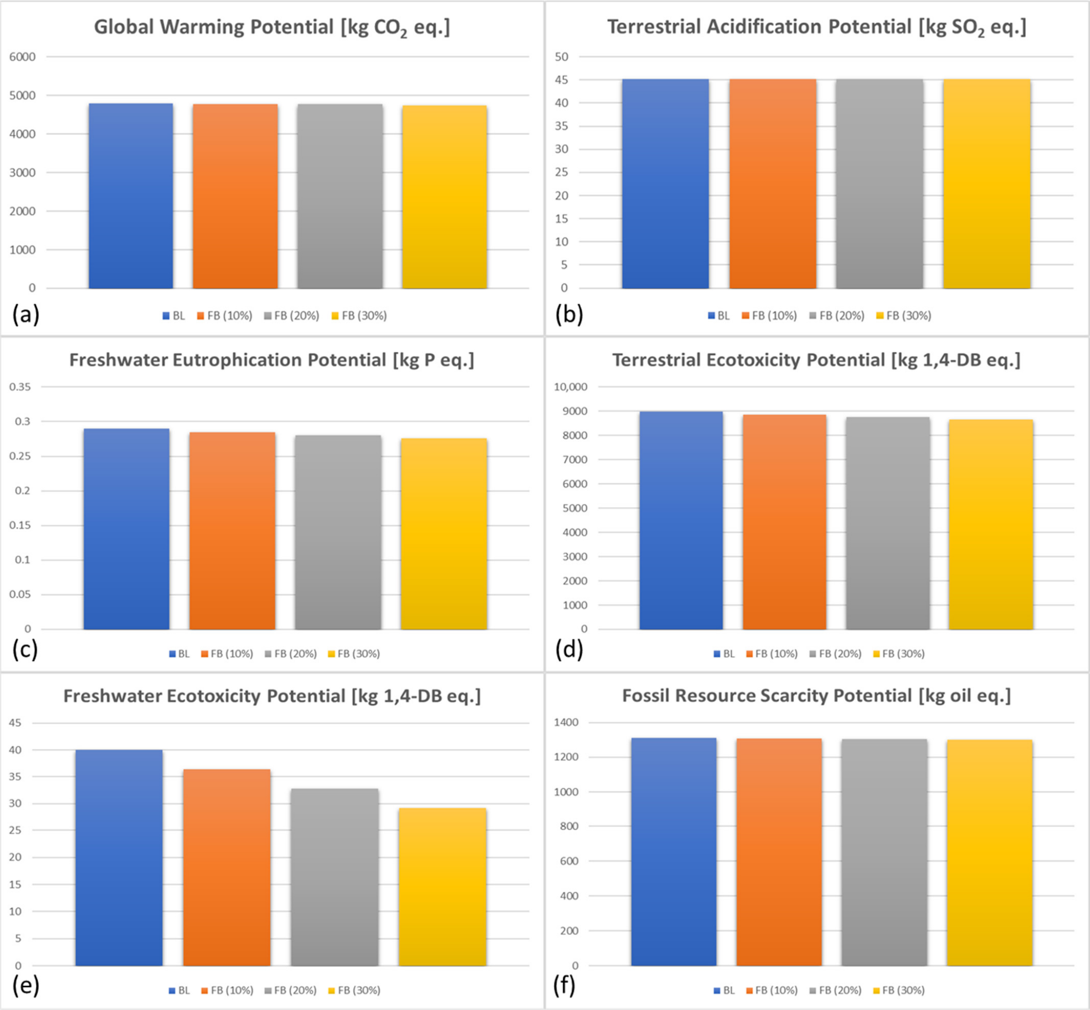

Figure 5. Environmental impact of the baseline (BL) and the different scenarios of pesticide use in floral bands (FB) on (**a**) global warming potential (kg CO_2 eq.), (**b**) terrestrial acidification potential (kg SO_2 eq.), (**c**) freshwater eutrophication potential (kg P eq.), (**d**) terrestrial ecotoxicity potential (kg 1,4-DB eq.), (**e**) freshwater ecotoxicity potential (kg 1,4-DB eq.), and (**f**) fossil resource scarcity potential (kg oil eq.).

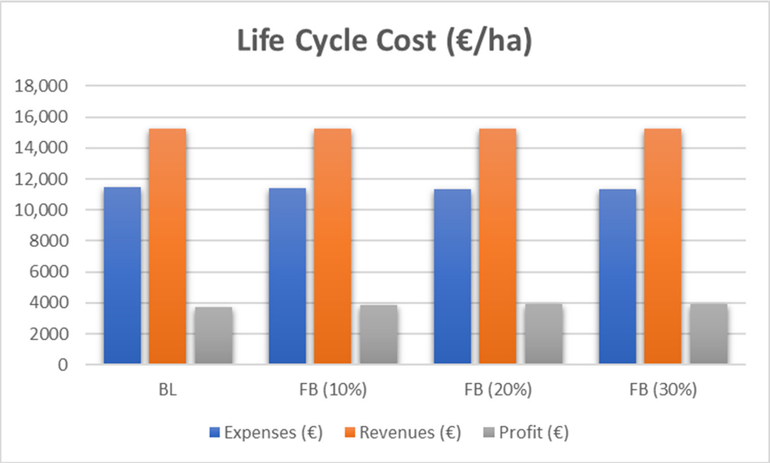

Figure 6. Economic performance of the baseline (BL) and the different scenarios of pesticide use in floral bands (FB).

3.5. Grazing CSA Sensitivity Analysis

Figures 7 and 8 exhibit the results of the sensitivity analysis in the grazing CSA in the environmental and economic performance of the system, respectively.

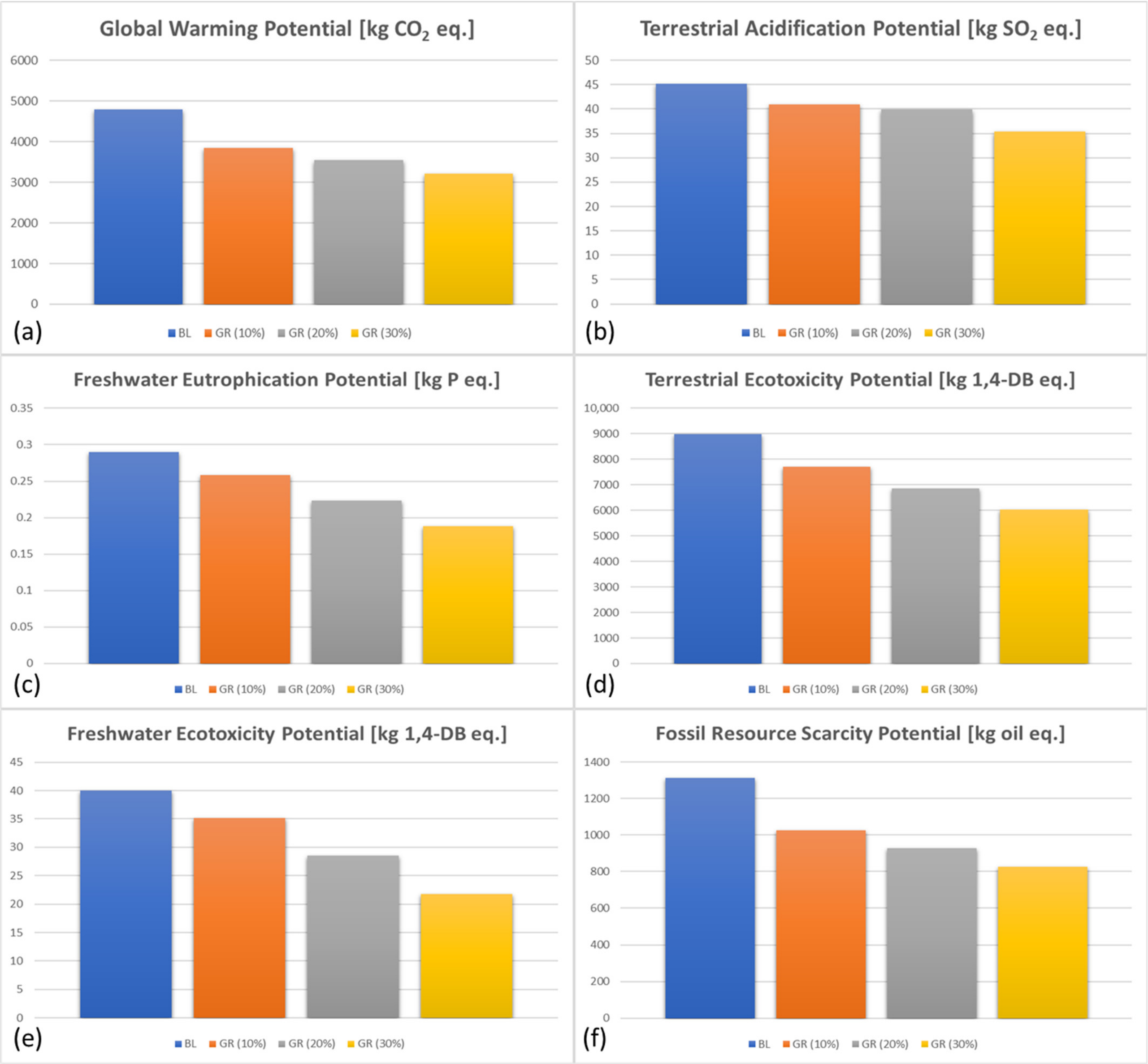

Figure 7. Environmental impact of the baseline (BL) and the different scenarios of pesticide use in grazing (GR) on (**a**) global warming potential (kg CO_2 eq.), (**b**) terrestrial acidification potential (kg SO_2 eq.), (**c**) freshwater eutrophication potential (kg P eq.), (**d**) terrestrial ecotoxicity potential (kg 1,4-DB eq.), (**e**) freshwater ecotoxicity potential (kg 1,4-DB eq.), and (**f**) fossil resource scarcity potential (kg oil eq.).

The grazing CSA practice sensitivity analysis evaluated pesticide reduction levels of 10%, 20%, and 30% under fixed assumptions of reduced diesel use and partial fertilizer replacement. Grazing exhibited the greatest changes in environmental performance among all CSA practices and sensitivity scenarios. Global warming potential decreased from 3839 kg CO_2 eq. at 10% reduction to 3215 kg CO_2 eq. at 30%, corresponding to a reduction of over 30% compared to the conventional apple orchard. Similarly declining trends were observed for terrestrial acidification, freshwater eutrophication, and both ecotoxicity indicators. Fossil resource scarcity decreased substantially, reaching 827 kg oil eq. at the highest reduction level.

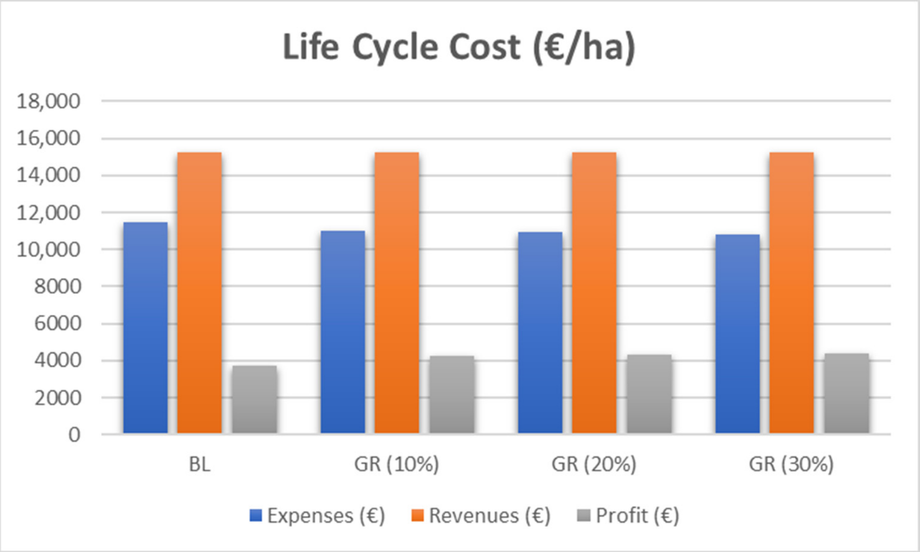

Figure 8. Economic performance of the baseline (BL) and the different scenarios of pesticide use in grazing (GR).

Economically, increased pesticide reductions resulted in small but consistent cost savings. Total expenses declined from 10,982 €/ha to 10,834 €/ha, increasing profit from 4267 €/ha to 4415 €/ha. Overall, grazing proved to be the most environmentally robust CSA practice, with stable economic performance across all sensitivity scenarios.

Although sensitivity analyses were performed for selected parameters (e.g., pesticide and fertilizer reductions), further analysis could be conducted to assess the influence of additional variables such as yield variability, market prices, and input costs. Expanding the sensitivity analysis would improve the robustness of the conclusions and better reflect real-world uncertainties.

3.6. Uncertainty Analysis and Limitations

The present study incorporates sensitivity analyses for selected parameters, primarily focusing on variations in pesticide and fertilizer reduction levels. However, additional sources of uncertainty remain that may influence the robustness of the results. Key parameters such as diesel consumption, manure substitution rates, pesticide emission factors, yield variability, and market prices can significantly affect both environmental and economic outcomes.

Furthermore, several assumptions adopted in the modeling framework—particularly those related to input reductions, availability of manure, and the absence of costs for grazing—introduce additional uncertainty. These assumptions reflect plausible but not universally applicable conditions and may vary across regions and farming systems.

A comprehensive uncertainty analysis, such as Monte Carlo simulation or probabilistic modeling, was beyond the scope of the present study. Therefore, the results should be interpreted with caution, especially for scenarios that rely heavily on modeled assumptions (e.g., grazing and organic farming). Future work should aim to incorporate broader uncertainty propagation methods to better assess the variability and reliability of the findings.

4. Conclusions

The present study provides a comparative, scenario-based assessment of the environmental and economic performance of selected CSA practices in apple farming under specific conditions in Navarra, Spain. The results indicate that, within the defined system boundaries and assumptions, CSA practices such as grazing, organic farming, and cover crops can contribute to improved environmental performance and, in some cases, enhanced economic outcomes. Among the studied techniques, grazing emerged as the most comprehensive option, achieving the largest reductions in global warming potential and fossil resource scarcity, largely through lower synthetic input use, reduced machinery operation, and efficient nutrient recycling. Organic farming proved particularly effective in minimizing eutrophication and ecotoxicity impacts, despite slightly increasing terrestrial acidification due to manure-related ammonia emissions. Cover crops offered balanced and consistent improvements across multiple indicators, notably reducing acidification and ecotoxicity. Floral bands provided more modest benefits, mainly associated with reduced pesticide use, with limited influence on nutrient-related impacts.

The results of the LCC analysis highlight that the profitability of CSA practices in apple orchards varies notably. Organic farming and grazing achieved the strongest economic performance, supported by reduced input costs, available subsidies, and, in the case of organic farming, higher market prices that offset increased diesel use and lower yields. Cover crops and floral bands delivered smaller but consistent profit gains, mainly due to low implementation costs and modest policy support, making them financially accessible and low-risk options. However, these economic outcomes should be interpreted with caution. Part of the dataset does not account for several external factors that can substantially influence farm profitability. Additionally, some CSA practices are implemented simultaneously, making it difficult to isolate the individual economic contribution of each measure, particularly for practices with limited direct effects on orchard management, such as floral bands. Farm profitability is influenced by numerous variables, including farm-specific management decisions, climatic variability, market dynamics, and structural characteristics, that were beyond the scope of the present analysis.

Overall, the findings of the environmental and economic assessments underscore that CSA practices can meaningfully enhance orchard sustainability, but their effectiveness depends on farm-specific environmental priorities, management constraints, and local policy incentives, market conditions, and farm-level cost structures, respectively. However, the results are subject to several limitations, including the exclusion of orchard establishment and capital investments, reliance on scenario-based assumptions, and the use of context-specific data. Consequently, the findings should not be interpreted as universally applicable or as definitive evidence of the superiority of specific practices. Instead, they should be viewed as indicative insights that highlight the potential benefits and trade-offs of CSA practices under certain conditions. Further research based on broader datasets and full life cycle approaches is required to support more generalizable conclusions.

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Abbreviations

The following abbreviations are used in this manuscript:

LCA	Life cycle assessment
LCC	Life cycle costing
CSA	Climate-smart agriculture
BL	Baseline
OF	Organic farming
CC	Cover crops
FB	Floral bands
GR	Grazing

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