BEATLES
BEHAVIOURAL CHANGE TOWARDS
Climate-Smart Agriculture

CO-CREATING BEHAVIORAL CHANGE TOWARDS CLIMATE-SMART FOOD SYSTEMS

D3.2 Sustainability assessment v2

PROJECT ACRONYM: BEATLES
PROGRAMME: HORIZON Europe
Grant Agreement: No 101060645
TYPE OF ACTION: HORIZON Research & Innovation Actions
START DATE: 1 July 2022
DURATION: 48 months

Funded by the European Union

Document Information

Issued by:	National Technical University of Athens (NTUA)
Issue date:	10/06/2025
Due date:	18/06/2025
Work package leader:	National Technical University of Athens (NTUA)
Start date:	01/06/2023
Dissemination level:	PU (Public)

Document History

Version	Date	Modifications made by
0.1	10/06/2025	Draft version prepared by NTUA
0.2	18/06/2025	Reviewed by SEI
1.0	28/06/2025	Final version submitted to the European Commission

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Executive Summary

This deliverable (D3.2) includes the sustainability assessment and the Cost-Benefit Analysis (CBA) of 25 Climate Smart Agriculture (CSA) practices applied across five Use Cases (UCs), building on the results of the 2024 D3.1, which provided the baseline sustainability assessment for each UC. The sustainability assessment included the Life Cycle Assessment (LCA), the Life Cycle Costing (LCC) and the social LCA (s-LCA) and was used to evaluate the five selected CSA practices applied on each UC and tailored to their local contexts. In order to conclude the combination of environmental, social, and economic trade-offs connected to each CSA practice in relation to its corresponding baseline, a CBA was also carried out. Similar to the 2024 D3.1 methodology, the necessary data were collected by the UC leaders and supplementary data were provided by appropriate databases or literature. For the LCA assessment, the ReCiPe 2016(H) method was selected and the software SimaPro was used for the impact assessment.

The results demonstrated that a number of CSA practices significantly improved each of the three sustainability pillars. The scenarios of no-tillage and variable rate fertilization in the Lithuanian UC (wheat cultivation), longevity breeding and Naturland farming[1] in the German UC (organic dairy farming), cover crops and floral bands in the Spanish UC (organic apple farming), biogas and frequent slurry discharge in the Danish UC (pig farming), and biodiversity-focused and compost-based soil management in the Dutch UC (potato and onion farming) are a few examples. In addition to improving soil health, biodiversity, and stakeholder well-being, these practices reduced GHG emissions, input dependency, and operating costs. However, future adoption strategies need to take into account some upstream social trade-offs especially in practices involving imported hardware (e.g. in CSAs involving renewable energy systems from solar panels).

The Theory of Change (ToC) framework was once more used to gauge stakeholder opinions of the BEATLES CSAs. In addition to cautious optimism from farmers, feedback from workshops, multi-actor group events, and public webinars showed that advisors, researchers, and policy makers were very interested and involved. However, there is still a strong need to address the impact of policy on decision-making and to provide more focused, context-specific examples.

[1] Naturland e.V. (2021, August). *A one-to-one comparison of the Naturland Standards with the EU organic regulation* (p. 1). Naturland e.V.

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List of Terms and Definitions

Abbreviation	Definition
CAP	Common Agricultural Policy
CAPEX	Capital Expenditure
CBA	Cost-Benefit Analysis
CSA	Climate Smart Agriculture
GPS	Global Positioning System
GWP	Global Warming Potential
DALYs	Disability Adjusted Life Years
EU	European Union
EWM	Extensive Wetland Management
FU	Functional Unit
IPM	Integrated Pest Management
ILO	International Labour Organization
KPAD	KPAD Ltd
KWIN	KWantitatieve INformatie
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCC	Life Cycle Cost
LCSA	Life Cycle Sustainability Assessment
NTUA	National Technical University of Athens
ISO	International Organization for Standardization
OPEX	Operational Expenditure
PSILCA	Product Social Impact Life Cycle Assessment
s-LCA	Social Life Cycle Assessment
ToC	Theory of Change
UC	Use Case
VRF	Variable Rate Fertilization
WHO	World Health Organization
WP	Work Package

Table 1: Terms and Definitions

1. Introduction

BEATLES has set up five (5) selected use cases (UCs) across the EU (wheat farming in Lithuania, dairy farming in Germany, apple farming in Spain, pig farming in Denmark, onions and potato farming in the Netherlands) that represent diverse food systems in transition to climate-smart agriculture and value chains along with various stakeholders across the value chain (farmers, advisors, processors, retailers, investors, consumers, policy makers), indicative of the food systems approach adopted.

D3.2 presents a comprehensive sustainability assessment of 25 specific Climate Smart Agricultural (CSA) practices (5 for each of the 5 UCs), selected based on certain criteria listed in D3.1 (potential environmental benefits, ease or difficulty of adoption, current level of use, and level of importance for the particular UC), among practices provided in D1.2 by NTUA, KPAD, the UC leaders, and partners from WP2, WP4, and WP5. These practices were initially introduced in D3.1 and are further evaluated in the current deliverable (D3.2) through Life Cycle Assessment (LCA), Life Cycle Costing (LCC), social Life Cycle Assessment (s-LCA) and Cost-Benefit Analysis (CBA). This deliverable allows for a cross-cutting comparison with baseline scenarios (the Use Cases as they function today, without implementing a CSA practice), by combining the social, economic, and environmental performance of each CSA practice. The findings are intended to aid in the creation of transformative pathways, such as business plans and policy suggestions, in the direction of a climate-smart and sustainable EU agri-food industry.

2. Methodology

2.1. Environmental Life Cycle Assessment

The environmental Life Cycle Assessment was conducted in line with the methodological framework described in D3.1. The objective was the application of LCA methodology on 5 different CSA practices per UC (25 CSA practices in total) to quantify and compare the environmental impacts of the baseline versus the CSA scenarios, using the same functional units and system boundaries defined previously. In addition to highlighting any trade-offs between impact categories, the goal of this analysis is to determine which CSA practices provide the greatest potential benefits for environmental burdens, such as global warming, freshwater eutrophication or ecotoxicity potential.

As outlined in D3.1, the LCA followed the ISO 14040/14044 standards[2,3] and was conducted in four distinct steps: (1) definition of goal & scope, (2) Life Cycle Inventory development, (3) Life Cycle Impact Assessment and (4) Interpretation of the results. The ReCiPe 2016 Midpoint (H) method was used to quantify the 18 impact categories that are presented in Figure 1 (Huijbregts et al. 2017). The most relevant to the studied systems midpoint impact indicators were selected to describe the environmental impact of the selected CSA practices, including Global Warming Potential (GWP), Fossil Resource Scarcity, Terrestrial & Freshwater Ecotoxicity, Freshwater Eutrophication, and Terrestrial Acidification. All assessments were conducted under a cradle-to-farm gate boundary. The same functional unit and allocation principles were applied as in D3.1, ensuring comparability between baseline and CSA scenarios.

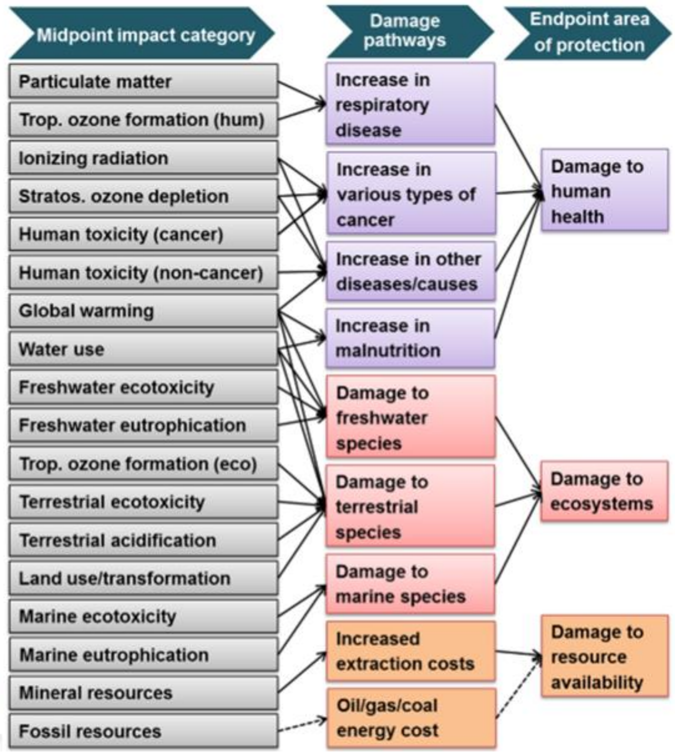


Figure 1: ReCiPe 2016 – overview of impact categories (Huijbregts et al. 2017).

[2] International Organization for Standardization (ISO). (2006). *ISO 14040:2006 Environmental management — Life cycle assessment — Principles and framework.* Geneva: ISO.
[3] International Organization for Standardization (ISO). (2006). *ISO 14044:2006 Environmental management — Life cycle assessment — Requirements and guidelines.* Geneva: ISO.

2.2. Life Cycle Cost Analysis & Cost-Benefit Analysis

A summary of Life Cycle Costing (LCC) and Cost-Benefit Analysis (CBA), two essential elements for evaluating the financial feasibility of CSA practices, was provided in Deliverable D3.1. LCC focuses on assessing all costs, including capital (CapEx) and operating (OpEx) expenditures, related to a system or product over the course of its whole life cycle. LCC facilitates decision-making by incorporating financial data to evaluate options from a cost-efficiency standpoint, even in the absence of a standardized methodology like LCA. In the meantime, CBA includes steps like determining costs and benefits, discounting future values, and performing risk and sensitivity analyses. This deliverable reports detailed CBA and LCC analyses for each CSA practice.

2.3. Social Life Cycle Assessment

Deliverable D3.1 introduced the Social Life Cycle Assessment (s-LCA) as a complementary method to traditional environmental LCA, aiming to assess the social impacts of products throughout their entire life cycle. The four main stages of the s-LCA methodology (goal and scope definition, life cycle inventory, impact assessment, and result interpretation) were applied to each of the 25 CSA practices in accordance with ISO 14040 guidelines, similar with the environmental LCA presented above. The SOCA 2 database, which is based on PSILCA 3, was used for the analysis[4]. It offers more than 70 social indicators that are divided into four categories: Value Chain Actors, Workers, Local Community, and Society. These indicators were contextualized with activity variables like "worker hours," which were derived from LCC and LCA data, and impact factors that were risk-assessed using international data sources (such as the ILO, WHO, and World Bank). Despite its limitations in terms of scale, comparability, and data availability, s-LCA is an emerging and developing field that provides insightful information about potential social risks and benefits. As such, instead of being used for cross-UC comparisons, s-LCA in BEATLES is used to assess and contrast baseline conditions with upcoming CSA implementations within each UC.

2.4. Theory of Change (ToC)

By developing creative business plans and policy suggestions, the BEATLES project seeks to support systemic shifts to climate-smart and sustainable agri-food systems. The development of a Theory of Change (ToC) framework for CSA practices, which facilitates the planning, execution, and assessment of CSA interventions, is central to this approach. The ToC places a strong emphasis on accountability, openness, and evidence-based decision-making. The early involvement of a variety of value chain and policy actors, such as farmers, advisors, processors, retailers, consumers, and policymakers, is a crucial component of the BEATLES approach. BEATLES integrates instructional materials with behavioral and experimental research to jointly develop context-specific solutions, backed by international stakeholder networks and skilled trainers.

The ToC plan includes: (1) creating business plans to facilitate equitable shifts to CSA; and (2) suggesting policy instruments that take behavioral insights and perceptions of fairness into account to promote dedication and long-term change. Involving stakeholders aids in identifying opportunities and obstacles along the value chain and helps assess partnerships, learning progress, outputs and outcomes. The ToC strategy developed for the BEATLES project was presented in detail in the previous D3.1. The Typeform platform[5] has been used to implement a number of targeted questionnaires and participatory activities (such as training, webinars, and workshops) to aid in this process. These tools make it easier to gather data and evaluate effects, and the outcomes help shape stakeholder comprehension and engagement tactics.

[4] SOCA v3 Documentation: https://nexus.openlca.org/ws/files/35767
[5] Typeform: http://www.typeform.com

2.5. Selection of CSA practices

The target for WP3 is the sustainability assessment of at least 25 CSA practices. For this reason, 5 CSA practices per UC have been chosen, which are also examined in other WPs (WP2, WP4, WP5). The specific practices were selected from the practices outlined in D1.2 (co-creating behavioural change towards climate smart food systems), presented in D3.1 and also listed in Table 2 for reference.

UC1 (Lithuania – wheat farming)	UC2 (Spain – organic apple farming)	UC3 (Germany – organic dairy farming)	UC4 (Denmark-pig farming)	UC5 (The Netherlands-potato & onion farming)
Intercropping	Cover crops	Organic/Naturland: 40% forage, 10% maize, 10% grains for feed, 40% clover grass – reduced number of animals, and other parameters according to Naturland standards	Frequent discharge of slurry	Sustainable irrigation systems [including energy consumption of the systems (diesel, electricity, green electricity)]
No-tillage system	Floral bands	Feed conversion to 100% forage	Acidification of slurry	Green energy (ratio of green/grey energy)
(Extensive) wetland management	Grazing	Regional protein source	Use of biogas	Precision fertilization and soil management
Alternative green energy	Organic farming	Breeding for longevity	Green protein for feed	Biodiversity measures (farm level)
Precision farming (variable rate fertilization or irrigation)	Renewable energy (e.g. solar energy)	Agrophotovoltaic systems	Technologies for ventilation	Crop protection (all IPM measures, total impact)

Table 2: Selected CSA practices per UC

3. Application of the LCA assessment methodology to the BEATLES project Use Cases

The first two stages (Goal and Scope definition & Life Cycle Inventory) of the methodology utilized for the environmental, economic, and social assessment of the examined systems were similar across all three Life Cycle assessments and are described in subsections 3.1.2, 3.2.2, 3.3.2, 3.4.2 and 3.5.2. The description of each type of assessment is provided separately in the next subsections.

3.1. Use Case Pilot #1: Wheat farming, Lithuania

3.1.1. Description of the CSA practices

Extensive Wetland Management (EWM) | Description

Extensive Wetland Management (EWM) is an agricultural practice that involves cultivating crops in fields that are deliberately maintained in a flooded or semi-flooded state throughout the growing season. This approach results in the generation of a natural wetland environment that supports crop growth without the need for artificial irrigation or synthetic inputs. This method leverages the nutrient-rich characteristics of wetland soils and water, which naturally contain the essential macro- and micronutrients required for plant development. Consequently, there is typically no need for additional fertilization, reducing both costs and environmental impacts associated with nutrient runoff. However, one key requirement before establishing EWM is the pre-season cleaning of the field, which involves a low-input process, to prepare the soil and ensure adequate water flow and nutrient distribution during the flooded phase. Once in operation, the system is self-sustaining, requiring minimal human intervention and external inputs (Nath & Lal, 2017).

EWM not only preserves water resources by eliminating the need for supplementary irrigation but also supports broader ecological functions such as groundwater recharge, biodiversity conservation, and climate regulation. By integrating farming with wetland ecosystems, this approach offers a sustainable alternative that aligns agricultural productivity with environmental stewardship.

Intercropping | Description

Intercropping, particularly the combination of pea and wheat, is a sustainable agricultural practice that involves growing two different crops simultaneously on the same field. In a pea-wheat intercrop system, wheat plays a protective role for the more delicate pea plants, shielding them from harsh weather conditions and suppressing weed growth through canopy coverage. This symbiotic relationship allows for better resource utilization, as the two crops exploit different soil layers and nutrients, enhancing overall field productivity and soil health (Naudin et al., 2014).

While intercropping may lead to a slight reduction in wheat yield due to competition for light, water, and nutrients, this trade-off is balanced by a noticeable improvement in the performance of the pea crop. Especially, in pedoclimatic regions where pea monocultures do not exhibit a high yield, peas grown in an intercropped system benefit from improved support, better microclimate conditions, and reduced pest pressure, often resulting in higher and more stable yields (Maitra et al., 2021).

No Tillage | Description

No-tillage systems in wheat farming offer a more natural and less disruptive way to grow crops by leaving the soil undisturbed throughout the growing cycle. Instead of plowing or turning the soil, farmers plant wheat directly into the previous season's crop residues. This simple shift makes a big difference—not just for the soil, but for the whole farming system. By not disturbing the soil, its structure stays intact, which helps retain moisture, reduce erosion, and support beneficial organisms like earthworms and microbes (Daryanto et al., 2017). These systems also cut down on the need for fuel and heavy machinery, since fewer field passes are required. That means lower diesel use, less wear and tear on equipment, and a smaller carbon footprint.

Variable Rate Fertilizer (VRF) | Description

Variable Rate Fertilizer (VRF) application is a precision agriculture practice that enables the strategic and efficient use of fertilizers by tailoring input rates to the specific needs of different zones within a cultivated field. This approach is grounded in the analysis of spatial data collected through technologies such as soil sampling, yield mapping, GPS, and remote sensing, which are synthesized into a pre-set field map (Chen et al., 2018). The use of VRF represents a significant shift from uniform fertilizer application methods, promoting both agronomic efficiency and environmental sustainability. By applying fertilizers only in areas, they are needed and in the most appropriate amounts, farmers can significantly reduce the overall volume of fertilizers used. This results in a decrease of the input costs but also minimizes the risk of nutrient leaching, runoff, and soil degradation. Additionally, because the system avoids unnecessary field passes, it leads to a reduction in diesel fuel consumption, thereby decreasing greenhouse gas emissions and operational wear on farm machinery (Hernandez & Mulla, 2008).

Although the adoption of VRF technology requires an initial investment in data collection tools and variable-rate equipment, the long-term benefits include improved crop yields, enhanced soil health, and optimized resource utilization. Over time, variable rate fertilization supports a more sustainable cultivation model by aligning production practices with environmental conservation goals and economic efficiency.

Renewable Energy | Description

Integrating systems that can exploit solar energy into farming land use offers a sustainable way to produce renewable energy while still using the land for agriculture, such as grazing or forage production. The exploitation of solar energy involves installing solar panels above the cultivation, allowing dual use of the area for both energy and food production. This approach helps optimize land use, supports the energy transition, and can contribute to the farm's economic resilience.

3.1.2. Goal and Scope definition

The objective of the assessments conducted (LCA, LCC, and S-LCA) was to evaluate the environmental, economic, and social impact potentials of applying the CSA practices described in subsection3.1.1. in the Lithuanian UC scenario.

Product systems:

Baseline: The baseline scenario across all comparisons was a conventional wheat farm that did not apply any of the CSA practices described. It was located in the southwestern part of Lithuania, cultivating approximately 4 ha predominantly of wheat each year and applying traditional tillage practices involving mechanical ploughing and soil disturbance before seeding.

Extensive Wetland Management (EWM): The product system was a wheat farm that applies extensive wetland management practices. The main processes that were included within the product system were the following: wheat farming utilizing extensive wetland management and field cleaning to prepare the field for the implementation of the selected practice.

Intercropping: The product system was a farm that applies intercropping of pea and wheat. The main processes that were included within the product system were intercropping of pea and wheat in the same field.

No tillage: The product system was a wheat farm that applies no tillage practices. The main processes that were included within the product system were cultivation of wheat without applying any tillage practices.

Variable Rate Fertilization (VRF): The product system was a wheat farm that applies variable rate fertilizer practices. The main processes that were included within the product system were the following: cultivation of wheat utilizing variable rate fertilizer methodology.

Renewable Energy: The product system was a wheat farm that integrates a 32 kW solar panel system to generate renewable energy for on-site use. With any surplus energy supplied to the grid. The main processes that were included within the product system are the following: generation of renewable energy through the solar panels and cultivation of wheat.

Functional unit: The selected functional unit was 1 kg of harvested grains per year

System boundaries: The objective of the study was to compare the application of the CSA practices with conventional farming in wheat cultivation over a period of 1 year. To achieve this, a cradle-to-gate approach was adopted, focusing solely on processes occurring within the farm. More specifically, the boundaries of the system encompass all stages involved in wheat cultivation. Upstream processes related to agricultural inputs (e.g., fertilizers and electricity) were considered, in line with standard LCA methodology, while downstream stages such as processing, packaging, distribution, and consumption were excluded.

Allocation procedures: Since there are no multiple products involved, no allocation was needed.

Environmental impact assessment methodology: ReCiPe 2016 (H, hierarchist) was used in order to convert the LCI data into a set of environmental impact scores using characterization factors which convert emissions and resource use into potential environmental impacts at global or regional scales. Although the system boundaries were cradle-to-gate, these broader-scale impact potentials allow for consistent comparison of environmental burdens across different processes and regions. Detailed description of the method is provided in subsection 2.1.2.

Data requirements: To conduct the LCA analysis, data were gathered through the distribution of questionnaires to relevant Use Case stakeholders, supplemented by data from verified databases such as Ecoinvent, Agri-footprint and Agribalyse, which cover the geographical area of the European Union 28 (EU-28). The collected data refer to the year 2023.

3.1.3. Life Cycle Inventory

The Life Cycle Inventory (LCI), compiled from data collected through interviews and supplemented with relevant literature sources, is summarized in Table 3, with all flows aggregated to 1 ha per year of cultivation as the Reference Flow. The values for the baseline scenario are shown in the second column, while the subsequent columns display the percentage change associated with each CSA practice. For newly introduced parameters, the actual values are presented instead of percentage changes. The results are presented per 1 kg of grains per year, using this as the functional unit. The estimation of the initial emission distribution fractions of the livestock and of the applied chemical agents was based on emission modelling provided in literature (Nemecek et al., 2019).

Parameter	Baseline (BL)	Extensive Wetland Management (EWM)	Intercropping (IC)	No Tillage (NT)	Variable Rate Fertilizer (VRF)	Renewable Energy (RE)
INPUTS						
Land use (ha)	1	1	1	1	1	1
Wheat seeds (kg)	200	200	100	200	200	200
Pea seeds (kg)	-	-	80	-	-	-
Phosphorus fertilizer (kg)	6	-	6	6	-	6
Nitrogen fertilizer (kg)	66	-	66	66	30.6	66
Herbicides (kg)	0.96	-	0.96	0.96	0.96	0.96
Water (m^3)	0.2	-	0.2	-	0.2	0.2
Diesel (L)	92	50	101	78.2	82.9	92
OUTPUTS						
Grains (tonne)	5.025	5.025	5.19	5.025	5.025	5.025
Packaging (waste) (kg)	0.5	-	0.5	0.5	0.5	0.5
Emissions to air						
Herbicides (g)	0.033	-	0.033	0.033	0.033	0.033
Emissions to water						
Herbicides (g)	2.72E-06	-	2.72E-06	2.72E-06	2.72E-06	2.72E-06
Emissions to soil						
Herbicides (g)	222	-	222	222	222	222
AVOIDED PRODUCTS						
Electricity (kWh)	-	-	-	-	-	8000

Table 3: Life Cycle Inventory of a wheat farm – Lithuanian UC. The values are given per ha of land per year (reference flow). "-" indicates zero value.

3.1.4. Environmental Life Cycle Impact Assessment (e-LCIA)

ReCiPe 2016 (H, hierarchist) was applied for the conversion of the LCI data presented in Table 3 into a set of environmental impact potential scores. The results of the baseline scenario have also been updated, using more recent values from the external database sources. The revised values of the 18 midpoint indicators being presented in Table 4. The main midpoint indicators (check Figure 1) that resulted from life cycle impact assessments of the various product systems, as well as their respective percentage differences from the baseline scenario presented in Figure 2.

Impact category	Unit	Value
Global warming	kg CO_2 eq	3.41E-02
Stratospheric ozone depletion	kg CFC11 eq	4.62E-07
Ionizing radiation	kBq Co-60 eq	2.50E-05
Ozone formation, Human health	kg NO_x eq	2.65E-03
Fine particulate matter formation	kg $PM_{2.5}$ eq	8.73E-05
Ozone formation, Terrestrial ecosystems	kg NO_x eq	4.24E-03
Terrestrial acidification	kg SO_2 eq	3.07E-04

Freshwater eutrophication	kg P eq	2.67E-05
Marine eutrophication	kg N eq	1.64E-06
Terrestrial ecotoxicity	kg 1,4-DCB	5.63E-03
Freshwater ecotoxicity	kg 1,4-DCB	1.08E-04
Marine ecotoxicity	kg 1,4-DCB	1.58E-04
Human carcinogenic toxicity	kg 1,4-DCB	3.41E-05
Human non-carcinogenic toxicity	kg 1,4-DCB	1.21E-02
Land use	m^2a crop eq	4.30E-03
Mineral resource scarcity	kg Cu eq	3.02E-05
Fossil resource scarcity	kg oil eq	2.98E-02
Water consumption	m^3	8.48E-05

Table 4: Lithuanian UC Baseline scenario – midpoint impact indicators (FU: 1 kg of grain)

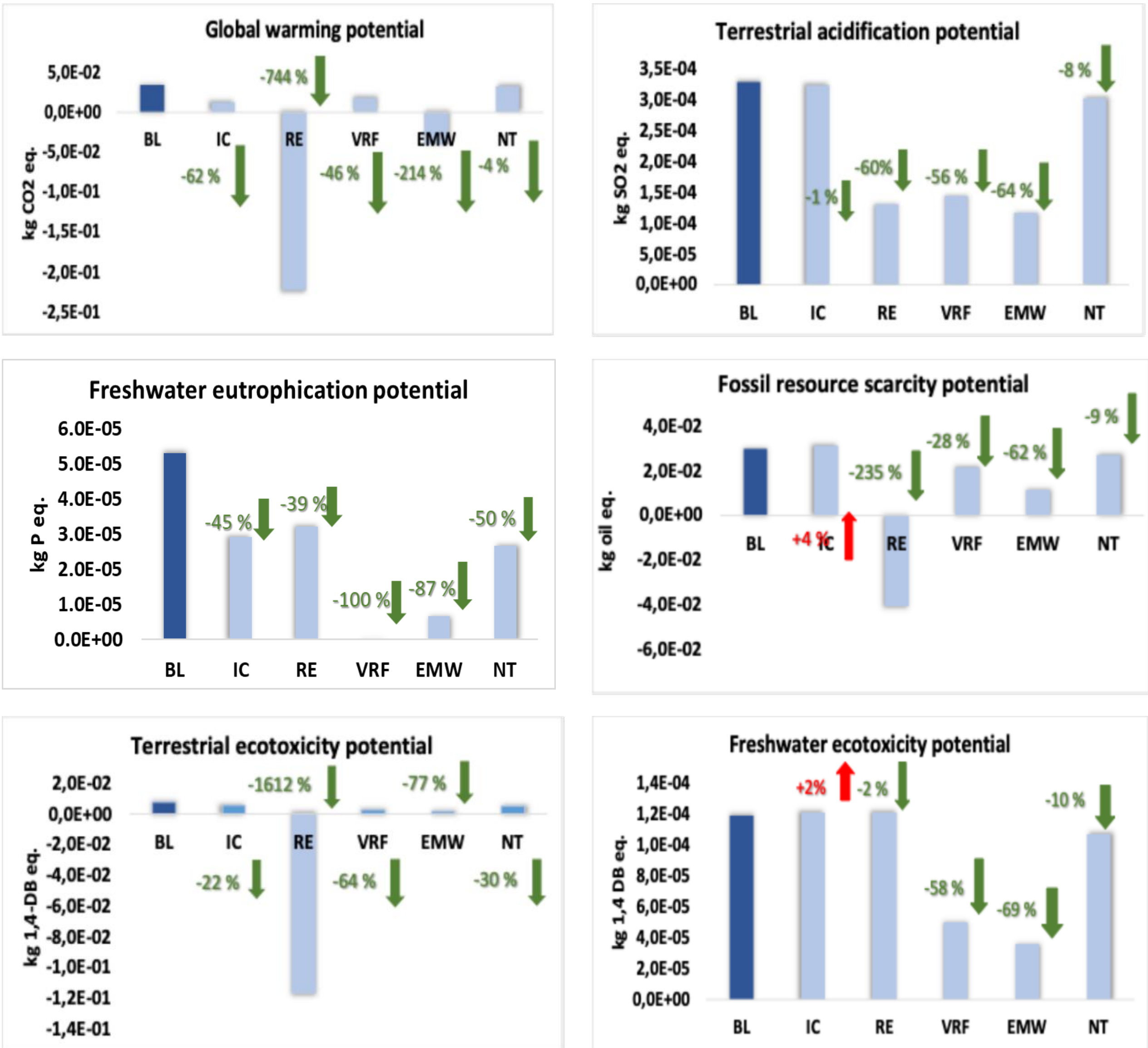


Figure 2: Environmental impact potential comparison of the Lithuanian baseline scenario vs. the different scenarios of the application of CSA practices – selected midpoint impact indicators are

shown per 1 kg of grain. [Scenarios include: BL – Baseline, IC – Intercropping, RE – Renewable Energy, VRF – Variable Rate Fertilizer, EWM – Extensive Wetland Management, and NT – No Tillage].

The LCA conducted for the five different CSA practices applied in wheat farming demonstrated differentiated environmental performance across these scenarios. Each practice contributes uniquely to reducing environmental impact potentials, with some delivering substantial improvements across several midpoint impact categories.

The **Renewable Energy (RE)** scenario demonstrated the most significant environmental improvements across nearly all indicators. The Global Warming Potential (GWP) dropped substantially by 744%, reflecting a significant shift in energy inputs. Additionally, Terrestrial Ecotoxicity Potential decreased by 1612%, while Fossil Resource Scarcity fell by 235%, and Freshwater Eutrophication Potential showed a complete elimination (100% reduction). These results highlight the powerful role of renewable energy integration in reducing environmental burdens. However, modest reductions were seen in Terrestrial Acidification (60%) and Freshwater Ecotoxicity (2%).

Intercropping (IC) presented a moderate environmental benefit, most notably a 62% reduction in GWP and a 45–48% drop in eutrophication and ecotoxicity potentials. However, it was the only scenario where an increase in Fossil Resource Scarcity (4%) and Freshwater Ecotoxicity (2%) was observed, likely due to additional input requirements or management complexity. Nevertheless, it must be noted that apart from the environmental benefits of this specific CSA, intercropping also facilitates the production of crops in pedoclimatic regions that do not favor their cultivation, thus further solidifying its importance as a CSA.

The **Variable Rate Fertilizer (VRF)** strategy led to consistent reductions across most categories, including a 214% improvement in GWP and 87% reduction in Freshwater Eutrophication Potential. Other improvements included 56% in Terrestrial Acidification and 69% in Freshwater Ecotoxicity, suggesting precision nutrient management as a viable tool for mitigating diverse environmental impacts.

Extensive Wetland Management (EWM) also exhibited significant environmental benefits compared to the baseline, with major reductions in Freshwater Eutrophication (87%) and GWP (46%). Improvements were observed across all other indicators as well, reinforcing the ecological benefits of managing wetlands as carbon and nutrient buffers.

The **No Tillage (NT)** approach showed the smallest overall gains, with only slight reductions in GWP (4%), Terrestrial Acidification (8%), and modest declines in Eutrophication (50%) and Ecotoxicity (10–30%). This suggests that while NT offers benefits related to soil structure and erosion, its broader environmental impact may be more limited without accompanying measures.

In summary, the results clearly demonstrated that the integration of CSA practices into a wheat farming system can significantly reduce environmental burdens. Each different CSA practice exhibited its own distinct benefits and sometimes drawbacks; a combined application would had the potential to provide improved benefits, supporting the broader sustainability goals in wheat production.

3.1.5. Life Cycle Cost Analysis (LCC)

A comparative LCC analysis was conducted for the different scenarios, taking into account annual operating costs, annual revenues, any subsidies provided, and any additional capital expenses required for the adoption of CSA practices. The main outputs of the LCC analysis are presented in Table 5.

Intercropping | LCC

The application of the intercropping CSA resulted in an increased requirement for diesel, while new expenses were also observed for the acquisition of pea seeds. On the other hand, a slight decrease in the expenses of the wheat seeds purchase was also observed. As a result, the total revenue of this studied CSA equaled 792 €/ha, compared to the baseline (738 €/ha). Although the increase of the revenue in the CSA was marginal, further optimization of the intercropping technique in terms of the intercrop yield could significantly improve the economic performance..

No Tillage | LCC

In the no tillage CSA, a significant cost was removed, since the farm did not use irrigation water. As a result, the total profit for this specific CSA was 791 €/ha, compared to the 738 €/ha of the baseline.

Variable Rate Fertilizer (VRF) | LCC

In the VRF CSA, a significant amount of fertilizer and diesel was saved, therefore a significant decrease in costs associated with the cultivation of wheat was observed. Therefore, the total profit for this specific CSA was 654 €/ha, compared to the 738 €/ha of the baseline.

Extensive Wetland Management (EMW) | LCC

The utilization of extensive wetland management as a CSA resulted in a significant decrease in all operating expenditures, since the only costs were associated with the field cleaning that required a small quantity of diesel. As a result, the total revenue for this specific CSA was 1,643 €/ha, compared to the 1,285€ of the baseline.

Renewable Energy (RE) | LCC

The average installation cost of the solar panels is 703 €/kW; thus, the CapEx for the installation of the 32 kW solar panel systems was calculated at 22,500€. This cost is supported by the EU Next Generation Funds subsidy scheme. A straight-line depreciation method was assumed for the cost that was not covered by the subsidy scheme (10500€), with a depreciation period of 25 years. The produced energy that was not consumed within the farm system was assumed to be sold to the grid for 0.3€/kWh. As a result, the total revenue for this specific CSA was 1,357 €/ha.

Cost category (€/ha/year)		Baseline	Intercropping	No Tillage	Variable Rate Fertilizer	Extensive Wetland Management	Renewable Energy
EXPENSES	Diesel	€ 141.31	€ 107.52	€ 105.98	€ 141.31	€ 76.8	€ 141.31
	Water	€ 0.02	€ 0.02	-	€ 0.02	-	€ 0.02
	Wheat seeds	€ 188	€ 180	€ 188	€188	€ 188	€ 188
	Fertilizers	€ 26.04	€ 68	€ 26.04	€ 3.6	-	€ 26.04
	Herbicides	€ 5.44	-	€ 5.44	€ 5.44	-	€ 5.44
	Other general costs	€10.82	€ 26.87	€ 9.76	€ 10.15	€ 7.94	€ 10.82
	Equipment use/maintenance	€ 175	€ 175	€ 225	€ 226.86	€ 175	€ 179.86
	Equipment depreciation (5 years)	-	-	-	€ 55.96	-	€ 51.79
	Total	€ 546.64	€ 567.41	€ 560.23	€ 631.34	€ 453.18	€ 603.28
RE	*Change over BL:*	-	1.97%	2.49%	15.49%	-17.1%	10.36%
	Wheat grains	€ 1135	-	€ 1135	€ 1135	1135	€ 1135

Grains-Peas	-	€ 1199.22	-	-	-	-
Subsidies	€ 150	€ 150	€ 216	€ 150	€ 208	€ 150
Other	-	-	-	-	€ 300	-
Electricity	-	-	-	-	-	€ 71.43
Total	€ 1285	€ 1349.22	€ 1351	€ 1285	€ 1643	€ 1356.53
Change over BL:	-	5.00%	5.14%	-	27.86%	5.57%
Profit	€ 738.36	791.81	€ 790.77	€ 653.66	€ 1189.82	€ 753.25

Table 5: Comparative LCC analysis (annual basis) of the baseline scenario and the different CSA practices for the Lithuanian UC.

3.1.6. Social Life Cycle Impact Assessment (s-LCIA)

The production flows and relevant inventory data of all the examined Lithuanian CSA scenarios were taken from the resulting LCIAs shown in Table 3. According to the received questionnaire, the data inputs for most of the impact factors of the CSAs were similar to the baseline scenario and thus were directly taken from Table 11 of the previous D3.1. These included the "Worker hours" activity variable and the impact factors with their associated risk levels. The only exception was the intercropping scenario, which was recalculated based on a slightly increased production of 5.19 tonnes, and the "Sector average wage per month", "Hours of work per employee per week", "Women in the sectoral labor force", "Men in the sectoral labor force", "Gender wage gap", "Membership for social responsibility along the supply chain", "Certified Environmental Management Systems", "International migrant workers in the sector", "Embodied agricultural area footprints", "Embodied water footprints", "Embodied CO_2eq footprints" and "Embodied Value Added" impact factors, for which their values were reassessed, according to the received questionnaire data for each CSA. The changes to the data inputs, with regards to the baseline scenario described in the 2024 D3.1, are summarized in Table 6 below:

Input	Baseline	No tillage	Renew-able energy	Inter-crop-pping	EWM	VRF
Worker hours[6]	0.3804	0.3804	0.3804	0.3683	0.3804	0.3804
Sector average wage, per month	Medium	High	Low	High	Low	Medium
Hours of work per employee, per week	Medium	Low	Low	High	High	Medium
Women in the sectoral labor force	Very High	Very High	Medium	No Risk	Very High	Very High
Men in the sectoral labor force	No Risk	No Risk	Medium	Very High	No Risk	No Risk
Gender wage gap	No Data	No Data	No Risk	No Data	No Data	No Data
Membership for social responsibility along supply chain	Very High	Very High	Very Low	Very High	Very Low	Very High

[6] Activity variable as defined in SOCA methodology, calculated by unit labour costs and hourly labour costs.

Input	Baseline	No tillage	Renew-able energy	Inter-crop-pping	EWM	VRF
Certified Environmental Management Systems	Very High	Very Low	Very Low	Very Low	Very Low	Very High
International migrant workers in the sector	Very Low	Very Low	Medium	Very Low	Very Low	Very Low
Embodied agricultural area footprints	High	High	High	High	High	High
Embodied water footprints	Very low	No Risk	Very low	Very low	No Risk	Very low
Embodied CO_2eq footprints	Medium	Medium	Medium	Medium	Medium	Medium
Embodied Value Added	Medium	Medium	High	Very High	Very Low	Medium

Table 6: Deviations from the input of s-LCIA data, compared to the baseline scenario for Lithuania, from the 2004 D3.1. The impact factors not shown here remained unchanged and thus were taken directly from the baseline scenario, as presented in Table 11 of the 2024 D3.1).

The results from the s-LCIA analyses for all the examined CSA scenarios are shown in Figure 3 below. Along with the studied CSAs, the results of the baseline scenario have also been updated due to database updates (ILO, WHO etc.) that changed the risk levels of some impact factors. A more detailed analysis of each CSA examined is given below. Generally, the results were in line with the changes of the LCI. However, some of the impact factors resulted in high social footprints, despite the fact that they had very low-medium risks. This was found for all examined CSAs and the baseline scenario as well, and was attributed to impacts from upstream flows. More specifically, for the baseline scenario, most impactful flows were the ones related with the production and use of diesel on a global scale, followed by production of wheat seeds and production & use of chemicals. Any CSA that contributed a positive change to the above resulted in reduced impacts.

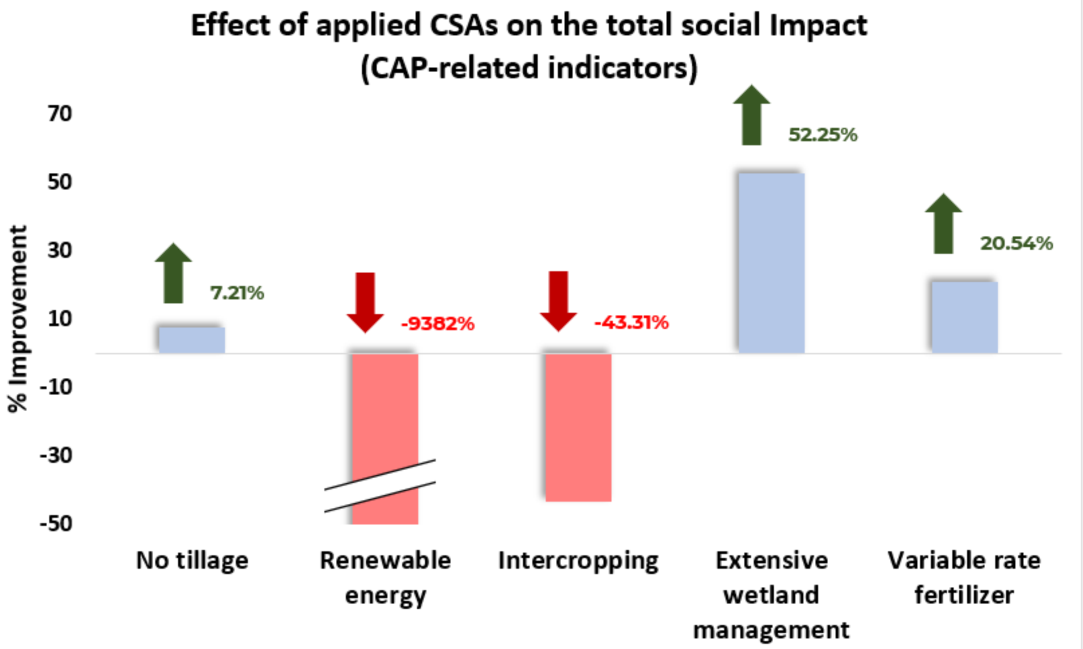


Figure 3: Comparison of the changes in the social impacts from the investigated CSAs, regarding the EU CAP-relevant social indicators – impacts per ha per year (Lithuanian UC) (0 value represents the baseline - note that for the alternative green energy scenario, the actual bar exceeds below the scale of Y-axis).

No Tillage | s-LCIA

Beginning with the no tillage scenario, this one performed slightly better than the baseline scenario, resulting in a 9% decrease in total DALYs. This result was expected, as the anticipated changes were mostly based on changes in the LCI and close to baseline scenario. Focusing on the CAP-relevant indicators that are more in accordance with the BEATLES project, the no tillage scenario resulted in 7% reduced social footprints. The 4 most important factors were the Fair Salary, followed by Embodied Biodiversity Footprints, GHG Footprints and Unemployment rate. Notably, the most impactful flows of the no tillage scenario followed the ones from the baseline scenario, and as a result, the slight reduction of the social footprints is attributed mostly to the slight reduction of the amount of diesel used.

Renewable Energy | s-LCIA

Moving on to the renewable energy scenario, this one performed much worse than the baseline scenario, resulting in ~110x more DALYs in total. This result was not expected, as the anticipated changes only included the flows relative to the renewable energy system. Focusing on the CAP-relevant indicators that are more in accordance with the BEATLES project, the renewable energy scenario resulted in ~94x increased social footprints. The 4 most important factors were the Fair Salary, followed by Embodied Biodiversity Footprints, GHG Footprints and Industrial water depletion. As a result, the renewable energy scenario resulted in significantly higher social impacts than the baseline scenario, due to the impacts associated with the production and installation of the renewable energy system on global scale (solar panels, mounting system, inverter).

Intercropping | s-LCIA

Subsequently for the intercropping scenario, this one performed slightly worse than the baseline scenario, resulting in a 13% increase in total DALYs. This result was expected, due to some changes to the impact factors, the "Worker hours" activity variable (meaning that the same amount of effort from workers, who were paid similarly with the baseline scenario, produce slightly more product - 5.190tn instead of 5.025tn) and changes in the LCI. Focusing on the CAP-relevant indicators that are more in accordance with the BEATLES project, the intercropping scenario resulted in 43% increased social footprints. The 4 most important factors were the Fair Salary, followed by Embodied Biodiversity Footprints, GHG Footprints and Embodied Water Footprints. As a result, the increase of the social footprints is attributed mostly to the slight increase of the amount of diesel used, as well as the increased Embodied Water Footprints of the pea seeds.

Extensive Wetland Management (EWM) | s-LCIA

Moving on to the extensive wetland management scenario, this one performed better than the baseline scenario, resulting in a 42% decrease in total DALYs. This result was expected, since the inputs of some impact factors were improved, as well as several impactful flows were absent, as presented in LCI (e.g. fertilizers, herbicides, emissions, reduced diesel etc.). Focusing on the CAP-relevant indicators that are more in accordance with the BEATLES project, the EWM scenario resulted in 52% reduced social footprints. The 4 most important factors were the Fair Salary, followed by Embodied Biodiversity Footprints, GHG Footprints and Unemployment rate. As a result, the reduction of the social footprints is attributed mostly to the reduction of the amount of diesel used (~45% less) and the absence of chemicals.

Variable Rate Fertilizer | s-LCIA

Finally, for the variable rate fertilizer scenario, this one performed slightly better than the baseline scenario, resulting in a 12% decrease in total DALYs. This result was expected, as the anticipated changes were mostly based on changes in the LCI. Focusing on the CAP-relevant indicators that are more in accordance with the BEATLES project, the VRF scenario resulted in 21% reduced social footprints. The 4 most important factors were the Fair Salary, followed by Embodied Biodiversity Footprints, GHG Footprints and Unemployment rate. As a result, the reduction of the social footprints is attributed mostly to the slight reduction of the amount of diesel and fertilizers used.

Conclusions | s-LCIA

According to the results from the s-LCIA analyses, from the social impact perspective, the best results were acquired from the extensive wetland management scenario (52% reduced footprints), followed by variable rate fertilizer (21% reduced footprints). No tillage scenario performed slightly better than the baseline one (7% reduced footprints) and can be considered in case the improvement of the social footprints is a secondary objective of the transition-to-CSA strategy. On the other hand, intercropping and especially renewable energy scenarios were found to bear significantly increased social footprints (43% and ~95x increased footprints respectively) and as such, it is suggested that they will be examined as secondary options, in case the previous ones do not fulfil the needs of the transition-to-CSA strategy. Particularly for the renewable energy scenario, it's worth reminding that the increased social footprints were attributed to the production stage of the solar panels in global scale (as noted above) and are not associated with their use in the farm, nor their impact in local communities and/or workers.

3.1.7. Cost-Benefit Analysis

CSA	Costs	Benefits		
		Environmental	Economic	Social
No Tillage	No irrigation infrastructure or water costs Reduced OpEx : 680 €/ha	↓ GWP by 4% ↓ Terrestrial acidification by 8% ↓ Eutrophication by 50% ↓ Ecotoxicity by 10–30%	20% less diesel use (↓ operating fuel costs) Reduced production costs by 4% ↑ Revenue: €791/ha, increased compared to baseline CAP subsidy: additional €66/ha for eco-scheme Reduced fuel and labor costs improve cost-efficiency	Reduced labor time by 30% ↓ Total DALYs by 9% ↓ Social footprint by 7% Major impact areas: Fair Salary, GHG Footprints, Unemployment, Biodiversity
Intercropping	↑ Diesel use ↑ Pea seed costs ↓ Slight wheat seed costs ↑ Total DALYs by 13% ↑ Social Footprints by 43% ↑ Embodied Water Footprints (pea seeds) Risks from diesel, pea seed, and chemical production	↓ GWP by 62% ↓ Eutrophication by 45–48% ↓ Ecotoxicity by 45–48%	Long-term yield potential in marginal/ pedoclimatically poor areas ↑Revenue: 792 €/ha vs. 738€/ha to baseline	-

CSA	Costs	Benefits		
		Environmental	Economic	Social
VRF	Opex ~ 900€/ha, slightly reduced due to less diesel & fertilizers No additional CapEx required	↓ GWP by 214% (relative score improvement, due to reduced fertilizer and fuel use. ↓Freshwater eutrophication potential by 87%, due to precise fertilizer application & reduced nutrient runoff. ↓ Terrestrial Acidification by 56%, due to lower nitrogen-based emissions. ↓ Freshwater Ecotoxicity by 69%, due to reduced chemical inputs.	↑ Revenues: €654/ha. Lower input costs improved profit margins despite similar crop yield levels. ↓ Fertilizer and diesel input costs. Efficient resource use directly cut variable production costs.	↓ DALYs by 12%, due to lower emissions and chemical exposure, improving overall health impacts in the supply chain. ↓ Social footprints by 21%, Efficiency gains led to less upstream environmental and social pressure.
EWM	Minimal cost for field cleaning diesel only 45% less diesel costs compared to baseline	↓ Freshwater eutrophication, 87%: Wetlands act as nutrient sinks, filtering runoff before it reaches water bodies. ↓ GWP, 46%: Due to reduced emissions from avoided fertilizer, diesel, and chemical use.	Net profit increased to ~1200 €/ha due to low input costs. OpEx costs reduced to ~450€/ha, due to decreased fertilizer, irrigation, or chemical use.	↓ Total DALYs, 42%: Lower emissions and chemical use reduced health risks throughout the supply chain. ↓ Social footprint, 52%: Reflecting significant gains across key indicators like Fair Salary and GHG Footprints. Minimal upstream impacts: Reduced diesel and elimination of chemicals decreased global-scale life cycle risks.

CSA	Costs	Benefits		
		Environmental	Economic	Social
Renewable Energy	CapEx of 22,500 € for a 32 kW solar panel system. 10,500 € depreciated over 25 years (after subsidy) High upstream impacts from PV production and installation ↑ Social footprint (~95x) and ↑ DALYs (~110x): Mainly due to upstream impacts of manufacturing the solar system. Main impacts linked to solar panel, inverter, and mounting system production globally	↓ GWP by 744%: Drastic reduction due to solar replacing fossil-based energy sources. ↓ Terrestrial Ecotoxicity by 1612%, due to avoidance of emissions from fossil fuel use. ↓ Fossil Resource Scarcity by 235%: Solar energy reduced dependency on fossil fuels. ↓ Freshwater Eutrophication by 100%: Renewable system eliminated key pollutant emissions.	Additional income from selling surplus electricity to grid at €0.3/kWh Total revenue increased to 1357€/ha, rising from baseline: Driven by electricity sale and lower energy costs.	-

Table 7: Summary of Cost – Benefit Analysis for the CSA practices in the Lithuanian UC

The comparative analysis of sustainable agricultural practices reveals varied cost, environmental, economic, and social implications across five scenarios: no tillage, intercropping, variable rate fertilization (VRF), extensive wetland management (EWM), and renewable energy integration. No tillage stood out for its cost-efficiency due to the elimination of water and irrigation infrastructure and reduced operational expenses (OpEx of 680 €/ha). These cost savings, combined with a 66 €/ha CAP eco-scheme subsidy and a 20% reduction in diesel usage, led to a 50% revenue increase over the baseline. Socially, this practice resulted in notable improvements such as a 9.45% reduction in DALYs and a 7.21% decrease in the social footprint, driven primarily by reduced fossil fuel consumption.

In contrast, intercropping—while environmentally beneficial—was economically and socially burdensome in the short term. Despite significant reductions in global warming potential (62%), eutrophication (45–48%), and ecotoxicity, its higher diesel use and the cost of pea seeds led to a sharp drop in revenue (20 €/ha) and increased social impacts (43% rise in social footprint, 13% increase in DALYs). The environmental benefits were overshadowed by upstream burdens from seed and diesel production, suggesting that while intercropping may be promising in marginal areas, its practical application requires optimization in input management and yield stability.

The VRF scenario demonstrated balanced sustainability across all three pillars. A moderate decrease in OpEx (~900 €/ha) and savings from more efficient fertilizer and diesel usage contributed to a 12.03% profit increase (390 €/ha). Environmentally, it achieved major reductions in greenhouse gas emissions and acidification potential, thanks to precise nutrient management. Social outcomes were similarly positive, including a 20.54% reduction in social footprints and a nearly 12% decrease in DALYs. It also supported fair wages and job stability through demand for skilled labor in precision agriculture.

EWM emerged as a highly sustainable natural solution, with the lowest OpEx (~450 €/ha) and the highest net profit (~1200 €/ha). It required minimal inputs, using natural wetland functions to mitigate nutrient runoff and reduce emissions. Environmental improvements included an 87% reduction in freshwater eutrophication and a 46% drop in global warming potential. Social benefits were equally strong, with a 42% reduction in DALYs and a 52% decrease in social footprint, driven by the near-complete elimination of chemical inputs and fossil fuel dependency.

Finally, the renewable energy scenario demonstrated exceptional environmental (3241% drop in global warming potential, 100% reduction in eutrophication) and economic outcomes (2600 €/ha revenue) through the adoption of a 32 kW solar panel system. However, the social footprint spiked due to the upstream impacts of photovoltaic infrastructure production, increasing DALYs and social burden drastically. This highlights the importance of ethical sourcing and supply chain transparency in renewable energy deployment. Overall, while all scenarios contribute to climate-smart agriculture, their success hinges on context-specific trade-offs between environmental goals, financial viability, and social responsibility.

3.2. Use Case Pilot #2: Organic dairy farming, Germany

3.2.1. Description of the CSA practices

Naturland farming | Description

Dairy farming requires substantial quantities of high-quality animal feed in order to assure the well-being of the livestock. The utilization of organic farming in the dairy farm involves a holistic approach that aligns animal husbandry with environmentally sustainable agricultural practices. Organic dairy farming emphasizes ecosystem health, soil fertility, and animal welfare while reducing dependency on synthetic inputs (Akintan et al., 2025). One of the key shifts in organic dairy farming is the substitution of conventional feed with organically cultivated alternatives, such as peas, which offer a sustainable and protein-rich source of nutrition for livestock. Peas can be grown without synthetic fertilizers or pesticides, making them an ideal crop within organic crop rotation systems that enhance soil structure and biodiversity.

However, organic dairy farms often utilize larger cultivation areas to compensate for the lower productivity associated with organic crop inputs. This extended land use allows for greater pasture availability, which not only supports the natural grazing behavior of the livestock but also contributes to soil regeneration, carbon sequestration, and water conservation (Nicholas et al., 2004). Manure from the cows is typically recycled as compost or organic fertilizer, closing nutrient loops and minimizing environmental impact.

The shift to “naturland” farming can initially result in lower yields in the final products, such as milk, however, once the system is fully established, naturland can result in products of higher quality compared to conventional methods.

Forage & Clover | Description

Forage and clover rely entirely on the utilization of grassland to provide the required amount of forage feed and represents a highly sustainable approach to dairy farming. Feed conversion excludes the usage of conventional and processed animal feed and instead focuses on grazing systems where livestock can obtain their nutrition directly from pasture. By shifting to 100% forage-based diets, farmers can significantly reduce environmental impacts associated with feed production, such as deforestation, fertilizer runoff, and fossil fuel use for feed transport and processing (Moorby & Fraser, 2021).

Grassland-based feeding systems rely on natural pastures to provide the necessary feed for the animals, without using synthetic fertilizers. Instead, the livestock’s manure naturally returns nutrients to the soil, helping plants grow and keeping the land healthy. This process reduces the need for chemical inputs, lowers costs, and supports a variety of plant and animal life by maintaining native grasses and their ecosystems. Grasslands also store carbon in the soil, which helps reduce greenhouse gases and fight climate change.

While these systems may need more land than conventional feed methods, they provide several advantages. Livestock can move freely and graze as they would naturally, which improves their well-being, while the final products often exhibit better nutritional quality, including more healthy fats. Grazing systems also lower the risk of health problems in the livestock that can result from high-energy, grain-based diets.

Regional Protein | Description

The inclusion of regional protein sources into dairy farming is a strategic move toward greater sustainability and self-sufficiency. The substitution of imported animal feed with locally-sourced alternatives, can result in a significant decrease in the environmental footprint of the dairy farm, while simultaneously supporting local agriculture and economies (Lehuger et al., 2009).

Additionally, locally-sourced protein feed, such as peas, and regionally grown grains offer a viable alternative to imported soy or corn-based feeds. These crops can be integrated into existing crop rotations, improving soil fertility and enhancing biodiversity. Additionally, regional protein sources are often better suited to the local climate and soil conditions, requiring fewer external inputs and increasing overall farm resilience. Finally, the adoption of regional protein as animal feed contributes to improved traceability and transparency in the food supply chain, allowing farmers and consumers to make informed decisions about sustainability and feed origin.

Breeding | Description

Breeding for longevity in dairy cows is an effective way to reduce greenhouse gas (GHG) emissions and improve overall farm sustainability. By selecting cows that live longer and stay productive for more years, farmers can increase the total amount of milk each cow produces in their lifetime. This means that the environmental burden of raising the feedstock, including the GHGs emissions before they start producing milk, is spread over more quantities of produced milk, lowering emissions per kilogram of milk (De Vries & Marcondes, 2020).

Longer-living cows also tend to be healthier and more robust, which benefits animal welfare. Breeding for longevity focuses less on maximum short-term milk yield and more on traits like disease resistance, fertility, and strong body structure. As a result, cows have fewer health issues and require less veterinary care or early replacement, reducing both environmental and economic costs.

Land Use (Agrophotovoltaic Systems) | Description

Integrating agrophotovoltaic (APV) systems into dairy farm land use offers a sustainable way to produce renewable energy while still using the land for agriculture, such as grazing or forage production. APV involves installing solar panels above farmland, allowing dual use of the area for both energy and food production. This approach helps optimize land use, supports the energy transition, and can contribute to the farm's economic resilience.

Dairy farms have two main options for implementing APV systems. One option is to rent out land to external energy companies, which install and manage the solar infrastructure. This model requires no capital investment from the farm and provides a stable additional income through lease agreements, making it a low-risk and accessible way to benefit from renewable energy.

Alternatively, the farms can choose to install and operate the APV systems themselves. This route involves significant capital (CAPEX) and operational expenditures (OPEX), including equipment, installation, and maintenance. However, it offers long-term benefits, such as lower electricity costs, energy independence, and the opportunity to sell surplus energy back to the grid—creating a new revenue stream and enhancing sustainability.

Both models can improve land-use efficiency and reduce the carbon footprint of the dairy farm, but the best choice depends on the farm’s financial resources, risk tolerance, and long-term strategic goals.

3.2.2. Goal and Scope definition

The objective of the assessments conducted (LCA, LCC, and S-LCA) was to evaluate the environmental, economic, and social impact potentials of applying the CSA practices described in subsection3.2.1. in the German UC scenario.

Product systems

Baseline: The product system is a representative conventional dairy farm in the Bavaria region, that focuses on milk production, with an average of 60 cows replaced each year. Moreover, the dairy farm produces significant other co-products, including calves and beef meat and does not apply any of the CSA practices studied.

Naturland Farming: The product system was a dairy farm that applies organic farming practices. Therefore, the synthetic fertilizers were replaced by equivalent amounts derived from organic sources (manure). No other chemical agents were utilized and the electricity consumption remained the same as the conventional dairy farm. The scenario covered the initial years of the farm's transition to organic farming; therefore, the annual yield of the produced milk was lower

(7000 L/cow compared to 8000 L/conventional cow), while the other products remained the same. The main processes that were included within the product system were the following: on-farm feed production, feeding and livestock management.

Forage & Clover: The product system was a dairy farm that applies feed conversion and especially utilization of grassland to provide the required amount of forage feed in a dairy farm the main processes that were included within the product system were the following: on-farm feed production, feeding and livestock management.

Regional Protein: The product system was a dairy farm utilizing locally sourced and produced animal feed. The main processes that were included within the product system were the following: on-farm feed production, feeding and livestock management.

Breeding: The product system was a dairy farm that utilizes breeding.The main processes that were included within the product system were on-farm feed production, feeding and livestock management.

Land Use: The product system was a conventional dairy farm that rents a portion of its land to external facilitators to install agrophotovoltaic system and produce renewable energy. The main processes that were included within the product system were the following: on-farm feed production, feeding and livestock management.

Functional unit: The selected functional unit was 1 cow.

System boundaries: The objective of the study was to compare the application of the CSA practices with conventional dairy farming over a period of 1 year. To achieve this, a cradle-to-gate approach was adopted, focusing solely on processes occurring within the dairy farm. More specifically, the boundaries of the system encompassed all the stages from the cultivation of animal feed till the acquisition of the final products. Upstream processes related to agricultural inputs (e.g., fertilizers and electricity) were considered, in line with standard LCA methodology, while downstream stages such as processing, packaging, distribution, and consumption were excluded.

Allocation procedures: Since the main purpose was to compare the environmental performance of organic farming to conventional dairy farming and the products remained the same, no allocation was needed.

Environmental impact assessment methodology: ReCiPe 2016 (H, hierarchist) was used in order to convert the LCI data into a set of environmental impact scores using characterization factors which convert emissions and resource use into potential environmental impacts at global or regional scales. Although the system boundaries were cradle-to-gate, these broader-scale impact potentials allow for consistent comparison of environmental burdens across different processes and regions. Detailed description of the method is provided in subsection 2.1.2.

Data requirements: To conduct the LCA analysis, data were gathered through the distribution of questionnaires to relevant Use Case stakeholders, supplemented by data from verified databases such as Ecoinvent, Agri-footprint and Agribalyse, which cover the geographical area of the European Union 28 (EU-28). The collected data refer to the year 2023.

3.2.3. Life Cycle Inventory

The Life Cycle Inventory (LCI), compiled from data collected through interviews and supplemented with relevant literature sources, is summarized in Table 8, with all flows aggregated to 1 cow per year as the Reference Flow. The values for the baseline scenario are shown in the second column, while the subsequent columns display the values associated with each CSA practice. For newly introduced parameters, the actual values are presented instead of percentage changes. The results are presented per cow, using this as the functional unit. The estimation of the initial emission distribution fractions of the livestock and of the applied chemical agents was based on emission modelling provided in literature (Nemecek et al., 2019).

Parameter	Baseline (BL)	Naturland farming (NL)	Forage & Clover (F&C)	Regional protein (R.PR)	Breeding (BR)	Land use (LU)
INPUTS						
Cow (piece)	1	1	1	1	1	1
Land use (ha)	45	44.84	55.7	40	45	40
Maize sillage (tonne)	6.07	3.73	-	6.07	6.07	6.07
Grassland silage (tonne)	0.67	0.67	-	0.434	0.67	0.67
Soybeans (tonne)	1.17	-	-	1.17	1.02	1.17
Grain & catch crio (tonne)	1.52	1.52	-	1.52	-	1.52
Grain (tonne)	1.87	1.87	-	1.87	1.87	1.87
Peas (tonne)	-	0.435	-	-	-	-
Grass, produced in farm (tonnes)	-	-	11.3	-	-	-
Phosphorus fertilizer (kg)	22.3	-	22.3	22.3	22.3	22.3
Potassium fertilizer (kg)	29.1	-	29.1	29.1	29.1	29.1
Nitrogen fertilizer (kg)	108	-	108	108	108	108
Water (m^3)	30	30	30	30	30	30
Electricity (kWh)	400	400	400	400	400	400
OUTPUTS						
Milk (kg)	8000	7000	8000	8000	8000	8000
Meat (kg)	150	150	150	150	150	150
Calves (piece)	1.06	1.06	1.06	1.06	1.06	1.06
Cow (piece)	0.26	0.26	0.26	0.26	0.26	0.26
Emissions to air						
Ammonia (kg)	29.8	29.8	29.8	29.8	29.8	29.8

Parameter	Baseline (BL)	Naturland farming (NL)	Forage & Clover (F&C)	Regional protein (R.PR)	Breeding (BR)	Land use (LU)
Methane (biotic) (kg)	99	99	99	99	99	99
Nitrogen oxides (kg)	82.1	82.1	82.1	82.1	82.1	82.1
Carbon dioxide, fossil (kg)	1.81	1.81	1.81	1.81	1.81	1.81

Table 8: Life Cycle Inventory of a dairy farm – Germany UC. The values are given per cow per year (reference flow). "-" indicates zero value.

3.2.4. Environmental Life Cycle Impact Assessment (e-LCIA)

ReCiPe 2016 (H, hierarchist) was applied for the conversion of the LCI data presented in Table 8 into a set of environmental impact potential scores. The results of the baseline scenario have also been updated, using more recent values from the external database sources. The revised values of the 18 midpoint indicators being presented in Table 9. The main midpoint indicators (check Figure 1) that resulted from life cycle impact assessments of the various product systems, as well as their respective percentage differences from the baseline scenario presented in Figure 4.

Impact category	Unit	Value
Global warming	kg CO_2 eq	4200.54
Stratospheric ozone depletion	kg CFC11 eq	0.01
Ionizing radiation	kBq Co-60 eq	4.58
Ozone formation, Human health	kg NO_x eq	364.10
Fine particulate matter formation	kg $PM_{2.5}$ eq	9.45
Ozone formation, Terrestrial ecosystems	kg NO_x eq	585.93
Terrestrial acidification	kg SO_2 eq	72.08
Freshwater eutrophication	kg P eq	0.08
Marine eutrophication	kg N eq	0.79
Terrestrial ecotoxicity	kg 1,4-DCB	148.61
Freshwater ecotoxicity	kg 1,4-DCB	1.41
Marine ecotoxicity	kg 1,4-DCB	1.82
Human carcinogenic toxicity	kg 1,4-DCB	0.23
Human non-carcinogenic toxicity	kg 1,4-DCB	1982.79
Land use	m^2a crop eq	11271.37
Mineral resource scarcity	kg Cu eq	12.03
Fossil resource scarcity	kg oil eq	263.55
Water consumption	m^3	7.89

Table 9: German UC Baseline scenario – midpoint impact indicators (FU: 1 cow)

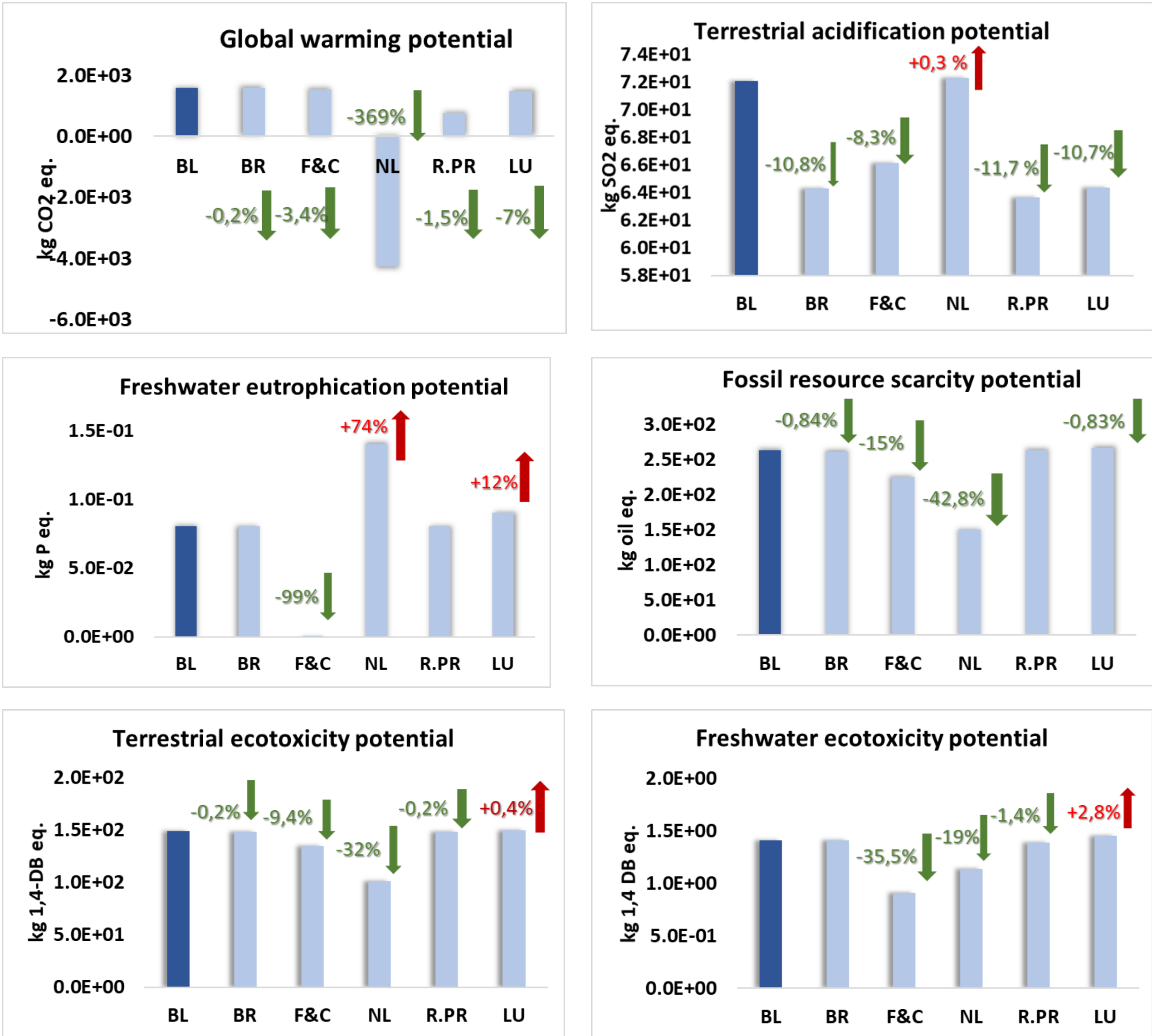


Figure 4: Environmental impact potential comparison of the German baseline scenario vs. the different scenarios of the application of CSA practices – selected midpoint impact indicators are shown per 1 cow. [Scenarios include: BL – Baseline, BR – Breeding, F&C – Forage & Clover, NL – Naturland Farming, R.PR – Regional Protein, and LU – Land Use].

The LCA conducted for the five different CSA practices applied in dairy farming demonstrated differentiated environmental performance across these scenarios. Each practice contributes uniquely to reducing environmental impact potentials, with some delivering substantial improvements across several midpoint impact categories.

The **naturland farming** scenario presented a complex environmental profile. The exclusion of synthetic fertilizers results in a significant decrease in the GWP potential (367%) compared to the baseline. Similarly, a significant decrease in the values of terrestrial ecotoxicity and fossil resource scarcity is observed, with the values rising up to 32% and 43%, respectively. On the other hand, the inclusion of peas as animal feed leads to a significant increase in the value of freshwater eutrophication potential, possibly due to the necessity of organic fertilizers in the production of peas.

The adoption of **forage & clover** led to several positive environmental impacts, particularly in freshwater eutrophication potential, which was reduced by up to 99% due to the fact that all animal feed components are excluded from the farm and the farm solely relies on grass consumption. Terrestrial acidification potential decreased by 8% across, and substantial improvements were also observed in ecotoxicity indicators, attributed to the exclusion of conventional animal feed components from the boundaries of the dairy farm. Finally, a slight decrease (3.2%) in GWP was also observed in the adoption of the feed conversion CSA.

The implementation of **regional protein** exhibited a slight environmental improvement compared to the baseline, with the GWP and the terrestrial acidification potential values decreasing by 2% and 12%, respectively. On the other hand, all other studied midpoints exhibited values that were similar to the ones obtained in the baseline.

Breeding exhibited a similar environmental performance as the CSA of regional protein, meaning that a slight improvement to the baseline was observed. This is mainly attributed to the fact that compared to the baseline the inputs and outputs of the system do not change significantly. However, breeding can result in the acquisition of high-quality final products, with this improvement being difficult to highlight from an environmental point of view.

The **Land Use** CSA scenario exhibited a mixed environmental performance across categories. The scenario achieves a notable 7% reduction in Global Warming Potential (GWP) compared to the baseline, indicating improved carbon efficiency. Additionally, a significant improvement in terrestrial acidification potential (10.7%) is observed. However, other indicators reveal less favorable outcomes, with the Freshwater Eutrophication Potential increasing by 12%, and Freshwater Ecotoxicity Potential rising by 3%.

In summary, the results clearly demonstrate that the integration of CSA practices into a dairy farming system can significantly reduce environmental burdens. Each different CSA practice has its own distinct benefits and sometimes drawbacks; a combined application would have the potential to provide improved benefits, supporting the broader sustainability goals in dairy farming.

3.2.5. Life Cycle Cost Analysis (LCC)

A comparative LCC analysis was conducted for the different scenarios, taking into account annual operating costs, annual revenues, any subsidies provided, and any additional capital expenses required for the adoption of CSA practices. The main outputs of the LCC analysis are presented in Table 10. It must be noted that in all studied CSAs, CAPEX was not required since for their implementation the purchase and installation of new equipment was not necessary. The **Naturland farming** resulted in an increased requirement for cultivation area, which resulted in an increase in costs associated with land rent compared to the baseline (274 €/cow*yr vs 203 €/cow*year). However, the decrease in the acquisition of external animal feed due to the organic farming resulted in a decrease in the animal feed expenditures, decreasing from 808 to 662 €/cow*yr. Additionally, heifer-related costs reduced significantly from 929 € to 576 € per cow, a 38% decrease. Based on the aforementioned observations, the total OpEx was ~5,000€/cow*yr income of the organic/naturland farming CSA was 5400 €/cow*yr, which constituted a 6% decrease compared to the baseline. A slight decrease in milk yield in the current scenario led also to a 0,7% decrease in revenues; the combination of the above changes resulted in a 4x increase in the profit of the farm per year. In the scenario of feed partial substitution with **forage and clover**, all animal feed was directly derived from the farm, therefore all associated expenses were eliminated. Therefore, the total revenue for this specific CSA remained at 5,400 €/cow*yr, whereas the OpEx was reduced to 5,270 €/cow*yr, leading to an increased average profit of 130€/cow*yr. In the scenario of **regional protein**, a significant amount of imported animal feed was replaced with locally sourced alternatives (~1.3%). Therefore, a significant decrease in costs associated with the feeding of the livestock was observed. The total revenues for this specific scenario remained at 5,400 €/cow*yr, whereas the OpEx was reduced to 5,230 €/cow*yr, leading to an increased average profit of 170€/cow*yr. The efficient utilization of **breeding** as a CSA practice resulted in an extended life expectancy of livestock, as well as in final products of higher quality compared to the conventional dairy farm. The farm expenses remained stable, whereas the sale of excess heifers created a new source of income, bringing in 292 €/cow*yr. As a result, the total revenue for this specific CSA was 5,700 €/cow*yr, which constituted a 5% increase compared to the baseline. In the **land use** CSA practice, a portion of the farm's land was rented to an external company to install an agrophotovoltaic system. Therefore, extra income for the farm was available, rising up to 204 €/cow*yr. As a result, the total revenue for this specific CSA was 5,650 €/cow*yr, which constituted a 4.6% increase compared to the baseline.

	Cost category (€/ha/year)	Baseline	Land Use	Breeding	Regional Protein	Feed Conversion	Organic/ Naturland farming
EXPENSES	Heifers	€ 929	€ 929	€ 929	€ 929	€ 929	€ 576
	Energy (electricity)	€ 60	€ 60	€ 60	€ 60	€ 60	€ 60
	Water	€ 30	€ 30	€ 30	€ 30	€ 30	€ 30
	Fertilizers	€ 236	€ 236	€ 236	€ 236	€ 937	€ 342
	Feedstock	€ 808	€ 828	€ 808	€ 740		€ 662
	Maintenance	€ 1,467	€ 1,467	€ 1,467	€ 1,467	€ 1,467	€ 1,467
	Labor	€ 1,533	€ 1,533	€ 1,533	€ 1,533	€ 1,533	€ 1,533
	Rent	€ 203	€ 203	€ 203	€ 203	€ 287	€ 274
	Other (taxes, admin, etc)	€ 31	€ 31	€ 31	€ 31	€ 31	€ 31
	Total	€ 5,298	€ 5,318	€ 5,298	€ 5,230	€ 5,274	€ 4,976
	Change over BL:		0.37%	0.00%	-1.28%	-0.45%	-6.08%
REVENUES	Milk	€ 4,446	€ 4,446	€ 4,446	€ 4,446	€ 4,446	€ 4,410
	Meat	€ 498	€ 498	€ 498	€ 498	€ 498	€ 498
	Calves	€ 459	€ 459	€ 459	€ 459	€ 459	€ 459
	Rent	€ -	€ 250	€ -	€ -	€ -	€ -
	Heifers (sold)	€ -	€ -	€ 292	€ -	€ -	€ -
	Total	€ 5,403	€ 5,653	€ 5,695	€ 5,403	€ 5,403	€ 5,367
	Change over BL:		4.63%	5.40%	0.00%	0.00%	-0.70%
	Profit	€ 106	€ 336	€ 398	€ 173	€ 129	€ 392

Table 10: Comparative LCC analysis (per cow, annual basis) of the baseline scenario and the different CSA practices for the German UC.

3.2.6. Social Life Cycle Impact Assessment (s-LCIA)

The production flows and relevant inventory data of all the examined German CSA scenarios were taken from the resulting LCIAs shown in previous table 8. According to the received questionnaire, the data inputs for 4 out of 5 CSA scenarios were mostly similar with the baseline scenario, and thus were directly taken from table 16 of the previous D3.1. These included the "Worker hours" activity variable and the impact factors with their associated risk levels. The only exception was the naturland farming scenario, which resulted in different values for the "Worker hours" activity variable and the "Certified Environmental Management Systems", "Embodied Agricultural Area Footprints", "Embodied Water Footprints", "Embodied CO_2 Footprints", "Embodied CO2eq Footprints" and "Embodied Value Added" impact factors. The first one was recalculated, based on the reduced annual production of 7tn, while the impact factors changed their values according to the received questionnaire data for each CSA. The changes to the data inputs, with regard to the baseline scenario described in the 2024 D3.1, are summarized in Table 11 below:

Input	Baseline	Naturland farming	Forage & clover	Regional protein	Longevity breeding	Land use
Worker hours[6]	0.00367	0.00419	0.00367	0.00367	0.00367	0.00367
Certified Environ-mental Manage-ment Systems	Very High	Very Low	Very High	Very High	Very High	Very High
Embodied Agricultural Area Footprints	High	High	High	High	High	High
Embodied Water Footprints	Very High	Very High	Very High	Very High	Very High	Very High
Embodied CO_2eq Footprints	Medium	Medium	Medium	Medium	Medium	Medium
Embodied Value Added	Very High	High	High	High	Medium	Very High

Table 11: Changes of the data inputs of s-LCIA, from the German baseline scenario, shown in the 2024 D3.1 (the impact factors not shown were unchanged and thus were taken directly from the baseline scenario, as presented in Table 16 of the 2024 D3.1).

The results from the s-LCIA analyses for all the examined CSA scenarios are shown in Figure 5 below. Along with the studied CSAs, the results of the baseline scenario have also been updated due to database updates (ILO, WHO etc.) that changed the risk levels of some impact factors. A more detailed analysis of each CSA examined is given below. Generally, the results were in line with the changes of the LCI. However, some of the impact factors resulted in high social footprints, despite the fact that they had very low-medium risks. This was found for all examined CSAs and the baseline scenario as well, and was attributed to impacts from upstream flows. More specifically, for the baseline scenario, most impactful flows were the ones related with the production of feed and electricity demands on a global scale. Any CSA that contributed a positive change to the above resulted in reduced impacts.

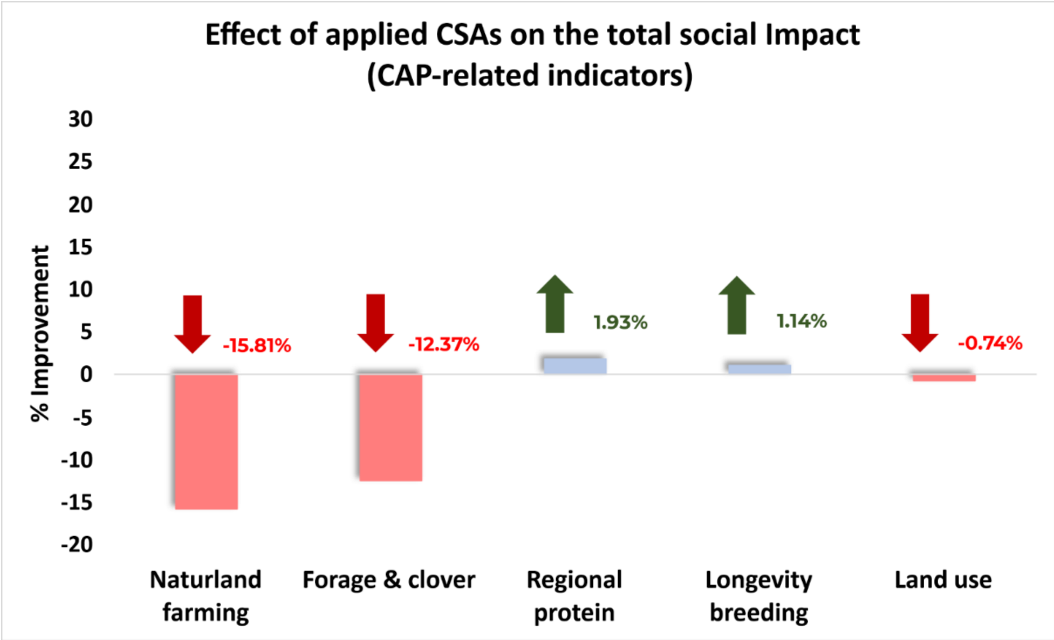


Figure 5: Comparison of the changes in the social impacts from the investigated CSAs, regarding the EU CAP-relevant social indicators – impacts per cow grown per year (German UC) (0 value represents the baseline for conventional dairy farming).

Naturland farming | s-LCIA

Beginning with the naturland farming scenario, this one performed slightly worse than the baseline scenario, resulting in a 4% increase in total DALYs. This result was expected, due to the increased "Worker hours" activity variable, meaning that the same amount of effort from workers, who were paid similarly with the baseline scenario, produce significantly less product (7tn instead of 8tn). Focusing on the CAP-relevant indicators that are more in accordance with the BEATLES project, the naturland farming scenario resulted in 16% increased social footprints. This change was attributed to an increase in the DALYs from the Embodied Water Footprints and Embodied Agricultural Area Footprints. The 4 most important factors were the Fair Salary, followed by Embodied Biodiversity Footprints, GHG Footprints and Embodied Water Footprints. As a result, it is anticipated that, if the annual production in the naturland farming scenario could remain at 8tn (in order to keep the same value for the "Worker hours" activity variable), the overall social impacts would have been significantly decreased for the naturland farming scenario, as the changes in feed composition and the absence of the synthetic fertilizers would lead to reduced values.

Forage & Clover | s-LCIA

Moving on to the forage & clover scenario, this one performed slightly better than the baseline scenario, resulting in a 9% decrease in total DALYs. This result was expected, as the anticipated changes were mostly based on changes in the LCI. Focusing on the CAP-relevant indicators that are more in accordance with the BEATLES project, the forage & clover scenario resulted in 12% increased social footprints, contrary with the decrease in total DALYs above. This change was attributed to an increase in the DALYs from the Embodied Water Footprints and Embodied Agricultural Area Footprints. The 4 most important factors were the Fair Salary, followed by Embodied Biodiversity Footprints, GHG Footprints and Embodied Water Footprints. As a result, for the forage & clover scenario, the increase of the social footprints is attributed mostly to the changes in feed composition, which included increased amounts of Embodied water and agricultural area footprints.

Regional Protein | s-LCIA

Subsequently for the regional protein scenario, this one performed slightly worse than the baseline scenario, resulting in a 1% increase in total DALYs. This result was expected, as the anticipated changes were mostly based on changes in the LCI. Focusing on the CAP-relevant indicators that are more in accordance with the BEATLES project, the regional protein scenario resulted in 2%

decreased social footprints, contrary with the increase in total DALYs above. This change was attributed to a decrease from the Fair Salary and Industrial Water Depletion impact factors. The 4 most important factors were the Fair Salary, followed by Embodied Biodiversity Footprints, GHG Footprints and Unemployment rate. As a result, for the regional protein scenario, the slight decrease of the social footprints is attributed mostly to the slight changes in feed composition, which included reduced amounts of Fair Salary and Industrial Water Depletion footprints.

Longevity breeding | s-LCIA

Moving on to the longevity breeding scenario, this one performed very close to the baseline scenario, resulting in a 0.8% decrease in total DALYs. This result was expected, as the anticipated changes were mostly based on the changes in LCI. Focusing on the CAP-relevant indicators that are more in accordance with the BEATLES project, the longevity breeding protein scenario resulted in 1% decreased social footprints. The 4 most important factors were the Fair Salary, followed by Embodied Biodiversity Footprints, GHG Footprints and Unemployment rate. As a result, for the longevity breeding scenario, the slight decrease of the social footprints is attributed mostly to the slight changes in feed composition.

Land Use | s-LCIA

Finally, for the land use scenario, this one performed very close to the baseline scenario, resulting in a 0.7% increase in total DALYs. This result was expected, as the anticipated changes were mostly based on the changes in LCI. Focusing on the CAP-relevant indicators that are more in accordance with the BEATLES project, the land use scenario resulted in 0.7% increased social footprints. The 4 most important factors were the Fair Salary, followed by Embodied Biodiversity Footprints, GHG Footprints and Unemployment rate. As a result, the land use scenario led to only marginal changes from the baseline scenario, since the values of the most impactful flows did not change.

Conclusions | s-LCIA

According to the results from the s-LCIA analyses, from the social impact perspective, the best results were acquired from the regional protein scenario (2% reduced footprints), followed by longevity breeding (1% reduced footprints) and land use (0.7% increased footprints). These scenarios performed close to the baseline and can be considered in case the improvement of the social footprints is a secondary objective of the transition-to-CSA strategy. On the other hand, forage & clover and naturland farming scenarios were found to bear slightly increased social footprints (12% and 16% increased footprints respectively) and as such, it is suggested that they will be examined as secondary options, in case the previous ones do not fulfil the needs of the transition-to-CSA strategy.

3.2.7. Cost-Benefit Analysis

The comparative analysis of five different CSA scenarios—Naturland, Forage & Clover, Regional Protein, Longevity Breeding, and Land Use—reveals varying trade-offs in cost, environmental impact, economic performance, and social sustainability. Among them, the Naturland farming system stood out for its substantial environmental improvements, particularly due to the elimination of synthetic fertilizers which resulted in a 367% reduction in global warming potential. However, this came at a cost: higher land and labor requirements, reduced milk yields, and increased heifer replacement costs. Despite these challenges, the scenario managed to remain economically viable thanks to significantly lower feed and fertilizer expenses and increased revenues from organic-certified milk.

The Forage & Clover scenario achieved the most dramatic cost savings by eliminating external feed purchases through complete feed autonomy, relying solely on farm-grown grass and clover silage. While this increased the land requirement by 20 hectares, no additional infrastructure was needed, and operational independence improved. Environmental performance was particularly strong, with a 99% reduction in freshwater eutrophication and moderate gains in global warming and acidification indicators. Economically, the model was resilient and efficient, while socially it produced a slight rise in certain footprint indicators but saw a reduction in DALYs, signaling a net positive social impact.

CSA	Costs	Benefits		
		Environmental	Economic	Social
Naturland Farming	Increased land rent (+42 €/cow·yr) due to larger area required (10 ha) Lower milk yield (7t vs 8t), reducing productivity per labor unit Cost for heifers: 576 €/cow·yr More labor hours required per unit of product Slight ↑ in DALYs (4%) from higher labor input and embodied impacts ↑ Social footprint (16%)—mostly from embodied upstream impacts	↓GWP by 367% due to elimination of synthetic fertilizers ↓ Terrestrial ecotoxicity and ↓ fossil resource scarcity by 32% and 43%, respectively Absence of synthetic fertilizers eliminates associated environmental burdens ↑ Freshwater eutrophication (negative) due to organic fertilization of peas	↓ Animal feed costs: from 808 to 662 €/cow·yr ↓ Fertilizer costs: -236 €/cow·yr ↑ Revenues to 5,390 €/cow·yr Potential for premium product pricing under Naturland label	More employment due to increased labor demand (↑ worker hours) Improved animal welfare: longer lifespan, fewer replacements

CSA	Costs	Benefits		
		Environmental	Economic	Social
Forage & Clover	Requirement for 20 additional ha of grassland (↑ land use) ↑ Land use footprint (58 ha vs 38 ha in baseline) Slight ↑ in Embodied Water Footprints and electricity demands ↑ Social footprint by 12.37%, mostly from Embodied Water and Agricultural Area Footprints Minor increase in risks due to upstream flows (electricity/feed system impacts)	↓ Freshwater eutrophication by 99% due to full exclusion of external feed inputs ↓ Terrestrial acidification by 8% due to elimination of conventional feed inputs ↓ Ecotoxicity indicators significantly, due to absence of conventional feed ↓ GWP by 3% CO_2 storage potential from increased grassland	100% feed self-sufficiency → €0 feed cost ↑Revenues to 917 €/cow·yr No additional investment needed (existing infrastructure used)	↓ Total DALYs by 9%, mainly due to improved feed production conditions
Regional Protein	84 t rapeseed x 40.42 €/dt	↓ GWP by 2% ↓ Terrestrial acidification potential by 12%	14 t wheat reduction x 18.7 €/dt saved Avoided cost: 70 t soy x 61 €/dt ↑ Total revenue: 1200 €/cow*yr	↓ Social footprint by 2% ↓ DALYs from Fair Salary and Industrial Water Depletion ↑ Overall DALYs by 1%, mainly due to feed production

CSA	Costs	Benefits		
		Environmental	Economic	Social
Breeding	OpEx at ~ 290 k€ annually, reduction ~ 30-35 k€ compared to the baseline No additional CapEx required	↓ GHG emissions per kg of milk (due to longer productive lifespan)	↓ 48.6% cost of acquiring new livestock ↓ Feed demand during rearing: 9 t less ↓ Vet and input costs (not quantified, but reduced) ↑ Revenue: 1970 €/cow*yr ↑ Calf price from 459 € to 750 € Potential income from selling 7 pregnant heifers: +17,500 €/year ↓ Working time due to fewer rearing animals	↓ Total DALYs by 0.8% ↓ Social footprint by 1% ↑ Animal welfare (healthier, longer-living cows) Lower risk levels for most social indicators except GHG Footprints (medium risk)
Land Use	Minor reduction in grass/feed yield (10–15% on 5 ha) Slight decrease in raw material availability for feed ↑ DALYs by 0.73% ↑ Social footprint by 0.74%	↓ Global Warming Potential by 7% ↓ Terrestrial Acidification Potential by 11%	↑Extra income via land rent: 205 €/cow*yr or 12,000 €/year ↑Total revenue: 270 €/cow*yr	Area still supports pasture use, no impact on animal welfare or labor demand

Table 12: Summary of Cost – Benefit Analysis for the CSA practices of in the German UC.

In the Regional Protein scenario, replacing imported soy with locally sourced rapeseed led to cost-effective feeding practices and marginal improvements in environmental impact, including a 1.5% drop in global warming potential. The proximity of feed sources also enhanced operational efficiency. While DALYs increased slightly, key social footprint indicators such as fair salary and industrial water use improved. The scenario illustrated how strategic feed substitution can support both regional economies and sustainability goals without drastic operational changes.
The Longevity Breeding scenario offered some of the most notable economic benefits. By reducing the frequency of livestock replacement through improved breeding strategies, the farm significantly cut costs and gained flexibility from the potential sale of excess heifers. Although environmental and social benefits were modest, they aligned with improved animal welfare and longer productive lifespans for cows, which reduced the environmental burden of rearing non-productive animals. The scenario demonstrated how internal herd management improvements can yield sustainable results across all dimensions.
Finally, the Land Use scenario introduced agriphotovoltaic systems to generate rental income while maintaining pasture use. This model offered substantial economic benefits with minimal disruption to farm operations and only a slight reduction in feed yield. Environmentally, greenhouse gas emissions were reduced by 7%, while social impacts remained almost neutral. The dual-use land strategy provided a low-effort means to enhance farm income and support renewable energy generation without significant compromise on sustainability metrics.
In summary, each scenario offered a unique blend of strengths: Naturland and Forage & Clover excelled environmentally, Regional Protein and Breeding enhanced economic and operational efficiency, and Land Use balanced passive income with sustainability. Together, they represent a diverse toolkit for farmers seeking resilient and eco-conscious agricultural models tailored to their local conditions and long-term sustainability goals.

3.3. Use Case Pilot #3: Organic apple farming, Spain

3.3.1. *Description of the CSA practices*

Organic farming | Description

The environmental impacts of apple farming can be significantly reduced through organic farming, an agricultural system that aligns with natural life-cycle processes. Organic farming emphasizes the use of environmentally friendly practices, promotes biodiversity, preserves natural resources, ensures high animal welfare standards, and caters to consumers' preferences for products grown with natural substances and processes (EU, 2007). Key practices in organic farming include wide crop rotation to optimize on-site resources, strict limits on synthetic chemicals, prohibition of genetically modified organisms (GMOs), and a focus on local, sustainable farming techniques (Longo et al., 2017).

In Navarra, organic apple production follows these principles, prioritizing ecosystem health and sustainability. Instead of relying on synthetic pesticides and fertilizers, farmers use organic alternatives such as compost, green manure, and integrated pest management techniques. These methods promote soil health, enhance biodiversity, conserve water and energy, and reduce waste. Organic apple farming also focuses on maintaining stringent standards to ensure high-quality, nutritious produce while protecting the environment and supporting ecosystem well-being.

The shift to organic farming can initially result in lower yields due to challenges such as soil transition and the absence of synthetic chemicals for pest and disease control. However, once the system is fully established, organic farming can achieve comparable or even higher yields than conventional methods, particularly in terms of product quality.

Cover crops | Description

Commercial fruit orchards often rely on intensive management practices, including synthetic fertilizer application and bare-soil weed control, to maximize productivity. Typically, a bare soil 'weed strip' or 'herbicide strip' is maintained under tree rows to reduce competition for water and nutrients. However, this practice negatively impacts soil health, increasing erosion, reducing soil organic matter, and degrading soil biota, which in turn weakens critical ecosystem services such as nutrient cycling, pest regulation, and pathogen suppression. Moreover, excessive reliance on chemical pesticides and fungicides, particularly for apple scab control, has led to growing resistance and an urgent need for alternative approaches.

To address these challenges, this CSA practice focuses on targeted vegetative cover and organic mulching as an integrated solution for biological pest control, soil conservation, and reduced chemical inputs. Instead of relying on naturally occurring ground cover, specific plant species are deliberately introduced to enhance biodiversity and optimize orchard resilience. These vegetative covers, particularly in alleyway spaces between tree rows, serve multiple functions:

- **Biological pest control** – Providing habitat for beneficial insects and acting as trap crops for pest management.
- **Weed suppression** – Reducing competition without the need for herbicide applications.
- **Carbon sequestration** – Contributing to climate mitigation by increasing soil carbon content.
- **Erosion prevention and soil health improvement** – Enhancing soil structure, moisture retention, and microbial activity.
- **Fungicide reduction** – Supporting natural decomposition of leaf litter, reducing pathogen pressure from diseases like apple scab.

A key innovation in this approach is the mulching technique, where cover crops, including nitrogen-fixing legumes, are grown in the alleyways, mowed, and then redistributed under tree rows using side-discharging mowers. This method provides a cost-effective and feasible alternative for growers by making use of existing equipment with minimal modifications. Research has demonstrated that plant-based mulches not only enhance soil fertility but also support functional soil biodiversity, including beneficial mycorrhizal fungi, detritivores, and decomposers that contribute to leaf litter decomposition and disease suppression. Additionally, diverse alleyway vegetation promotes pollinator habitats and increases natural enemy populations, further reducing the need for synthetic pesticides (Webber et al. 2022).

Research suggests that the method of cover crop incorporation—whether through tillage, herbicide application, roller-crimping, or mowing—does not impact the total amount of plant-available nitrogen (PAN) released. However, it can influence the timing of PAN release, which typically occurs 4 to 6 weeks after terminating the cover crop.

Floral bands | Description

Pesticide overuse, particularly in crops like apples, poses significant environmental risks, as these crops often require frequent treatments against pests such as *Dysaphis plantaginea* and *Cydia pomonella*. European agricultural policy supports biodiversity restoration and the reduction of pesticide use through subsidies, promoting environmentally sustainable practices (Howard et al., 2024). One such approach is the use of floral bands, which offer a cost-effective and efficient way to reduce pesticide reliance. These bands are planted in non-cultivated areas, such as field edges or sprinkler zones, and attract beneficial insects that naturally help control pests, with minimal maintenance required. They occupy about 2% of the crop area but are ideally placed in non-cultivated zones for maximum benefit.

A study conducted across seven European countries tested perennial flower strips in organic apple orchards. The results showed that these strips increased the presence of natural predators, slowed pest population growth, and reduced fruit damage. This research demonstrates how functional agrobiodiversity can lower insecticide use while maintaining effective pest control (Howard et al., 2024). By incorporating floral bands and adopting integrated pest management, farmers can enhance sustainability, reduce pesticide dependence, and contribute to the long-term health of agricultural ecosystems.

Grazing | Description

The production of blemish-free apples often requires intensive agrochemical use, which can harm the environment. A proposed solution is grazing sheep in orchards to help control apple scab and reduce pesticide use. Sheep eat fallen leaves, promoting decomposition and reducing the harboring of scab-causing organisms. Additionally, unharvested fruit on the orchard floor can harbor pest larvae, increasing pest problems. Rotational grazing by livestock has been shown to reduce pest populations, control weeds, and lower pesticide and herbicide use in tree fruit systems (Buehrer & Grieshop, 2014). Thus, grazing in apple orchards serves multiple purposes. It performs a clearing task without the need for machinery, which helps improve nutrient cycling, soil fertility, and agroecosystem biodiversity. Additionally, it prevents the spread of pests and diseases from fallen leaves and fruits, and reduces mole activity. Furthermore, it can offer an alternative for diversifying farm activities and may have positive social effects, such as fostering collaboration between producers in the area. Despite the environmental benefits and potential for additional revenue, research on integrating grazing with high-value tree systems in Europe remains limited.

Renewable energy | Description

The growing trend of global energy demand causes a rise in fossil fuel consumption and consequently carbon-based emissions. The majority of agricultural tasks depend on the direct or indirect use of fossil fuels, leading to the emission of great amounts of greenhouse gases (GHG). According to a recent report by the "Consultative Group on International Agricultural Research" (CGIAR), the energy consumed for food production ranges at 30% of the global energy demand, contributing to almost 19–29% of the annual GHG emissions. One of the main solutions is the replacement of conventional energy sources with renewable energy sources (Yildizhan et al., 2021). The adoption of photovoltaics in agriculture seems to be a promising way to expand their application without needing to cover more agricultural land.

3.3.2. Goal and Scope definition

The objective of the assessments conducted (LCA, LCC, and S-LCA) is to evaluate the environmental, economic, and social impact potentials of applying the CSA practices described in subsection3.1.1. in the Spanish UC scenario.

Product systems:

Baseline: The product system is an apple farm located in Spain. In the farm only apples are cultivated and produces, constituting them the only product of the system. All relevant agricultural practices are included in the apple farm, spanning from farming (including soil preparation, fertilizing, pruning, pruning waste management, irrigation etc.) to harvesting.

Organic farming: The product system is an apple farm that applies organic farming. The N, P, and K from synthetic fertilizers are replaced by equivalent amounts derived from organic sources (manure). No pesticides are applied. The use of diesel is increased, due to the need for more intensive techniques for weed and pest management. The scenario covers the initial years of the farm's transition to organic farming; therefore, the yield remains lower than the baseline scenario (30 tons/ha instead of 35 tons/ha), due to soil transition and pest and disease management without the use of synthetic chemicals.: The main processes that are included within the product system are the following: organic apple farming (including sub-processes, such as soil preparation, fertilizing, pruning, pruning waste management, irrigation, weeding, etc) and harvesting of apples.

Cover crops: The product system is an apple farm that utilizes cover crops. The main processes that are included within the product system are the following: cover crop cultivation, apple farming (including sub-processes, such as soil preparation, fertilizing, pruning, pruning waste management, irrigation, weeding, etc.) and harvesting of apples.

Floral bands: The product system is an apple farm that applies floral bands. The main processes that are included within the product system are the following: floral bands cultivation, apple farming (including sub-processes, such as soil preparation, fertilizing, pruning, pruning waste management, irrigation, weeding, etc) and harvesting of apples.

Grazing: The product system is an apple farm that combines grazing by sheep. Functions of the product system: The main processes that are included within the product system are the following: grazing, apple farming (including sub-processes, such as soil preparation, fertilizing, pruning, pruning waste management, irrigation, weeding, etc) and harvesting of apples.

Renewable energy: The product system is an apple farm that generates renewable energy for its own use and supplies any surplus energy to the grid. The main processes that are included within the product system are the following: production of solar energy, apple farming (including sub-processes, such as soil preparation, fertilizing, pruning, pruning waste management, irrigation, weeding, etc) and harvesting of apples.

System boundaries: The objective of the study was to compare the application of the CSA practices with conventional apple farming over a single harvesting cycle. To achieve this, a cradle-to-gate approach was adopted, focusing solely on processes occurring within the farm. More specifically, the boundaries of the system encompass all the stages from the soil preparation of the apples orchard till the harvesting of the apples. Upstream processes related to agricultural inputs (e.g., fertilizers, diesel, and pesticides) are considered, in line with standard LCA methodology, while downstream stages such as post-harvest processing, packaging, distribution, and consumption are excluded.

Allocation procedures: Since there are no multiple products involved, no allocation is needed.

Environmental impact assessment methodology: ReCiPe 2016 (H, hierarchist) was used in order to convert the LCI data into a set of environmental impact scores using characterization factors which convert emissions and resource use into potential environmental impacts at global or regional scales. Although the system boundaries are cradle-to-gate, these broader-scale impact potentials allow for consistent comparison of environmental burdens across different processes and regions. Detailed description of the method is provided in subsection 2.1.2.

Data requirements: To conduct the LCA analysis, data were gathered through the distribution of questionnaires to relevant stakeholders, supplemented by data from verified databases such as Ecoinvent, Agri-footprint and Agribalyse, which cover the geographical area of the European Union 28 (EU-28). The collected data refer to year 2023.

Assumptions/Limitations:

Organic farming

The collected data correspond to a model organic apple orchard with irrigation system in Navarra, standardized to 1 ha for consistency in LCA calculations. As a reference variety for conventional production, Golden apples were considered.

Cover crops

- The collected data correspond to a model apple orchard with irrigation system, that applies cover crops, in Navarra, standardized to 1 ha for consistency in LCA calculations. As a reference variety for conventional production, Golden apples were considered
- Studies confirm that plant-based mulches improve soil fertility, microbial diversity, and nutrient cycling, increasing soil carbon (C), nitrogen (N), and phosphorus (P) levels while reducing the need for synthetic fertilizers. The **reduction of nitrogen fertilizers** was calculated based on the available nitrogen from the cover crop to the soil, according to USDA (equation [1]), assuming 3% N content in the cover crop. A conservative estimate of cover crop nitrogen contribution is about 40% of total biomass N. The economic advantages of cover crops include reduced input costs and labor requirements, making this method both sustainable and financially viable (Wu et al. 2024; USDA, 2014; Wang et al., 2021).

PAN (Plant-Available Nitrogen) (kg/ha) = Dry biomass (kg/ha) % N x 0.4 **[1]**

- Based on the indications provided by literature (Wu et al. 2024; USDA, 2014; Wang et al., 2021), this study assumes a **20% reduction in pesticides, phosphorus and potassium fertilizer use** due to the benefits of cover cropping. To account for potential variability in pesticides, phosphorus and potassium fertilizer levels, **two additional scenarios** were analyzed, assuming **10%** and **30% reductions in pesticide, phosphorus, and potassium fertilizer use**. These scenarios help assess the sensitivity of the results to different levels of pesticide input reduction.
- The cover crops' cultivation and management are included in the dataset of "*Ecoinvent green manure growing, organic, until April RoW",* that represents the cultivation of green manure on an area of 1 ha. The dry matter yield is 2300 kg/ha. Green manure is not harvested but incorporated into the soil. The activity starts after the harvest of the previous crop. The input of seeds is included. The dataset includes all machine operations and corresponding machine infrastructure and sheds. Machine operations are: soil cultivation, sowing and mulching. Further, direct field emissions are included. This activity ends after mulching of the green manure.

Floral bands

The collected data correspond to a model apple orchard with irrigation system, that applies floral bands, in Navarra, standardized to 1 ha for consistency in LCA calculations. As a reference variety for conventional production, Golden apples were considered. Studies confirm that the application of floral bands can contribute to pest management and pesticides use reduction, but no further data are available (Howard et al., 2024); thus, **a 20% reduction in pesticides use** was assumed. To account for potential variability in pesticides levels, **two additional scenarios** were analyzed, assuming **10%** and **30% reductions in pesticides use**. These scenarios help assess the sensitivity of the results to different levels of pesticide input reduction. According to data collected through interviews, it is estimated that a support flower band occupies about 2% of the crop plot of the cultivation plot.

Grazing

The collected data correspond to a model apple orchard with irrigation system in Navarra that combines grazing, standardized to 1 ha for consistency in LCA calculations. As a reference variety for conventional production, Golden apples were considered.

- The grazing is done by sheep from neighboring farms, which are supplied free of charge.
- Studies confirm that grazing can contribute to pest and weed management, reducing thus the dependence on pesticides and other plant protection products. There are no accurate data available, neither from interviews nor from literature. Thus, based on the existing indications from literature (Buehrer & Grieshop, 2014; Pantera et al., 2018), in the current

study **a 20% reduction in total pesticides use** was assumed. To account for potential variability in pesticides levels, **two additional scenarios** were analyzed, assuming **10%** and **30% reductions in pesticides use**. These scenarios help assess the sensitivity of the results to different levels of pesticide input reduction.

- Based on data provided through interviews, a **30% reduction in diesel** burned in agricultural machinery was assumed.
- The **manure** produced during grazing naturally fertilizes the soil, reducing the reliance on synthetic fertilizers. Three different scenarios were studied to assess the impact potential of the natural fertilization process, considering **replacement rates of 10%, 30%, and 50%.**

Renewable energy

- The collected data correspond to a model apple orchard with irrigation system in Navarra, standardized to 1 ha for consistency in LCA calculations. As a reference variety for conventional production, Golden apples were considered. The farm produces energy for its own use and supplies any surplus energy to the grid.
- Based on data provided through interviews, a **50% reduction in energy** consumed was assumed.
- An average 6 peak sun hours per day was assumed for the Navarra region, based on meteorological data[7], leading to the production of 162 kWh per day by the installed panels (12 kWh and 15 kWh). Assuming that Navarra has 58 clear days per year[1], the total energy production can be 9,396 kWh. Adjusting the total energy production by taking into account any losses (15%), the final value is estimated to 7,987 kWh of solar energy.
- The surplus energy generated by the farm, which is not consumed on-site, is supplied to the grid as a credit.

3.3.3. Life Cycle Inventory

The Life Cycle Inventory (LCI), compiled from data collected through interviews and supplemented with relevant literature sources, is summarized in Table 13, with all flows aggregated using 1 ha of cultivated land as the Reference Flow. The values for the baseline scenario are shown in the second column, while the subsequent columns display the percentage change associated with each CSA practice. For newly introduced parameters, the actual values are presented instead of percentage changes. The results are presented per 1 kg of harvested apples per year, using this as the functional unit. The estimation of the initial emission distribution fractions of the applied chemical agents (fungicides, herbicides, insecticides and phytoregulators) was based on emission modelling for pesticides provided in literature (Nemecek et al., 2019). More specifically, the emissions to soil, water and air were estimated based on the percentage of the active compound per case and the appropriate coefficients provided for the category of temperate fruit trees. The estimation of the emissions of fertilizers in air, water and soil was based on IPCC guidelines (IPCC, 2019).

The dataset from Ecoinvent, for the installation of the solar panels, represents the production of grid-connected low voltage electricity with a 3 kWp[8] building integrated photovoltaic module in Spain. The 3 kWp module has been chosen as a basic module for building integrated PV electricity production. Larger modules can easily be built with these 3 kWp modules without producing a significant error in environmental impact calculations. The module is a multi-Si panel - made from silicon with multiple crystal grains- installed on a slanted roof.

[7] https://www.weatherbase.com/weather/weatherall-print.php3?cityname=Pamplona-Navarre-Spain&s=591946&units=

[8] Kilowatts peak, which represents the peak power of a PV system or panel under optimal conditions (e.g. sunny day)

Parameter	Baseline	Organic farming	Cover crops	Floral bands	Grazing	Renewable energy
INPUTS						
Land use (ha)	1	1	1	0.98	1	1
Cover crops application (ha)	-	-	0.8	-	-	-
Floral bands application (ha)	-	-	-	0.02	-	-
Photovoltaics installation pcs	-	-	-	-	-	9
Inorganic phosphorus fertilizer (kg)	44	-	30.8-39.6	44	22-39.6	44
Inorganic potassium fertilizer (kg)	376	-	210-338	376	188-338.4	376
Inorganic nitrogen fertilizer (kg)	101	-	70	101	50.5-90.9	101
Organic phosphorus fertilizer (kg)	-	24.28	-	-	10.1-50.5	-
Organic potassium fertilizer (kg)	-	121.4	-	-	37.6 – 188	-
Organic nitrogen fertilizer (kg)	-	181.5	-	-	4.4-22	-
Herbicides (kg)	1.83	-	1.02-1.65	1.02-1.65	1.02-1.65	1.83
Insecticides (kg)	0.38	-	0.24-0.27	0.24-0.27	0.24-0.27	0.38
Fungicides (kg)	2.88	-	1.29-2.07	1.29-2.07	1.29-2.07	2.88
Calcium (kg)	3	3	3	3	3	3
Boron	-	0.48	-	-	-	-
Paraffin (kg)	5.58	5.58	5.58	5.58	5.58	5.58

Parameter	Baseline	Organic farming	Cover crops	Floral bands	Grazing	Renewable energy
Water (m^3)	6360	6360	6360	6360	6360	6360
Diesel (kWh)	8250	12540	8250	8250	5775	4125
OUTPUTS						
Apples (tonnes)	35	30	35	35	35	35
Emissions to air						
Emissions from fungicides (kg)[9]	0.23	-	0.13-0.21	0.13-0.21	0.13-0.21	0.23
Emissions from insecticides (kg)[1]	0.031	-	0.02-0.028	0.02-0.028	0.02-0.028	0.031
Emissions from herbicides (kg)[1]	0.37	-	0.21-0.33	0.21-0.33	0.21-0.33	0.37
Dinitrogen monoxide (kg)[10]	1.59	2.86	0.89-1.43	1.59	1.59	1.59
Ammonia (kg)[2]	12.26	22.11	6.87-11.03	12.26	12.26	12.26
Emissions to water						
Emissions from fungicides (g)[1]	0.20	-	0.11-0.18	0.11-0.18	0.11-0.18	0.20
Emissions from insecticides (mg) [1]	28.5	-	16.0-25.7	16.0-25.7	16.0-25.7	28.5
Emissions from herbicides (mg)[1]	440	-	246-396	246-396	246-396	440

[9] Nemecek et al., 2019
[10] (IPCC, 2019)

Parameter	Baseline	Organic farming	Cover crops	Floral bands	Grazing	Renewable energy
Phosphate (kg)[2]	3.08	1.7	1.72-2.77	3.08	3.08	3.08
Nitrate (kg)[2]	44.73	80.64	25.05-40.26	44.73	44.73	44.73
Emissions to soil						
Emissions from fungicides (kg)[1]	0.69	-	0.39-0.69	0.39-0.69	0.39-0.69	0.69
Emissions from insecticides (kg)[1]	0.06	-	0.03-0.05	0.03-0.05	0.03-0.05	0.06
Emissions from herbicides (kg)[1]	1.39	-	0.78-1.25	0.78-1.25	0.78-1.25	1.39
Nitrate (kg)[2]	30.3	54.63	16.97-27.27	30.3	30.3	30.3
AVOIDED PRODUCTS						
Electricity (kWh)	-	-	-	-	-	3862

Table 13: Life Cycle Inventory of an apple orchard – Spanish UC. The values are given per ha per year (reference flow). "-" indicates zero value.

3.3.4. Environmental Life Cycle Impact Assessment (e-LCIA)

ReCiPe 2016 (H, hierarchist) was applied for the conversion of the LCI data presented in Table 13 into a set of environmental impact potential scores. The results of the baseline scenario have also been updated, using more recent values from the external database sources. The revised values of the 18 midpoint indicators being presented in Table 14. The main midpoint indicators (check Figure 1) that resulted from life cycle impact assessments of the various product systems, as well as their respective percentage differences from the baseline scenario are presented in Figure 6.

Impact category	Unit	Value
Global warming	kg CO_2 eq	4798.30
Stratospheric ozone depletion	kg CFC11 eq	0.02
Ionizing radiation	kBq Co-60 eq	80.30
Ozone formation, Human health	kg NO_x eq	30.28
Fine particulate matter formation	kg $PM_{2.5}$ eq	10.51
Ozone formation, Terrestrial ecosystems	kg NO_x eq	31.01
Terrestrial acidification	kg SO_2 eq	45.16

Freshwater eutrophication	kg P eq	0.29
Marine eutrophication	kg N eq	3.92
Terrestrial ecotoxicity	kg 1,4-DCB	8981.29
Freshwater ecotoxicity	kg 1,4-DCB	39.95
Marine ecotoxicity	kg 1,4-DCB	61.68
Human carcinogenic toxicity	kg 1,4-DCB	23.46
Human non-carcinogenic toxicity	kg 1,4-DCB	12498.24
Land use	m^2a crop eq	7043.99
Mineral resource scarcity	kg Cu eq	12.26
Fossil resource scarcity	kg oil eq	1313.02
Water consumption	m^3	23.83

Table 14: Spanish UC Baseline scenario – midpoint impact indicators (FU: 1 ha per year)

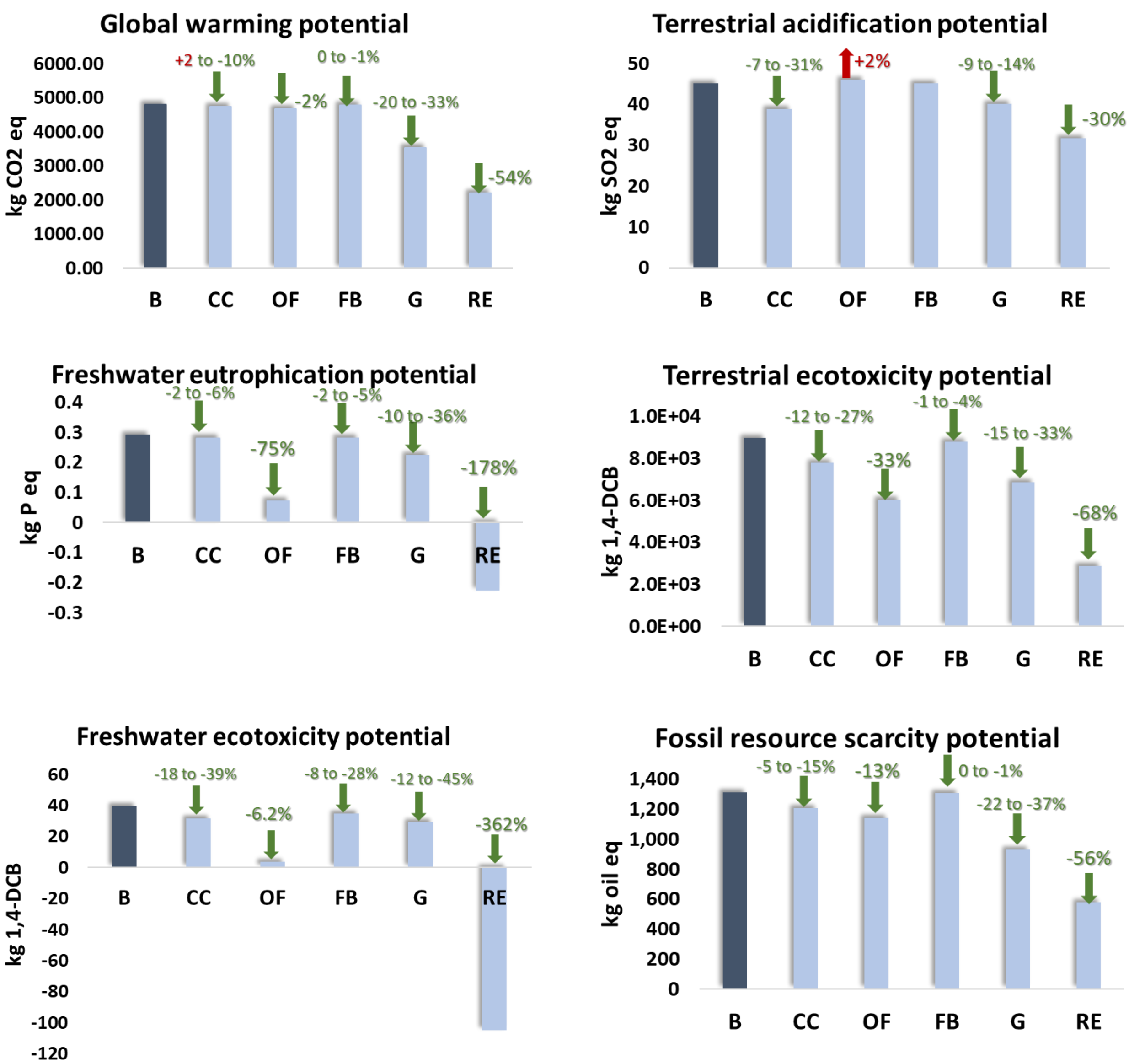


Figure 6: Environmental impact potential comparison of the Spanish baseline scenario vs. the different scenarios of the application of CSA practices – selected midpoint impact indicators are

shown per ha per year (Spanish UC). [Scenarios include: BL – Baseline, CC – Cover Crops, OF – Organic Farming, FB – Floral Bands, G – Grazing, and RE – Renewable Energy].

The LCA conducted for the five different scenarios about the CSA practices applied in apple orchards demonstrated differentiated environmental performance across these scenarios. Each practice contributes uniquely to reducing environmental impact potential, with some delivering substantial improvements across several midpoint impact categories.

The use of diesel in agricultural machinery has a great contribution to global warming potential. In **organic farming systems**, the need for diesel tends to increase due to more intense agricultural activities for pest management and weed control. This increase leads to greater contribution to global warming potential. However, this contribution is offset by the replacement of synthetic fertilizers by organic fertilizers (manure or compost) as well as by the elimination of non-organic plant protection products. Overall, model-based estimates indicate a 2% reduction in GWP, reaching 4.6E+03 kg CO_2 eq per ha per year. It should be noted, however, that these values are based on specific assumptions and the actual results for each farm may differ depending on farm-specific factors like yields, soil conditions, and management practices. Additionally, organic farming scenarios showed a 2% increase in terrestrial acidification. This is explained by the combined effects of applying manure and using more diesel. Freshwater eutrophication was significantly reduced by organic farming, with estimated values falling by 75% (down to 0.07 kg P eq). This was mainly because less phosphorus-based fertilizer was used. The replacement of synthetic pesticides by organic plant protection products, was linked to significant reductions in the terrestrial and freshwater ecotoxicity (by 33% and 91% respectively). Specifically, terrestrial ecotoxicity in the baseline scenario was up to 8540 kg 1,4-DCB per ha per year, due to the extensive use of synthetic pesticides, as well as diesel combustion. Organic farming scenario presented reduced values of this indicator (6085 kg 1,4-DCB per ha per year), emphasizing its environmental benefits.

The adoption of **cover crops** can lead to several positive environmental impacts. Their beneficial effects on pest control and carbon sequestration usually offset the initial increase in global warming potential that may result from additional field operations associated with their cultivation. In the scenarios studied, an estimated net reduction in global warming potential of up to 10% was observed. Their use may also lessen the need for pesticides and fertilizers, which could lead to a significant decrease in freshwater and terrestrial ecotoxicity as well as a 7–31% decrease in terrestrial acidification. Crop type, management techniques, and regional circumstances can all affect these effects.

Several environmental benefits are related to the **floral bands** integration into apple orchards, mainly in the form of less pesticide use. Reductions in freshwater ecotoxicity (8–28%) and terrestrial ecotoxicity (1–4%) were linked to even a 10% decrease in the use of synthetic pesticides. Although practical benefits rely on particular implementation practices, these results demonstrate the potential of ecological approaches.

Another promising strategy is **grazing**, which could reduce greenhouse gas emissions by up to 33% if it is assumed that less fertilizer, pesticide, and machinery will be needed. In particular, under ideal grazing conditions, global warming potential could decrease from 4798 kg CO_2 eq to 3220 kg CO_2 eq per ha annually. Reductions in freshwater eutrophication (10–36%), terrestrial acidification (9–14%), ecotoxicity, and fossil resource scarcity (up to 37%) are additional advantages for the specific grazing scenarios, demonstrating the potential resource-efficiency of integrated livestock-plant systems.

The transition to **renewable energy**, through the installation of photovoltaic panels, offers a big chance for environmental benefits. Global warming potential could be reduced by 50% by switching to renewable energy instead of fossil fuels, and other effects like terrestrial acidification potential and the potential scarcity of fossil resources could be decreased by 30% and 56%, respectively. Although the effectiveness will rely on site-specific feasibility and investment capacity, these findings highlight the potential of adopting renewable energy.

In summary, the modeled systems offer insightful information about the possible environmental effects of the different CSA practices. Each different CSA practice has its own distinct benefits and sometimes drawbacks; a combined application would have the potential to provide improved benefits, supporting the broader sustainability goals in apple production. Given that yields, resource use, and environmental conditions can differ significantly among individual farmers, these results may vary in farm-specific contexts.

3.3.5. Life Cycle Cost Analysis (LCC)

A comparative LCC analysis was conducted for the different scenarios, predicated on a set of modeled assumptions and average values unique to the modelled orchard. Farm-specific factors like management techniques, market prices, equipment depreciation, and access to subsidies can all have a substantial impact on actual costs, yields, and revenues. Therefore, the model can offer indicative insights into the economic implications of various CSA practices, based on the interpretated illustrative results. Annual operating costs, annual revenues, any subsidies provided, and any additional capital expenses required for the adoption of CSA practices were taken into account. The main outputs of the LCC analysis are presented in Table 15. 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 studied system boundaries. 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.

The integration of agri-environmental management commitments, 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). This investment supports the long-term sustainability of organic farming practices, contributing to both environmental and agricultural benefits. In this modeled scenario, due to their increased added value, the apples are sold at a price 20% higher than that of conventional apples. Synthetic plant protection products are not applied in this scenario, thus their cost is not included; synthetic fertilizers are replaced by equivalent amount of manure from neighboring farms that is supplied free of charge - only the transportation cost is included. The need for more intensive techniques for weed and pest management leads to increased total cost of diesel. At the studied product system, the cost of diesel use appears 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 neighbour farms, thus only the cost of its transportation is taken into account. For these reasons, the total costs are calculated up to ~10,800 € per ha per year (direct costs: 2,000 €, indirect costs: 8,800 €) and decreased by 5% compared to the baseline scenario. The increased by 20% market value of the final product, despite the reduced yield per ha, along with the subsidy provided, increase the revenues of the modelled farm per ha per year by 6%. The above contribute to profit increase by 46%, leading to a sum 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 3 different scenarios of **cover crops** selected for the LCA analysis were also studied for LCC. The reduced use of pesticides led to a subsequent reduction in cost of plant protection products. The extra subsidy provided for the application of cover crops was 100€/ha[11]. The cost for the planting and management of cover crops is estimated

[11] https://www3.sede.fega.gob.es/bdcgabcse/inicio/inicioAplicacion.action

to be quite low (seeds 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 modeled scenario, an apple orchard using cover crops could generate up to €15,320 in revenue, including any applicable subsidies. The total costs, assuming no additional capital expenditures, are estimated to be between €11,110 and €11,360. Under the specified assumptions, this leads to a projected profit margin of €3,960 to €4,210 per hectare annually, which represents a 6–13% increase over the baseline scenario. The 3 different scenarios of **floral bands** selected for the LCA analysis were also studied for LCC. The reduced use of pesticides led to a subsequent reduction in cost of plant protection products. An additional subsidy of 40€/ha was considered for the adoption of floral bands[12]. The costs for the planting and management of floral bands were estimated to be quite low (seeds 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 between 11,110€ and 11,360€. Revenues, including subsidies, could reach about 15,260€/ha in this scenario. Under the specified assumptions, this translates to an estimated annual profit of 3,960€ to 4,210€/ha, or a 3-7% increase over the baseline scenario. The 3 different scenarios of **grazing** selected for the LCA analysis were also studied for LCC. A reduced use of pesticides was assumed to result in lower expenditures for lant protection products. An extra subsidy of 29€/ha was included to account for policy support for grazing practices[13]. In the modelled scenarios, 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 10-50%, depending on the scenario studied. Similarly, the cost of pesticides was estimated to be reduced by 10-30%. 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 vary between 10,740€ and 11,090€, assuming no additional CaPex required. In comparison to the baseline scenario, this translates to a potential profit margin of 11-21%, or 4,160€-4,510€/ha annually. These numbers are only estimates, though, and are highly dependent on context-specific factors like local labor and fuel prices, livestock availability, and the availability of subsidies. In the scenario of **renewable energy**, the average installation cost of the solar panels was estimated at 703 €/kW, resulting in total CapEx of approximately 18,980€. for the installation of the 12 kW and 15 kW solar panel systems. This investment is partially supported by the EU Next Generation Funds subsidy scheme. A straight-line depreciation method was assumed for the cost that is not covered by the subsidy scheme (8860€), with a depreciation period of 25 years. Because solar energy partially replaced fossil fuel energy, operational cost savings were mainly linked to a 50% decrease in diesel consumption. Furthermore, it was assumed that any excess electricity that was not used on-site would be sold to the grid at a rate of €0.30/kWh. The installation of solar energy systems seems to have potential financial advantages under these simulated circumstances. While total expenses stay around 11,380€, revenues, including subsidies and money from the sale of electricity, could reach up to 16,370€/ha annually. In comparison to the baseline scenario, this translates into an estimated 33% increase in profit.

Cost category (€/ha/year)		Baseline	Organic farming	Cover crops	Floral Bands	Grazing	Renewable Energy
EX PE	Annualized CapEx	€ -	€ -	€ -	€ -	€ -	€ 354
	Energy	€ 908	€ 1,379	€ 908	€ 908	€ 635	€ 454

[12] https://www3.sede.fega.gob.es/bdcgabcse/inicio/inicioAplicacion.action

[13] https://www3.sede.fega.gob.es/bdcgabcse/inicio/inicioAplicacion.action

	Water	€ 532	€ 532	€ 532	€ 532	€ 532	€ 532
	Fertilizers	€ 526	€ -	€ 423	€ 526	€ 372	€ 526
	Manure transportation	€ -	€ 60	€ -	€ -	€ -	€ -
	Plant protection products	€ 741	€ 90	€ 596	€ 596	€ 596	€ 741
	Maintenance	€ 1,447	€ 1,893	€ 1,447	€ 1,447	€ 1,447	€ 1,447
	Own labor opportunity cost	€ 591	€ 591	€ 591	€ 591	€ 591	€ 591
	Labor	€ 4,490	€ 4,062	€ 4,490	€ 4,490	€ 4,490	€ 4,490
	Other (taxes, admin, etc)	€ 2,248	€ 2,248	€ 2,248	€ 2,248	€ 2,248	€ 2,248
	Total	€ 11,482	€ 10,855	€ 11,235	€ 11,337	€ 10,911	€ 11,028
	Change over BL:		-5.5%	-2.2%	-1.3%	-5%	-4%
REVENUES	**Apples**	€ 15,050	€ 15,480	€ 15,050	€ 15,050	€ 15,050	€ 15,050
	Subsidies	€ 170	€ 696	€ 270	€ 210	€ 199	€ 170
	Electricity credit	€ -	€ -	€ -	€ -	€ -	€ 1,145
	Total	€ 15,220	€ 16,176	€ 15,320	€ 15,260	€ 15,249	€ 16,366
	Change over BL:		6.28%	0.66%	0.26%	0.19%	7.53%
Profit		€ 3,738	€ 5,320	€ 4,086	€ 3,923	€ 4,338	€ 5,338

Table 15: Comparative LCC analysis (annual basis) of the baseline scenario and the different CSA practices for the Spanish UC.

3.3.6. Social Life Cycle Impact Assessment (s-LCIA) – Apple farming, Spain

The production flows and relevant inventory data of all the examined Spanish CSA scenarios were taken from the resulting LCIAs shown in previous Table 13. According to the received questionnaire, the data inputs for 4 out of 5 CSA scenarios were similar with the baseline scenario, and thus were directly taken from Table 21 of the previous D3.1. These included the "Worker hours" activity variable and the impact factors with their associated risk levels. The only exception was the organic farming scenario, which resulted in different values for the "Worker hours" activity variable and the "Certified Environmental Management Systems" impact factor. The first one was recalculated, based on the reduced annual production of 30tn, while the latter changed its value to "Yes" and its risk level became "Very Low" accordingly. The changes to the data inputs, with regards to the baseline scenario described in previous D3.1, are summarized in Table 16 below:

Input	Baseline	Organic farming	Cover crops	Floral bands	Grazing	Renew-able energy
Worker hours[6]	0.0207h	0.0241h	0.0207h	0.0207h	0.0207h	0.0207h
Certified Environ-mental Manage-ment Systems	Very High	Very Low	Very High	Very High	Very High	Very High

Table 16: Changes of the data inputs of s-LCIA, from the Spanish baseline scenario, shown in previous D3.1 (the impact factors not shown were not changed and thus were taken directly from the baseline scenario, as presented in Table 21 of the previous D3.1).

The results from the s-LCIA analyses for all the examined CSA scenarios are shown in Figure 7 below. Along with the studied CSAs, the results of the baseline scenario have also been updated due to database updates (ILO, WHO etc.) that changed the risk levels of some impact factors. A more detailed analysis of each CSA examined is given below. Generally, the results were in line with the changes of the LCI. However, some of the impact factors resulted in high social footprints, despite the fact that they had very low-medium risks. This was found for all examined CSAs and the baseline scenario as well, and was attributed to impacts from upstream flows. More specifically, for the baseline scenario, most impactful flows were the ones related with the production and use of diesel on global scale, followed by irrigation and production & use of fertilizers. Any CSA that contributed a positive change to the above resulted in reduced impacts.

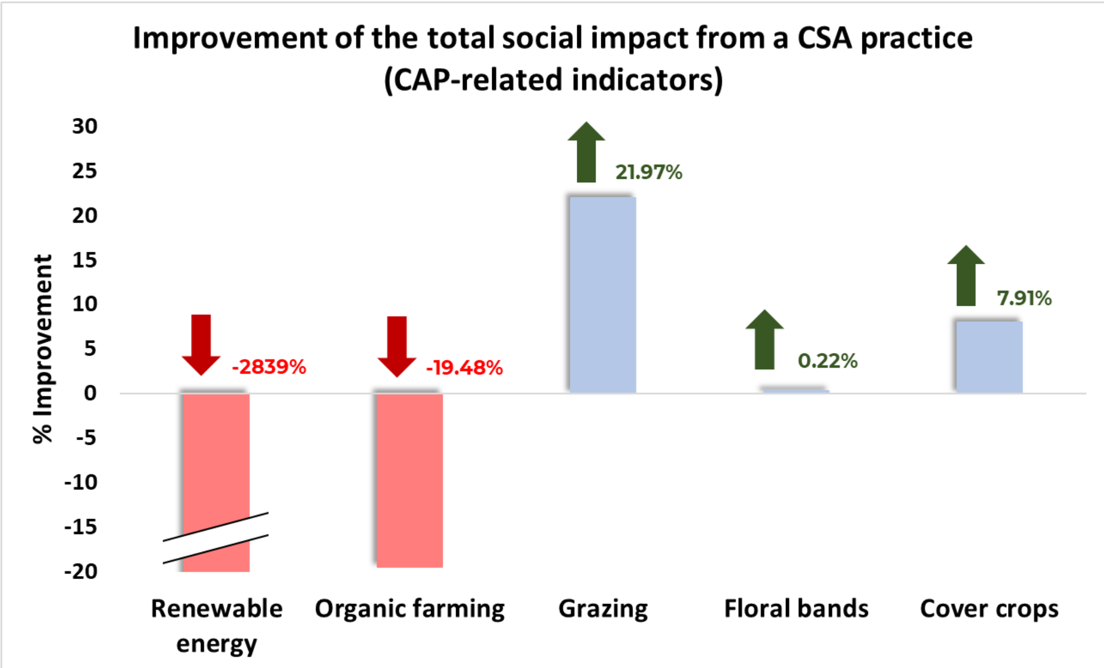


Figure 7: Comparison of the changes in the social impacts from the investigated CSAs, regarding the EU CAP-relevant social indicators – impacts per kg of apples per year (Spanish UC) (0 value represents the baseline - note that for the renewable energy scenario, the actual bar exceeds below the scale of Y-axis).

Renewable energy | s-LCA

Beginning with the renewable energy scenario, this one performed much worse than the baseline scenario, resulting in ~33x more DALYs in total. This result was not expected, as the anticipated changes only included the flows relative to the renewable energy system. Focusing on the CAP-relevant indicators that are more in accordance with the BEATLES project, the renewable energy scenario resulted in 29x increased social footprints. The 4 most important factors were the Fair Salary, followed by Embodied Biodiversity Footprints, GHG Footprints and Unemployment rate. As a result, the renewable energy scenario resulted in significantly higher social impacts than the baseline scenario, due to the impacts associated with the production and installation of the renewable energy system on global scale (solar panels, mounting system, inverter).

Organic farming | s-LCA

Moving on to the organic farming scenario, this one performed worse than the baseline scenario, resulting in a 22% increase in total DALYs. This result was expected, due to the increased "Worker hours" activity variable, meaning that the same amount of effort from workers, who were paid similarly with the baseline scenario, produce significantly less product (30tn instead of 35tn). Focusing on the CAP-relevant indicators that are more in accordance with the BEATLES project, the organic farming scenario resulted in 19% increased social footprints. The 4 most important factors were the Fair Salary, followed by Embodied Biodiversity Footprints, GHG Footprints and Unemployment rate. As a result, it is anticipated that, if the annual production in the organic farming scenario could remain at 35tn (in order to keep the same value for the "Worker hours" activity variable), the overall social impacts would have been significantly decreased, as the absence of the synthetic fertilizer flow would lead to reduced values.

Grazing | s-LCA

Subsequently for the Grazing scenarios, all 3 grazing scenarios examined performed much better than the baseline scenario, especially scenario #3 that used reduced amounts of chemicals. The grazing scenarios resulted in 21-31% decrease in total DALYs. This result was expected, as the anticipated changes were mostly based on changes in the LCI. Focusing on the CAP-relevant indicators that are more in accordance with the BEATLES project, the grazing scenario resulted in up to 27% reduced social footprints. The 4 most important factors were the Fair Salary, followed by Embodied Biodiversity Footprints, GHG Footprints and Unemployment rate. As a result, since there is a big difference in both the amounts of diesel (30% decrease) and synthetic fertilizers (up to 50 % decrease in scenario #3) used in the grazing scenario, compared with the baseline, it is expected that the social impacts decrease accordingly; from scenario #1 that uses the highest amounts of synthetic fertilizers, close to the baseline ones, to scenario #3 that uses the least amounts of them.

Floral bands | s-LCA

Moving on to the floral bands scenarios, all 3 floral bands scenarios examined performed very close to the baseline scenario, with very marginal improvements, resulting in 0.2-0.5% decrease in total DALYs. Since the inputs for the floral bands scenarios were the same as with the baseline scenario, this result was expected, as the anticipated changes were mostly based on changes in the LCI. Focusing on the CAP-relevant indicators that are more in accordance with the BEATLES project, the floral bands scenario resulted in up to 0.4% reduced social footprints. The 4 most important factors were the Fair Salary, followed by Embodied Biodiversity Footprints, GHG Footprints and Unemployment rate. As a result, since none of the most impactful flows were changed for the floral bands scenarios, it is expected that the social impacts are very similar with those of the baseline scenario, with only marginal differences due to slight reduction of the quantities of chemicals; from scenario #1 that uses the highest amounts of them, close to the baseline ones, to scenario #3 that uses the least amounts of them.

Cover crops | s-LCA

Finally, for the Cover crops scenarios, all the 3 cover crops scenarios examined performed better than the baseline scenario, especially scenario #3 that used reduced amounts of chemicals. The cover crops scenarios resulted in 6-9% decrease in total DALYs. This result was expected, as the anticipated changes were mostly based on changes in the LCI. Focusing on the CAP-relevant indicators that are more in accordance with the BEATLES project, the cover crops scenario resulted in up to 12% reduced social footprints. The 4 most important factors were the Fair Salary, followed by Embodied Biodiversity Footprints, GHG Footprints and Unemployment rate. As a result, since the only difference for the cover crops scenarios regarding the most impactful flows is the quantities of synthetic fertilizers used, it is expected that the social impacts decrease accordingly; from scenario #1 that uses the highest amounts of synthetic fertilizers, close to the baseline ones, to scenario #3 that uses the least amounts of them.

Conclusions | s-LCA

According to the results from the s-LCA analyses, from the social impact perspective, the best results were acquired from the grazing scenario (up to 27% reduced footprints), followed by cover crops (up to 12% reduced footprints). Floral bands scenario performed very close to the baseline one (up to 0.4% reduced footprints) and can be considered in case the improvement of the social footprints is a secondary objective of the transition-to-CSA strategy. On the other hand, organic farming and especially renewable energy scenarios were found to bear significantly increased social footprints (19% and 29x increased footprints respectively) and as such, it is suggested that they will be examined as secondary options, in case the previous ones do not fulfil the needs of the transition-to-CSA strategy. Particularly for the renewable energy scenario, it's worth reminding that the increased social footprints were mainly attributed to the production stage of the solar panels in global scale (as noted above) and are not associated with their use in the farm, nor their impact in local communities and/or workers.

3.3.7. Cost-Benefit Analysis

Organic farming and related sustainable practices such as cover crops, floral bands, grazing, and renewable energy present a holistic set of trade-offs in terms of cost, environmental sustainability, and socio-economic outcomes. Organic farming often faces initial economic challenges, including reduced yields—estimated at around 15%—and increased labor demands (up to 16% more working hours per hectare), leading to higher operating costs (~11 k€/ha annually). However, this is balanced by premium market pricing, lower long-term input costs, and government subsidies, resulting in profits exceeding 5 k€/ha. Organic systems also see a 50% rise in diesel consumption due to increased mechanical weed control, but this is countered by strong environmental performance—such as 91% reduction in freshwater ecotoxicity and significant social benefits including safer working conditions and reduced chemical exposure for communities.

Cover crops add ecological and economic value with minimal financial strain. Although they slightly increase labor and energy use, these costs are deemed negligible. They reduce global warming potential by up to 10% and eutrophication by up to 39%, while enhancing soil fertility, biodiversity, and pest control through natural mechanisms. Economically, cover crops contribute to improved farm profitability (4–4.2 k€/ha) with modest subsidies and low maintenance costs. Socially, the reduced pesticide usage improves public health (3% DALY reduction) and can stimulate local employment through slight increases in labor demand.

Floral bands are another cost-effective strategy that can be implemented with minimal disruption to operations. Planted in non-productive orchard areas, they incur very low costs while yielding environmental improvements such as up to 28% reduction in freshwater ecotoxicity and enhanced agro-biodiversity. Economically, they support profits of around 4–4.2 k€/ha with modest subsidies and pesticide savings. Social impacts are small but positive, improving worker safety and fostering public trust in sustainable agricultural practices.

CSA	Costs	Benefits		
		Environmental	Economic	Social
Organic Farming	OpEx at about 11 K€ for the production of 30 tons apples per ha annually in the studied scenario) Organic farming usually leads to lower yield in the first years of transition (about 15% reduction in the studied scenario), due to absence of synthetic plant protection products Increased machinery use (50% increased diesel consumption in the studied scenario), due to the additional need for weed and pest control 16% increase in working hours per ha per year in the studied scenario, due to more labor-intensive practices required for weed and pest management.	↓ GWP 2%, in the scenario studied, due to the absence of synthetic fertilizers and plant protection products ↓ terrestrial 33% and freshwater ecotoxicity 91% in the studied scenario, due to the absence of synthetic plant protection products ↓ eutrophication 75%, in the studied scenario, due to the absence of synthetic fertilizers Enhanced Soil Biological Activity and Regeneration, due to increased organic matter input and reduced soil disturbance Long-Term Ecosystem Resilience supported by diversified plant and microbial communities Pollinator Habitat Conservation, ensured by maintaining flowering plants and natural vegetation Water Quality Protection achieved through reduced nutrient runoff	Revenues (includ. subsidies) at about 15.5 k€/ha/year, in the studied scenario, due to the premium pricing of organic apples and the extra subsidies provided Profit above 5 k€/ha/year, in the studied scenario Access to subsidies ~700€/ha, in the studied scenario Premium price of organic apples (20% increase in the studied scenario) Lower Input Costs Over Time, due to the absence of synthetic fertilizers and plant protection products Market Differentiation and Export Potential	Improved Worker Health and Safety Community Health and Wellbeing Empowerment Through Participation in Sustainability Increased Consumer Trust and Engagement

CSA	Costs	Benefits		
		Environmental	Economic	Social
Cover Crops	Requirement for Increased energy consumption due to additional machinery use (rotavator, seeder, mower). Low implementation costs, negligible in the studied scenarios. OpEx remain at 11200€ (2% lower than the baseline scenario)	↓ GWP up to 10%, in the studied scenario, due to reduced use of synthetic fertilizers and plant protection products Significant decrease in ecotoxicity and eutrophication (up to 39% and 6% respectively, in studied scenarios), due to reduced reliance on synthetic fertilizers and plant protection products. Increased fertility, organic matter content, and soil structure, through biomass deposition. Improved pest control through beneficial insect habitat and trap crops. Enhanced water retention and decreased soil erosion, through ground cover and root systems stabilizing the soil. Reduced nutrient runoff, water quality protection via nutrient uptake by cover crops and reduced leaching. Contribution to carbon sequestration by storing carbon in plant biomass and soil.	Additional subsidy for the use of cover crops: 100€/ha Revenues (including subsidies) above 15 k€ per ha annually in the studied scenario. Profit margin: 6-13% higher than baseline, 4-4.2 k€ per ha/year, due to reduced costs for fertilizers and plant protection products. Minimal expenses for seeds and maintenance in the studied scenarios. Improved farm sustainability and resilience.	Improved worker health and safety due to reduced pesticides use (3% reduction in DALYs) Enhanced community well-being through better environmental quality. Increased labor demand may support local employment. Positive contribution to fair salary and reduced social risk indicators (e.g., embodied biodiversity, GHG footprints). Reinforces public trust and engagement in sustainable food systems.

CSA	Costs	Benefits		
		Environmental	Economic	Social
Floral bands	Low implementation costs (seeds, planting, and sporadic monitoring), deemed insignificant in the context of the study. No more workers are needed, but planting takes a little longer, which may lead to a slightly increased labor cost. Occupies approximately 2% of the plot area, though usually placed in non-productive zones, minimizing loss of productive land.	↓freshwater ecotoxicity 8-28%, due to decreased use of synthetic pesticides in the studied scenarios. ↓terrestrial ecotoxicity 1-4%, due to decreased use of synthetic pesticides in the studied scenarios. Improved environmental impact and lower chemical residues due to decreased use of synthetic pesticides. Improved biological pest control, due to more habitat for beneficial insects. Decreased runoff of phytosanitary products, particularly when bands are placed on the edges of the plot. Increased landscape heterogeneity and agro-biodiversity.	Subsidy of ~40€/ha for the adoption of floral bands. Total revenue potential (including subsidies) above 15 k€/ha annually in studied scenarios. Profit margin of ~4-4.2 k€/ha annually in studied scenarios, representing a 3-7% increase over the baseline scenario. Lower pesticide input costs due to improved natural pest regulation. Feasible without capital investment, providing a low-risk strategy for farmers.	Improved worker health and safety due to reduced pesticides use (0.2-0.5% reduction in DALYs) Social footprints in CAP-relevant categories can be reduced by up to 0.4% in the studied scenarios. Positive contribution to fair salary and reduced social risk indicators (e.g., embodied biodiversity, GHG footprints). DALYs overall by 0.2-0.5% in the studied scenarios, indicating slight improvements in public health. Reinforces public trust and engagement in sustainable food systems.

Grazing	Direct implementation costs of grazing are minimal, as no CapEx is required, and no feed or veterinary inputs were accounted for in the modelled system. Occasional damage to trees, although this is context-specific and not systemically significant.	↓33% in global warming potential: from ~5000 kg CO_2 eq to ~3200 kg CO_2 eq per ha annually in optimal scenarios, due to reduced need for machinery use as well as decreased use of synthetic fertilizers and plant protection products. ↓Freshwater eutrophication 10-36% in the studied scenarios, due to decreased use of synthetic fertilizers and plant protection products. ↓Terrestrial acidification 9-14% in the studied scenarios due to decreased use of synthetic fertilizers and plant protection products, as well as reduced use of diesel. ↓Fossil resource scarcity up to 37% in the studied scenarios due to reduced need for machinery use and thus less diesel consumption. Improved nutrient cycling and soil fertility through natural manure deposition. Enhanced biodiversity and suppression of pest and mole activity without chemical inputs.	Subsidy of 29€/ha. Total annual revenues, including subsidies, above 15 k€/ha in the studied scenarios. Total costs 10-11 k€/ha, resulting in a profit margin of ~4-4.5 k€/ha annually, or an 11-21% increase over the baseline scenario, due to reduced use of diesel and synthetic fertilizers and plant protection products. Organic fertilization and cost-efficient pest management, with no additional CapEx required. Collaboration with neighboring farms, enhancing local agricultural integration and reducing logistical barriers	21-31% decrease in DALYs, indicating improved human health outcomes. Social risk indicators under the CAP framework showed up to a 27% reduction in social footprints (Fair salary, embodied biodiversity, GHG emissions, unemployment) Cooperative models, where local producers share resources (e.g., livestock), foster community engagement, knowledge exchange, and regional resilience.

CSA	Costs	Benefits		
		Environmental	Economic	Social
Renewable Energy	Average installation cost 700 €/kW. After subsidies, the net investment cost is reduced to 8,800 €. Higher social impacts are traced to upstream manufacturing of solar panels, particularly due to energy-intensive processes and global material sourcing.	↓Global warming potential 50%, mainly due to lower diesel use. ↓ Terrestrial acidification 30% mainly due to lower diesel use. ↓ Fossil resource scarcity 56% due to lower diesel use. Replacement of fossil fuels with 100% renewable energy for irrigation and warehouse maintenance.	Complete on-site generation eliminates electricity purchase from the grid. Total annual revenue (including subsidies and energy resale): above 16 k€/ha. 33% increase in profit, through sale of extra energy produced to the grid. 50% decrease in energy costs, long-term financial sustainability, through use of renewable energy. Maximum spatial efficiency and non-invasive deployment are made possible by panels mounted on warehouses.	Solar energy utilization on-site increases energy autonomy and lowers worker exposure to diesel emissions. 59% decrease in DALYs

Table 17: Summary of Cost – Benefit Analysis for the CSA practices in the Spanish UC.

Grazing offers significant environmental and economic advantages with virtually no capital investment required. It drastically lowers GHG emissions—by up to 33%—and reduces fossil resource scarcity and eutrophication due to lower diesel use and natural nutrient cycling. Economically, grazing provides a profit boost of 11–21% over baseline systems, while requiring little additional input. Socially, the approach demonstrates strong benefits, including up to a 31% drop in DALYs and improved community cohesion through collaborative livestock sharing.

The use of solar energy involves upfront CapEx (~19 k€, offset to ~8.8 k€ via subsidies), but long-term operational savings and additional income from energy sales elevate total revenue to 16 k€/ha and profits to 5 k€/ha. Environmentally, solar systems cut global warming potential by 50% and eliminate on-farm fossil fuel dependence. Though upstream manufacturing of PV systems presents certain social risks, on-site clean energy enhances worker safety (59% DALY reduction) and promotes energy autonomy. Overall, combining these practices can foster a resilient, sustainable agricultural model with balanced economic returns and clear ecological and social gains.

3.4. Use Case Pilot #4: Pig farming, Denmark

3.4.1. Description of the CSA practices

Frequent discharge of slurry | Description

Manure management is a critical factor in the environmental footprint of pig farming, representing a significant source of CH_4, NH_3, and other greenhouse gas (GHG) emissions. Globally, livestock production accounts for approximately 80% of agricultural CH_4 emissions, while NH_3 emissions from livestock manure constitute 80-90% of total agricultural NH_3 emissions (Ma et al., 2023). Among manure handling systems, liquid manure (slurry) management poses a particularly high risk for CH_4 emissions, compared to solid manure systems, due to the anaerobic conditions favorable for methanogenesis (IPCC, 2019). Gaseous emissions occur both inside barns, from slurry pits under slatted floors, and during outdoor storage. The anaerobic environment of slurry during storage enables fermentation and methanogenic activity, making both housing and storage facilities key intervention points for emission mitigation (Gerber et al., 2013; Kupper et al., 2020).

One promising management approach is the frequent removal of slurry from animal housing to external storage. In Danish finisher pig houses, the slurry is removed with a vacuum flushing system every 5−6 weeks (Dalby et al., 2023). Research shows that increasing the frequency of manure discharge can substantially reduce CH_4 emissions, particularly in cool or temperate climates where lower external storage temperatures limit methanogenic activity. The biological adaptation and proliferation of methanogens is temperature-dependent; hence, frequent slurry export disrupts microbial growth cycles, reducing CH_4 production during initial storage phases. However, the impact on ammonia emissions is more complex and may vary with climate and specific management practices. For instance, while transferring slurry to cooler environments reduces CH_4 emissions, it may lead to increased NH_3 volatilization unless complementary mitigation measures are applied (Ma et al., 2023). The above findings underline the potential of frequent slurry removal as a low-cost, sustainable approach for in pig farming.

Acidification of slurry | Description

As described above, manure management is a critical process in pig farming regarding the GHG emissions of the farm. For this reason, various mitigation strategies targeting this stage have been developed. Acidification of slurry is one of the approaches developed to inhibit microbial activity and reduce gaseous losses, as it has a documented potential to reduce both NH3 and CH4 emissions (Shin et al., 2019; Sokolov et al., 2020).

In Denmark, the adoption of slurry acidification has progressed substantially. Currently, approximately 20% of all slurry is acidified prior to land application. The technology is fully integrated into national environmental legislation and recognized as a Best Available Technique (BAT) in the final draft of the BREF for the Intensive Rearing of Poultry and Pigs[14]. Danish farmers are further incentivized to implement this technology due to regulatory benefits, such as permission to expand farm operations based on verified reductions in NH_3 emissions, and exemptions from requirements like slurry injection or sub-plowing following surface application. Numerous studies confirm the effectiveness of slurry acidification in reducing NH_3 emissions during all phases of manure handling-in-house, during storage, and after field application (Fangueiro, Hjorth & Gioelli F, 2015).

The process involves daily pumping of slurry from livestock housing to an external process tank, where it is mixed with concentrated sulfuric acid (93-96% w/v) until a target pH of 5.5 is reached. This acidified slurry is then partially returned to the livestock building to maintain a slurry level of approximately 20 cm in the pit, while the excess is transferred to a long-term storage tank. The entire operation including the emptying and filling of slurry tanks and the acidification process-is managed via a PLC-controlled (computerized) valve system. Each valve can serve slurry tanks covering an area of approximately 800 to 1,500 m², with the process tank sized according to the maximum slurry volume managed per valve. Acid usage typically ranges from 10 to 14 kg per tonne of slurry, depending on the slurry's dry matter content and other properties. Attempts to reduce the frequency of acidification to twice per week resulted in no significant decrease in acid use, but did lead to a marked drop in ammonia reduction efficiency from 62% down to 38%. This underscores the importance of daily acidification for optimal emission control.

The primary environmental benefit of slurry acidification lies in its inhibition of microbial activity within the slurry, effectively suppressing the biological processes that generate methane (CH_4), ammonia (NH_3), and hydrogen sulfide (H_2S) gases. Pilot-scale studies have shown that methane emissions from acidified pig slurry stored for 83 days were more than 90% lower compared to untreated slurry (Petersen et al., 2014). This strongly suggests that acidification significantly mitigates methane emissions during slurry storage.

Regarding nitrous oxide (N_2O), current evidence does not indicate a direct effect of slurry acidification on emissions following land application. According to IPCC guidelines, no net change in N_2O emissions is expected as a result of acidification. However, by reducing ammonia volatilization, more nitrogen is retained in the slurry. When this nitrogen is accounted for in the farm's fertilization plan, effectively replacing synthetic fertilizers, an indirect reduction in nitrous oxide emissions may occur due to lower reliance on mineral nitrogen inputs (Kai et al. 2022).

Manure management - biogas production | Description

Anaerobic digestion is, a microbial process that breaks down organic materials in the absence of oxygen, and produces biogas, a renewable biofuel. Numerous feedstocks, such as household organic waste, livestock manure, industrial by-products, and agricultural residues, can be used in this process (Igliński et al., 2012; Bacenetti et al., 2014). The most plentiful organic waste source for biogas production in Europe is animal manure (Meyer et al., 2009).

There are several agronomic, environmental, and financial advantages to the anaerobic digestion of manure. It increases manure's fertilizer value, lowers pathogens and odors, and makes it

[14] https://en.lbst.dk/agriculture/acidification

possible to turn waste into energy. In addition, the process produces digestate, a nutrient-rich by-product that can be used as an organic fertilizer. This helps agricultural systems recycle nutrients and lessens the need for mineral fertilizers (Meyer et al., 2009).

Anaerobic digestion dramatically lowers CH_4 emissions from manure during post-digestion storage (Baral et al., 2018). However, especially for small-scale farms, the distance to centralized biogas facilities can be a logistical and financial obstacle (Skovsgaard & Jacobsen, 2017).

Despite being one of the most environmentally friendly substrates for anaerobic digestion, manure has a low potential energy. This is explained by its high moisture content, low volatile solids content, and high ammonium concentrations, all of which can suppress microbial activity. Therefore, to increase biogas yields, co-digestion with higher-energy substrates, like food industry waste, is frequently employed (Esteves, E.M.M. et al., 2022).

Biogas production from pig manure in Denmark occurs at both farm-scale facilities, operated by individual producers, and joint biogas plants, shared by multiple farms. The overall production process comprises the following steps: (1) Transport and Pre-Storage: Pig manure is collected from the stables and transferred to a pre-storage tank, (2) Anaerobic Digestion: The manure is heated to approximately 37°C and fed into an anaerobic digester, where it is often mixed with co-substrates from slaughterhouses or the fish processing industry, (3) Biogas Capture: Methane-rich biogas generated in the reactor is stored in a gas holder., (4) Energy Conversion: The biogas is combusted in a stationary engine or gas burner to produce electricity and/or heat., (5) Digestate Storage and Use: The residual digestate is stored and later applied to cropland as fertilizer, (7) Energy Utilization: Electricity is consumed on-site or exported to the national grid, while heat is used locally or supplied to district heating systems. At joint biogas plants, manure is typically transported 1.5 to 7.5 km, whereas farm-scale units involve minimal transportation (info provided during data collection[15]).

Green protein for feed | Description

With inclusion rates of up to 15% of feed dry matter, clover grass protein has been shown to be a successful soy substitute in organic pig diets without having an adverse effect on meat quality or growth performance. Research on traditional slaughter pigs has demonstrated that soy protein can be successfully substituted with local protein sources like fava beans and clover grass protein, with signs of better protein utilization. Interestingly, pigs fed grass protein produced about 2% more meat than those fed traditional soy-based feed, and the quality of the meat they ate was unaffected. Pleasant flavor, a steady supply throughout the summer and winter, and the potential to lessen dependency on concentrated feeds are further advantages of grass-based feed. A more sustainable feed strategy is supported by the addition of valuable protein from grass-derived roughage. However, the overall sustainability and nutritional value of biorefined grass products can be impacted by differences in the composition of biomass and processing conditions.

Fresh green biomass is harvested in the field to start the biorefining process of green protein for pig feed. Since the platform depends on fresh biomass, post-harvest processing must be done right away to reduce the degradation of macronutrients, especially proteins and simple carbohydrates. Following harvest, the biomass is taken to the processing plant, where it is macerated to increase surface area and break up plant cells, making it easier to extract the contents of the cells. A variety of mechanical techniques are used, such as pulping, shredding, and cutting. The biomass is separated into two fractions using the screw pressing technology: a solid fiber fraction called "press pulp" or "press cake" and a liquid called "green juice."

[15] https://www.lcafood.dk/processes/energyconversion/heatandpowerfrommanure.htm?

Soluble proteins, simple carbohydrates, free amino acids, lipids, enzymes, inorganic nutrients, and other soluble biomolecules like carotenoids and tannins are all present in the green juice. The lignocellulose components (cellulose, hemicellulose, and lignin) and remaining soluble compounds that are retained in its moisture content are abundant in press pulp. The press pulp, which has a dry matter content of about 30-40%, is suitable for ensiling and can be used directly as feed for pigs or further processed to create biomaterials, biofuels, or bioenergy.

The green juice is filtered to get rid of fibers and particles after screw pressing. For a subsequent separation cycle, these filtered fibers are recycled back into the press. By heating the green juice to 80-90ºC, which causes protein denaturation and coagulation, protein can be extracted from the juice. Heat exchangers are usually used for heating. The coagulated proteins are then separated into a moist solid fraction (protein concentrate) with a dry matter content of 40–50% using a decanter centrifuge. Precipitated proteins, plant lipids, and carbohydrates are all present in this protein concentrate. The residual soluble substances found in the remaining liquid fraction, also known as "brown juice", include free amino acids, organic acids (if fermentation takes place), oligo- and mono-saccharides, and inorganic nutrients (Jørgensen et al., 2021).

Ventilation technologies | Description

In order to reduce emissions, improve energy efficiency, and promote sustainable manure management, modern pig farming is progressively incorporating cutting-edge environmental technologies. Among these, air purification technologies in conjunction with optimized ventilation systems are widely used. Spot extraction systems utilize the natural airflow in slurry pits and are positioned strategically beneath the animal resting areas. Gaseous emissions, especially ammonia and odor, can be efficiently captured using this method and treated in integrated chemical and biological air cleaning units. According to the Danish Environmental Protection Agency[16], these systems have been shown to reduce ammonia and odor by up to 96% and 77%, respectively.

The amount of electricity used per produced finishing pig has been greatly decreased by advancements in ventilation technology. Even when paired with air cleaning operations, contemporary low-energy systems like SKOV's LPC fans with Dynamic Multistep control have lowered the energy consumption per pig from around 10 kWh in the past to as low as 2.5-4 kWh[3].

Another solution used on some Danish farms is slurry cooling. In addition to recovering thermal energy, embedded cooling pipes beneath the slurry pits lower the temperature of the manure that is stored, reducing emissions of ammonia and odor. The facility can repurpose this heat for preheating pens prior to the introduction of new batches, heating the floor, and heating the water[17].

The incorporation of these technologies is in line with EU regulations and Danish national goals to lessen the environmental impact and climate change of intensive livestock production systems. These developments highlight how crucial systemic approaches are to attaining sustainability in animal agriculture as the industry develops.

3.4.2. Goal and Scope definition

The objective of the assessments conducted (LCA, LCC, and S-LCA) is to evaluate the environmental, economic, and social impact potentials of applying the CSA practices described in subsection 3.4.1. in the Danish UC scenario.

[16] https://sgavmst.dk/skovbrug-og-landbrug/landbrug-og-husdyrbrug/teknologilisten/staldindretning
[17] https://mst.dk/erhverv/groen-produktion-og-affald/landbrug-og-husdyrbrug/teknologilisten/staldindretning

Product systems

Baseline: The product system was a farm representative of a conventional pig farm located in Denmark, with a farm area that served as the minimum requirement for distributing organic manure generated from the entire animal production was used as the baseline product system. Adhering to legal standards (Nitrates Directive), there's a maximum limit of 170 kg/N per ha from organic sources. The farm engaged in the production of piglets and finisher pigs, alongside cultivating wheat (177.5 ha) and barley (100 ha) for in-house feed production. Additionally, oilseed rape (canola) was cultivated across 48 ha, while rye grass is grown on 18.5 ha, with an additional 26 ha designated for other purposes like extensive permanent grass and fallow land. The stable infrastructure comprised two climate systems for piglets and finisher pigs, featuring partial slatted floors with 50-75% solid floor coverage. None of the CSA practices studied were applied in the specific product system.

Frequent discharge of slurry: The product system was a pig farm that also applied frequent discharge of slurry once a week aiming to reduce the CH_4 emissions due to methanogenic activity. The main processes that were included within the product system are the following: feed production, pig farming and manure management.

Acidification of slurry:: The product system was a pig farm that applied slurry acidification once a week, prior the use of manure as a fertilizer, aiming to reduce the CH_4 emissions due to methanogenic activity. The main processes that were included within the product system were the following: feed production, pig farming and manure management

Manure management - biogas production: The product system was a pig farm that supplied its manure as feedstock to a biogas production plant. The main processes that were included within the product system were feed production, pig farming and manure management.

Soya replacement by Green Protein concentrate: The product system was a pig farm that partially replaced soy in pig feed with green protein extract. The main processes that were included within the product system were the following: feed production, pig farming and manure management.

Ventilation technologies: The product system was a pig farm that applied innovative ventilation techniques aiming to reduce the emissions in the farm. The main processes that were included within the product system were feed production, pig farming and manure management.

System boundaries: The objective of the study was to compare the application of the CSA practices with conventional pig farming

To achieve the comparison with the baseline scenario, that includes three primary subsystems: feed production, pig farming (animal housing and growth), and manure management, a cradle to-gate approach was adopted.. All upstream inputs and emissions related to feed production and transportation, energy and water use on farms, direct emissions from animal housing, and manure management procedures are included in the analysis. Slaughtering, processing, packaging, and post-farm operations are not included in the system. The functional unit was 1 kg of pig meat grown at the farm gate.

Allocation procedures: Since there are no multiple products involved, no allocation is needed.

Environmental impact assessment methodology: ReCiPe 2016 (H, hierarchist) will be used in order to convert the LCI data into a set of environmental impact scores using characterization factors which convert emissions and resource use into potential environmental impacts at global or regional scales. Although the system boundaries are cradle-to-gate, these broader-scale impact potentials allow for consistent comparison of environmental burdens across different processes and regions. Detailed description of the method is provided in subsection 2.1.2.

Data requirements: To conduct the LCA analysis, data were gathered through the distribution of questionnaires to relevant stakeholders, supplemented by data from verified databases such as Ecoinvent, Agri-footprint and Agribalyse, which cover the geographical area of the European Union 28 (EU-28). The collected data refer to year 2023.

Assumptions/Limitations:

Frequent discharge of slurry : The farm applies weekly discharge of slurry in the finisher pig barns, reducing methane emissions by approximately 45% (Dalby et al., 2023). NH_3 emissions are assumed to remain the same.

Acidification of slurry: The farm applies slurry acidification, reducing ammonia emissions by approximately 62% and CH_4 emissions by 90%.

Manure management: About 100 m^3 of slurry and 13–15 tons of deep bedding material per day are processed by the anaerobic digestion facility from four farm properties. The plant receives a variety of external substrates, such as cheese, soap, flour, glycerin, and whey from dairy industry, in addition to biomass and manure from the farm (economically allocated). This reflects a co-digestion system with a variety of feedstocks. The plant's four anaerobic digesters, which have a combined volume of about 23,000 m^3, are made up of two steel tanks and two concrete tanks. Before being pumped into the reactors, feedstock is mixed once a day in a special mixing tank. The thermophilic temperature range for the process is 46–47°C. The generated biogas is pipelined to Arla's dairy after being cleaned but not upgraded. The digestate produced is used on the owner's farms and shared in part with nearby farms to produce crops. With an average of roughly 700 m^3/h, biogas production has fluctuated greatly, from lows of 300 m^3/h to peaks of about 900 m^3/h. Methane concentrations range from 55% to over 60%, with 57–58% being the current stable range. The facility primarily uses heat pumps and internal heat exchange to maintain operating temperatures, requiring little outside heating. The owner oversees daily operations and biomass feeding, and after initially hiring outside service providers, he has lowered maintenance costs by fixing the pumps in-house.

Soya replacement by Green Protein concentrate: The farm replaces 15% of soy in pig feed with green protein extract (clover grass protein).

Ventilation technologies: There are roughly 10,000 pig spots in the 12 sections that make up the pig housing system, each of which has 44 pens that can house 18 pigs plus 4 extra welfare pens. The finishing units have troughs for liquid feeding and partially slatted flooring (33% solid with floor heating). Underfloor exhaust provides about 10% of the ventilation. The 1,200 sows in the farm's herd are used to produce piglets, which weigh about 30 kg. Ventilation is provided by a combination of combi-diffuse systems with stepless regulation based on a temperature strategy of 17-22 °C. The facility uses LPC fans with Dynamic Multistep control, which is SKOV's most energy-efficient system. The current system uses approximately 4 kWh per pig, which is split between bypass ventilation (2 kWh), central spot extraction (1 kWh), and air cleaning (1 kWh), compared to the previous systems' typical consumption of 10 kWh per finishing pig. The spot extraction system captures about 40% of odor emissions and 60% of ammonia emissions. Two chemical and biological air cleaners receive the exhaust air via a central subterranean channel, with removal efficiencies of 96% and 77% for ammonia and odor, respectively. About 11.6 tons of NH_3-N are released by the system each year, of which 6.7 tons are recovered by the air cleaning system. In addition to lessening the impact on the environment, this recovery makes it possible to repurpose the ammonia as nitrogen fertilizer, which eliminates the need for synthetic fertilizers that require a lot of energy.

3.4.3. Life Cycle Inventory

The Life Cycle Inventory (LCI), compiled from data collected through interviews and supplemented with relevant literature sources, is summarized in Tables 18 & 19, with all flows aggregated using 1 kg of pig meat growth as the Reference Flow. The values for the baseline scenario are shown in the second column, while the subsequent columns display the percentage change associated with each CSA practice. For newly introduced parameters, the actual values are presented instead of percentage changes. The results are presented per 1 kg of pig meat growth, using this as the functional unit.

Parameter	Baseline	Acidification	Discharge	Green Protein	Ventilation	Biogas
INPUTS						
Pig Feed (kg)	2.63	2.63	2.63	2.63	2.63	2.63
Sulfuric acid (L)	-	0.12	-	-	-	-
Water (m^3)	3.74	3.74	3.74	3.74	3.74	3.74
Diesel (MJ)	0.99	0.99	0.99	0.99	0.99	0.99
Thermal energy (Wh)	-	-	-	-	-	45
Electric energy (Wh)	-	-	-	-	-	6.75
Housing system, fully-slatted floor (LU)	0.012	0.012	0.012	0.012	0.012	0.012
OUTPUTS						
Pig meat growth (kg)	1	1	1	1.02	1	1
Biogas (m^3)	-	-	-	-	-	0.075
Slaughterhouse waste (pig meat not suitable for consumption) (kg)	0.04	0.04	0.04	0.04	0.04	0.04
Emissions to air						
Ammonia (g)	17.5	6.65	17.5	17.5	7.0	17.5
Carbon dioxide, biogenic (kg)	0.5	0.5	0.5	0.5	0.5	0.5
Dinitrogen monoxide (g)	0.25	0.25	0.25	0.25	0.25	0.25
Hydrogen sulfide (g)	56.3	56.3	56.3	56.3	56.3	56.3

Parameter	Baseline	Acidification	Discharge	Green Protein	Ventilation	Biogas
Methane (g)	53.1	5.31	29.0	5.31	5.31	5.31
Particulates, < 2.5 um (kg)	0.00184	0.00184	0.00184	0.00184	0.00184	0.00184
Particulates, > 10 um (kg)	0.0177	0.0177	0.0177	0.0177	0.0177	0.0177
Particulates, > 2.5 um, and < 10um (kg)	0.0019	0.0019	0.0019	0.0019	0.0019	0.0019
AVOIDED PRODUCTS						
Inorganic nitrogen fertiliser, as N (g)	-	8.94	-	-	5.76	48.9

Table 18: Life Cycle Inventory of a pig farm – Danish UC. The values are given per kg of pig meat growth per year (reference flow). "-" indicates zero value.

Parameter	Baseline	Acidification	Discharge	Green Protein	Ventilation	Biogas
INPUTS						
Land use (m^2)	2.81	2.81	2.81	2.81	2.81	2.81
Wheat grain (kg)	0.589	0.589	0.589	0.589	0.589	0.589
Barley grain (kg)	0.183	0.183	0.183	0.183	0.183	0.183
Soybean oil (kg)	0.011	0.011	0.011	0.011	0.011	0.011
Soymeal (kg)	0.179	0.179	0.179	0.152	0.179	0.179
Clover, protein concentrate, biorefinery (kg)	-	-	-	0.027	-	-
Minerals (kg)	0.038	0.038	0.038	0.038	0.038	0.038
OUTPUT						
Pig Feed (kg)	1	-	-	-	-	-

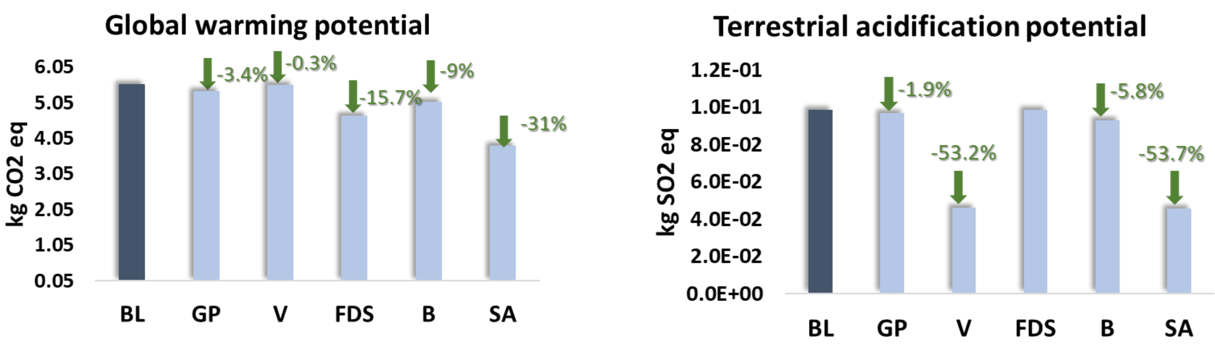
Table 19: Life Cycle Inventory for the production of pig feed – Danish UC. The values are given per kg of pig feed (reference flow). "-" indicates zero value.

3.4.4. Environmental Life Cycle Impact Assessment (e-LCIA)

ReCiPe 2016 (H, hierarchist) was applied for the conversion of the LCI data presented in Tables 18 & 19 into a set of environmental impact potential scores. The results of the baseline scenario have been updated due to database updates, with the revised values of the 18 midpoint indicators being presented in Table 20. The main midpoint indicators that resulted from life cycle impact assessment of the various product systems and differentiate among these systems are presented in Figure 8.

Impact category	Unit	Value
Global warming	kg CO_2 eq	5.53
Stratospheric ozone depletion	kg CFC11 eq	1.75E-05
Ionizing radiation	kBq Co-60 eq	0.24
Ozone formation, Human health	kg NO_x eq	8.73E-03
Fine particulate matter formation	kg $PM_{2.5}$ eq	1.01E-02
Ozone formation, Terrestrial ecosystems	kg NO_x eq	9.00E-03
Terrestrial acidification	kg SO_2 eq	0.10
Freshwater eutrophication	kg P eq	1.45E-03
Marine eutrophication	kg N eq	3.33E-03
Terrestrial ecotoxicity	kg 1,4-DCB	4.81
Freshwater ecotoxicity	kg 1,4-DCB	7.08E-02
Marine ecotoxicity	kg 1,4-DCB	8.97E-02
Human carcinogenic toxicity	kg 1,4-DCB	2.40E-01
Human non-carcinogenic toxicity	kg 1,4-DCB	2.19
Land use	m^2a crop eq	11.69
Mineral resource scarcity	kg Cu eq	6.90E-03
Fossil resource scarcity	kg oil eq	0.64
Water consumption	m^3	0.16

Table 20: Danish UC Baseline scenario – midpoint impact indicators (FU: 1 kg of pig meat growth)



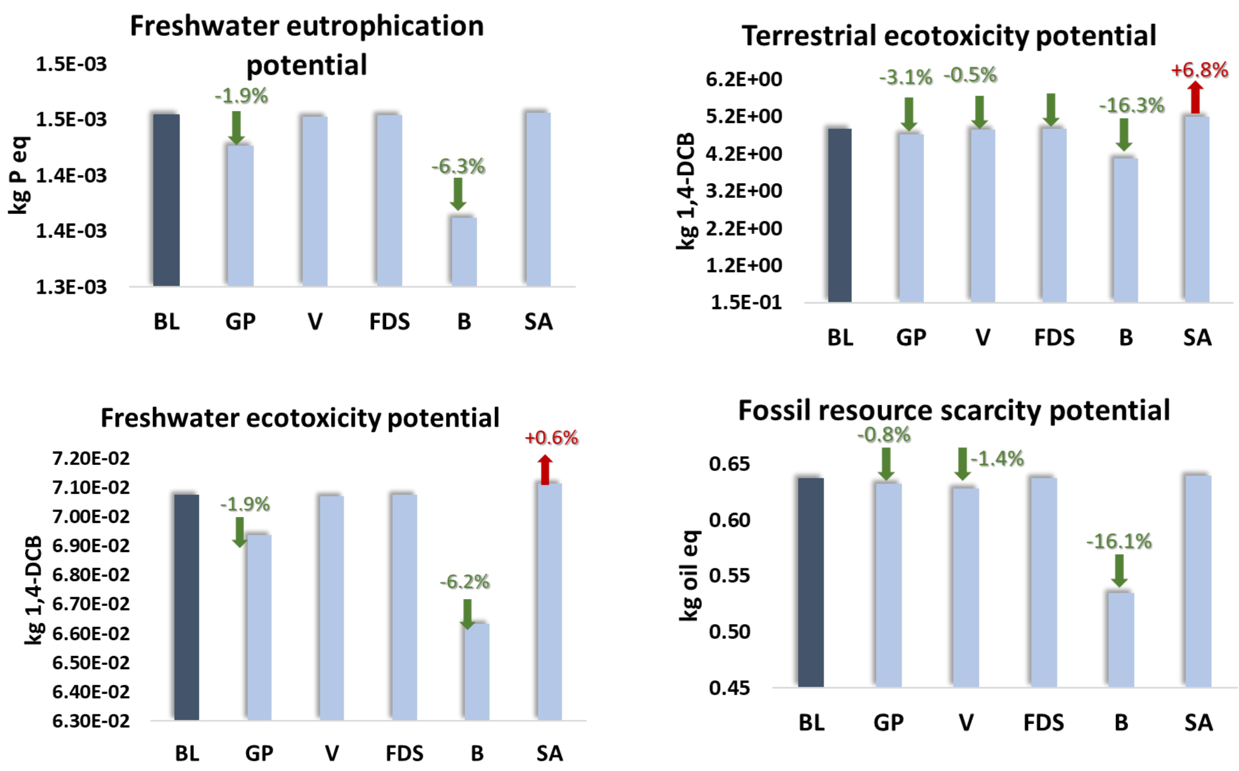


Figure 8: Environmental impact potential comparison of the Danish baseline scenario vs. the different scenarios of the application of CSA practices – selected midpoint impact indicators are shown per kg of pig meat growth (Danish UC). [Scenarios include: BL – Baseline, GP – Soya replacement by Green Protein concentrate, V - Sustainable Ventilation Technologies, FDS - Frequent Discharge of Slurry, B - Biogas Production, SA - Slurry Acidification].

The LCA conducted for the five different CSA practices applied in pig farming demonstrated differentiated environmental performance across these scenarios. Each practice contributes uniquely to reducing environmental impact potentials, with some delivering substantial improvements across several midpoint impact categories.

All practices have been reported to reduce **global warming potential**, with slurry acidification providing the greatest results, resulting in 3.82 kg CO_2 eq of the GWP, 31% lower that the baseline scenario. Acidification of slurry reduced ammonia volatilization and related nitrous oxide emissions leading to this notable improvement. Similarly, the frequent discharge of slurry has a beneficial effect on CH_4 and NH_3 emissions, as reported previously, providing a 15.7% reduction of GHG emissions. With corresponding values of 0.0463 and 0.0457 kg SO_2 eq, less than half the baseline, the use of innovative ventilation systems and the acidification of slurry both exhibit the best performance in terms of **terrestrial acidification potential**. These decreases are consistent with improved ammonia extraction via slurry acidification and ventilation systems. With slight improvements in the scenarios of soy replacement by green protein extract and valorization of manure for biogas production, the effect in **freshwater eutrophication potential** is essentially constant across all scenarios. Good nutrient management techniques are reflected in the constant eutrophication values across all systems. **Terrestrial ecotoxicity potential**, however, varies significantly: The scenario of biogas production reduced the potential impact by 16.3%, whereas the scenario of slurry acidification exceeds the baseline (4.81 kg 1,4-DCB) by reaching 5.14 kg 1,4-DCB. The latter could be the consequence of using more chemicals (sulfuric acid) in slurry systems as cleaning agents or in acidification treatments. Similarly, it has slightly higher **freshwater ecotoxicity potential**, indicating environmental trade-offs that need to be considered when designing systems. Similarly, scenarios of biogas and slurry acidification have the lowest usage of **fossil resources**, suggesting effective energy recovery or a decreased reliance on fossil inputs. The green protein scenario exhibits slight improvements, demonstrating the advantages for the environment of using locally produced green protein instead of imported soy protein.

3.4.5. Life Cycle Cost Analysis (LCC)

A comparative LCC analysis was conducted for the different scenarios, taking into account annual operating costs, annual revenues, any subsidies provided, and any additional capital expenses required for the adoption of CSA practices. Other stages, such as farm 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 the different manure management techniques under the same conditions. This approach aligns with the cradle-to-gate system boundaries and minimizes uncertainties associated with multi-year projections. The main outputs of the LCC analysis are presented in Table 21. The more **frequent discharge of slurry** in the finisher pig barns (weekly, instead of every 6 weeks) does not require the purchase of any new equipment, thus no CapEx are included in the calculations. Only OpEx are taken into account for this CSA practice, as the analysis focused on a single pig production cycle. The life cycle costs of the annual pig farming for the scenario of frequent slurry discharge in the Danish UC are presented in Table 21, along with the revenues including subsidies, sale of pig meat and credits from avoided synthetic nitrogen fertilizer due to improved nitrogen retention in manure. At the studied product system, no important variations were observed in terms of OpEx or CapEx, and the fertilizer substitution credit was minor. As a result, this CSA practice does not lead to significant cost benefits or drawbacks within the studied system boundaries. The estimated CapEx for **slurry acidification** was about 775,000 €, covering the acidification unit, process tank, pumps, control systems, and necessary infrastructure. It is strongly recommended to use acid-resistant concrete for the process tank, which increases the production cost by 12-15% compared to conventional concrete. A 10-year depreciation period was assumed[18]. The extra cost required for the use of sulfuric acid was added in the OpEx, increasing them by 0.8%. The fertilizer substitution credit due to the additional nitrogen available in manure during acidification increased the revenues by 0.6%. The above resulted to reduced net profit at about 0.44€ per kg of pig meat growth and a total of about 553,460 € per year in the studied farm. It should be noted that while slurry acidification is efficient in reducing NH_3 emissions and improving nutrient efficiency, its implementation costs may limit its adoption when supportive subsidies are not available. The establishment of the **biogas plant**, transport line and storage facilities costed €3.6 million, with a 15-year depreciation period assumed. The analysis focused on a single pig production cycle. The life cycle costs of the annual pig farming for the scenario of slurry acidification in the Danish UC are presented in Table 21, along with the revenues including subsidies, sale of pig meat and credits from avoided synthetic nitrogen fertilizer due to the application of digestate as a fertilizer. The extra cost required for the energy used for biogas production is minor (0.005€/kg pig meat growth), increasing the OpEx from 1.21 to 1.22€/kg pig meat growth. The biogas produced is sold to the CHP installation at 0.8€/m^3 and is assumed to have a consistent methane concentration of 57-58% v/v. The revenues are increased to 1.74€/kg pig meat growth, due to the extra income from the biogas product. The The high CapEx result in a reduced net profit of about €0.39/kg of pig meat growth, which equates to a total annual profit of €451,880 for the farm under study, even with the additional revenue from biogas sales. It should be mentioned that although biogas production from manure has environmental benefits and helps with circular resource use, the high initial cost makes this solution more practical under cooperative models or subsidies. The **green protein concentrate** was assumed to be sourced from external suppliers, at a market price of 5€/kg, as the protein extraction from clover or other plant sources requires special biorefining equipment and expertise that are not available on the farm. The production cost for biorefining is still high in general, and is not yet competitive with

[18] (PDF) Final report: Information about Techniques to consider in the Determination of BAT for the Intensive Rearing of Cattles. Available from: https://www.researchgate.net/publication/389609320_Final_report_Information_about_Techniques_to_consider_in_the_Determination_of_BAT_for_the_Intensive_Rearing_of_Cattles [accessed May 26 2025]

conventional protein sources such as soy. The higher cost of green protein concentrate leads to reduced net profit of 0.35€/kg pig meat growth. Green protein concentrate is still a new product with low production volumes and high processing costs that are not yet offset by economies of scale, in contrast to soy, which benefits from extensive global production and well-established supply chains. For the **innovative ventilation technologies** scenario, the chemical air purification plant required a capital investment of €270,000, and the ventilation ducts needed an additional €231,660. The purification system annualized cost was estimated to be €30,000, while the ventilation infrastructure was €11,865. Since the air purification technology has little effect on daily farm operations or input costs, the operational expenses stayed relatively constant at 1.21 €/kg pig meat growth. The fertilizer substitution credit from the improved nitrogen retention in the manure caused a slight increase in revenues. The net profit was reduced slightly from 0.47€ to 0.45€/ kg pig meat growth, mostly as a result of the new ventilation and purification systems' higher capital costs. This result illustrates a trade-off between economic return and environmental benefit: chemical air purification can greatly lower ammonia emissions and enhance the quality of the air for workers and livestock, but it is still not very profitable in the absence of incentives or subsidies.

	Cost category (€/ha/year)	Baseline	Discharge	Acidification	Green Protein	Ventilation	Biogas
EXPENSES	**Annualized CapEx**	€ -	€ -	€ 0.03	€ -	€ 0.03	€ 0.14
	Energy (diesel)	€ 0.03	€ 0.03	€ 0.03	€ 0.03	€ 0.03	€ 0.04
	Chemical fertilizers	€ 0.01	€ 0.01	€ 0.01	€ 0.01	€ 0.01	€ 0.01
	Manure	€ 0.03	€ 0.03	€ 0.03	€ 0.03	€ 0.03	€ 0.03
	Animal Feed	€ 0.78	€ 0.91	€ 0.78	€ 0.78	€ 0.78	€ 0.78
	Sulfuric acid		€ -	€ 0.01	€ -	€ -	€ -
	Water	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00
	Rent	€ 0.14	€ 0.14	€ 0.14	€ 0.14	€ 0.14	€ 0.14
	Labor	€ 0.18	€ 0.18	€ 0.18	€ 0.18	€ 0.18	€ 0.18
	Other (taxes, admin, etc)	€ 0.03	€ 0.03	€ 0.03	€ 0.03	€ 0.03	€ 0.03
	Total	€ 1.21	€ 1.33	€ 1.22	€ 1.21	€ 1.21	€ 1.22
	Change over BL:		10.13%	0.97%	0.00%	0.00%	0.51%
REVENUES	**Pigs**	€ 1.61	€ 1.61	€ 1.61	€ 1.61	€ 1.61	€ 1.61
	Subsidies	€ 0.07	€ 0.07	€ 0.07	€ 0.07	€ 0.07	€ 0.07
	N fertilizer credit	€ -	€ -	€ 0.01	€ -	€ 0.01	€ -
	Biogas	€ -	€ -	€ -	€ -	€ -	€ 0.06
	Total	€ 1.68	€ 1.68	€ 1.69	€ 1.68	€ 1.69	€ 1.74
	Change over BL:		-0.08%	0.63%	-0.08%	0.63%	3.49%
	Profit	€ 0.47	€ 0.35	€ 0.47	€ 0.47	€ 0.48	€ 0.52

Table 21: Comparative LCC analysis (annual basis) of the baseline scenario and the different CSA practices for the Danish UC.

3.4.6. *Social Life Cycle Impact Assessment (s-LCIA)*

General | s-LCIA

The production flows and relevant inventory data of all the examined Danish CSA scenarios were taken from the resulting LCIAs shown in previous Tables 18 & 19. According to the received questionnaire, the data inputs for most of the impact factors were similar with the baseline scenario for all the examined CSAs, and thus were directly taken from Table 26 of the previous D3.1. These included the "Worker hours" activity variable and the impact factors with their associated risk levels. The changes from the Table 26 of the precious D3.1 included the "Worker hours" activity variable for the Green protein scenario, which was recalculated based on a slightly increased production of 1.02kg pig meat, and the "Living wage, per month", "Sector average wage, per month", "Women in the sectoral labor force", "Men in the sectoral labor force", "Gender wage gap", "Membership for social responsibility along supply chain", "Certified Environmental Management Systems", "International migrant workers in the sector", "Embodied Agricultural Area Footprints", "Embodied Water Footprints", "Embodied CO2 Footprints", "Embodied CO2eq Footprints" and "Embodied Value Added" impact factors, for which their values were reassessed, according to the received questionnaire data for each CSA. The changes to the data inputs, with regards to the baseline scenario described in previous D3.1, are summarized in Table 22 below:

Input	Baseline	Ventilation technologies	Acidification	Green protein	Frequent slurry discharge	Biogas
Worker hours[6]	0.001586	0.001586	0.001586	0.001555	0.001586	0.001586
Living wage, per month	Very High	Very High	Very High	Very High	Very High	Very High
Sector average wage, per month	Medium	Medium	Medium	Medium	Medium	Medium
Women in the sectoral labor force	High	Very High	Very High	Very High	High	Very High
Men in the sectoral labor force	Low	Very Low	Very Low	No Risk	Low	No Risk
Gender wage gap	Low	Low	Low	No Data	Low	No Data
Membership for social responsibility along supply chain	Medium	Medium	Medium	Very Low	Medium	Medium
Certified Environmental Management Systems	Very High	Very High	Very High	Very Low	Very High	Very High
International migrant workers in the sector	Very High	Very High	Very High	Very High	Very High	Very Low
Embodied Agricultural Area Footprints	High	High	High	High	High	High
Embodied Water Footprints	Very Low	Very Low	Very Low	Very Low	Very Low	Very Low
Embodied CO2 Footprints	High	High	High	High	High	High

Input	Baseline	Ventilation technologies	Acidification	Green protein	Frequent slurry discharge	Biogas
Embodied CO_2eq Footprints	High	High	High	High	High	Medium
Embodied Value Added	Medium	Medium	Medium	High	Medium	High

Table 22: Changes of the data inputs of s-LCIA, from the Danish baseline scenario, shown in previous D3.1 (the impact factors not shown were not changed and thus were taken directly from the baseline scenario, as presented in Table 26 of the previous D3.1).

The results from the s-LCIA analyses for all the examined CSA scenarios are shown in Figure 9 below. Along with the studied CSAs, the results of the baseline scenario have also been updated due to database updates (ILO, WHO etc.) that changed the risk levels of some impact factors. A more detailed analysis of each CSA examined is given below. Generally, the results were in line with the changes of the LCI. However, some of the impact factors resulted in high social footprints, despite the fact that they had very low-medium risks. This was found for all examined CSAs and the baseline scenario as well, and was attributed to impacts from upstream flows. More specifically, for the baseline scenario, most impactful flows were the ones related with the operation of the pig housing system on global scale (required electricity), followed by the production of pig feed (wheat grain). Any CSA that contributed a positive change to the above resulted in reduced impacts.

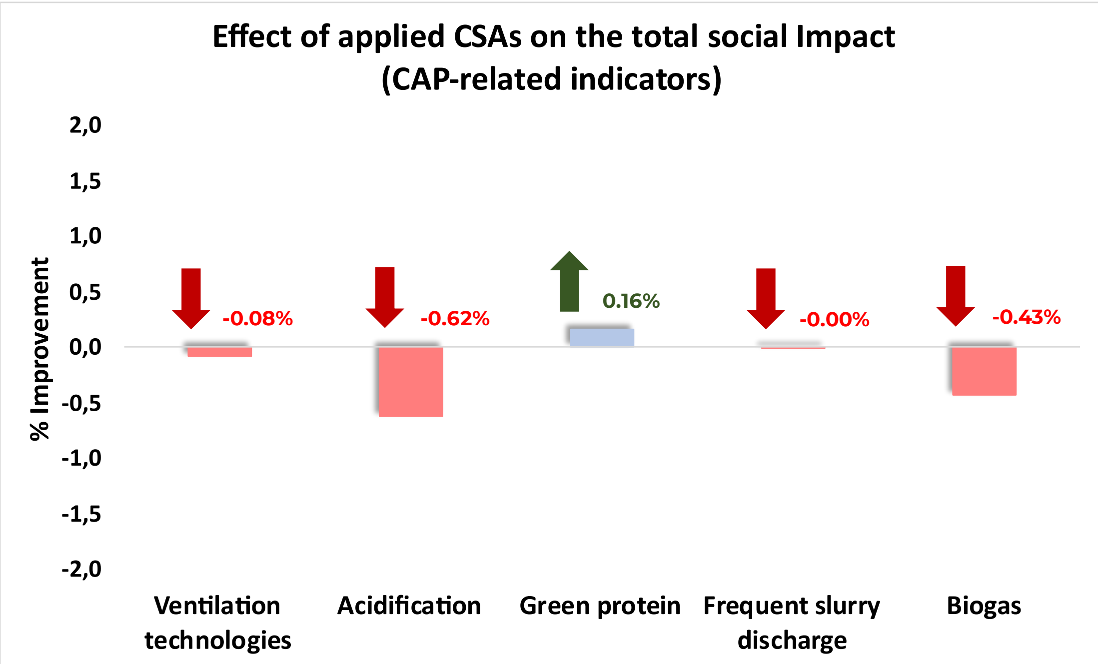


Figure 9: Comparison of the changes in the social impacts from the investigated CSAs, regarding the EU CAP-relevant social indicators – impacts per kg of produced pig meat per year (Danish UC) (0 value represents the baseline).

Ventilation technologies | s-LCIA

Beginning with the ventilation technologies scenario, this one performed very close to the baseline scenario, resulting in a 0.004% increase in total DALYs. This result was expected, as the anticipated changes were mostly based on changes in the LCI, as well as on higher gender discriminations that lead to a very slight increase in total DALYs. Focusing on the CAP-relevant indicators that are more in accordance with the BEATLES project, the ventilation technologies scenario performed close to the baseline, resulting in just 0.1% increased social footprints. The 4 most important factors were the Fair Salary, followed by Embodied Biodiversity Footprints, GHG Footprints and Unemployment rate. Notably, there were no significant changes regarding the most impactful flows and as a result, the ventilation technologies scenario led to only marginal changes from the baseline.

Acidification | s-LCIA

Moving on to the acidification scenario, this one performed slightly worse than the baseline scenario, resulting in a 0.161% increase in total DALYs. This result was expected, as the anticipated changes were mostly based on changes in the LCI, as well as on higher gender discriminations that lead to a very slight increase in total DALYs. Focusing on the CAP-relevant indicators that are more in accordance with the BEATLES project, the acidification scenario resulted in 0.6% increased social footprints. The 4 most important factors were the Fair Salary, followed by Embodied Biodiversity Footprints, GHG Footprints and Unemployment rate. Notably, there were no significant changes regarding the most impactful flows, but instead, the main additional burden from the acidification scenario comes from the additional flow related to the production of sulfuric acid, albeit relatively low; which explains why the acidification scenario led to only slightly higher social impacts than the baseline

Green protein | s-LCIA

Subsequently for the green protein scenario, this one performed slightly better than the baseline scenario, resulting in a 0.100% decrease in total DALYs. This result was expected, due to the slight decrease in the “Worker hours” activity variable, meaning that the same amount of effort from workers, who were paid similarly with the baseline scenario, produce slightly more product (1.02kg instead of 1kg); as well as due to the changes in the LCI and on higher gender discriminations that lead to a very slight increase in total DALYs. Focusing on the CAP-relevant indicators that are more in accordance with the BEATLES project, the green protein scenario resulted in 0.2% reduced social footprints. The 4 most important factors were the Fair Salary, followed by Embodied Biodiversity Footprints, GHG Footprints and Unemployment rate. Notably, there were no significant changes regarding the most impactful flows and as a result, the green protein scenario led to only marginal changes from the baseline. Additionally, compared with the quite similar ventilation technologies scenario, the green protein scenario resulted in marginally better social footprints, due to the slightly higher produced output.

Frequent slurry discharge | s-LCIA

Moving on to the frequent slurry discharge scenario, this one performed similar with the baseline scenario. This result was expected, as the anticipated changes were mostly based on changes in the LCI . Focusing on the CAP-relevant indicators that are more in accordance with the BEATLES project, the frequent slurry discharge scenario performed similar with the baseline one. The 4 most important factors were the Fair Salary, followed by Embodied Biodiversity Footprints, GHG Footprints and Unemployment rate. Notably, the frequent slurry discharge scenario presented minimal changes from the baseline scenario, and as a result, it performed similar with the baseline.

Manure management – Biogas production | s-LCIA

Finally, for the biogas production scenario, this one performed slightly worse than the baseline scenario, resulting in a 0.087% increase in total DALYs. This result was expected, as the anticipated changes were mostly based on changes in the LCI, as well as on higher gender discriminations that lead to a very slight increase in total DALYs. Focusing on the CAP-relevant indicators that are more in accordance with the BEATLES project, the biogas scenario resulted in 0.4% increased social footprints. The 4 most important factors were the Fair Salary, followed by Embodied Biodiversity Footprints, GHG Footprints and Unemployment rate. Notably, there were no significant changes regarding the most impactful flows, but instead, the main additional burden from the biogas production scenario comes from the additional flows related to the production of biogas (electricity, heat), albeit relatively low; which explains why the biogas production scenario led to only slightly higher social impacts than the baseline.

Social Life Cycle Impact Assessment (s-LCIA) – Conclusions

According to the results from the s-LCIA analyses, from the social impact perspective, the best results were acquired from the green protein scenario (0.2% reduced footprints), although close to the baseline scenario. The frequent slurry discharge scenario performed similar with the baseline, followed by the ventilation technologies scenario, which performed marginally worse than the baseline (0.1% increased footprints) and finally the biogas production and acidification scenarios, both of which performed slightly worse than the baseline (0.4 and 0.6% increased footprints respectively). Generally, all examined scenarios performed very close to the baseline one (up to 0.8% difference in resulted footprints) and thus all of them can be considered in case the improvement of the social footprints is a secondary objective of the transition-to-CSA strategy.

3.4.7. Cost-Benefit Analysis

Among the climate-smart agriculture (CSA) practices evaluated, frequent slurry discharge stands out as a cost-effective, low-barrier option for small to mid-sized pig farms. By utilizing existing infrastructure, the practice avoids additional capital expenditures and maintains low operating costs. While minor health and safety expenditures are necessary due to exposure to hazardous gases like hydrogen sulfide, these are negligible compared to the overall OpEx. Environmentally, the practice offers a 15.7% reduction in global warming potential (GWP) driven largely by a 45% drop in methane emissions, with added reductions in ammonia volatilization and terrestrial acidification. Economically, the strategy maintains high profitability (~0.47 €/kg) and improves nitrogen retention, slightly enhancing manure's fertilizer value. Socially, it contributes to improved barn air quality and worker safety without disrupting labor demand.

In contrast, slurry acidification delivers more pronounced environmental benefits—most notably a 31% drop in GWP and a >90% reduction in methane emissions—by effectively stabilizing nitrogen in the manure and reducing both ammonia and nitrous oxide emissions. However, these benefits come with significantly higher CapEx (approx. €775,000) and marginally higher OpEx (+0.8%), mainly due to the use of sulfuric acid. The technology yields a slightly lower profit (~0.44 €/kg), although it remains economically viable under subsidy frameworks such as the EU CAP. Social benefits include improved air quality and potential cooperative ownership models, though upstream supply chain impacts (e.g., from acid production) slightly increase the overall social footprint.

CSA	Costs	Benefits		
		Environmental	Economic	Social
Frequent Discharge of Slurry	No CapEx, as it made use of already-existing infrastructure Costs associated with health and safety may arise, as there are requirements for respirators, gas detectors, and training. However, these are negligible compared to total OpEx (1.21€/kg pig meat growth), having no significant impact.	↓ GWP 15.7% ↓ Methane emissions ~45%, due to weekly discharge of manure and decrease of anaerobic ↓ terrestrial acidification, due to less NH_3 emissions	No major cost burden, making it suitable for smaller farms Stable net profit (~0.47 €/kg pig meat), as no significant additional costs are required Minor fertilizer credit due to improved nitrogen retention Eligible for subsidies under modernization / GHG-reduction schemes	Beneficial effect on health, as it improved air quality in and around barns No impact on employment or income in current setup High potential for cooperative application and shared learning

CSA	Costs	Benefits		
		Environmental	Economic	Social
Acidification of Slurry	CapEx ~775,000 (including acid-resistant concrete (+12–15% cost), tanks, pumps, control systems, and an acidification unit). ↑OpEx 0.8%, due to the use of sulfuric acid. ↓Profit, 0.44 € /kg of pig meat growth; annual return about 553,500 euros. ↑Ecotoxicity (5.14 vs. 4.81 kg 1,4-DCB), due to sulfuric acid use. ↑ social footprint 0.62%, due to global upstream flows (such as the production of energy, feed, and acid). Key social impact indicators: Fair Salary (54.62 DALYs), Biodiversity (49.15), GHGs (36.46), Unemployment (14.31). H_2S detectors, ventilation, and training are necessary for safety concerns.	↓ GWP 31% (to 3.82 kg CO_2-eq). ↓NH_3 and N_2O emissions, 64%. ↓ CH_4 emissions from stored slurry, more than 90%. ↓Terrestrial acidification potential, >50%: (~0.0457 kg SO_2-eq). Reduced use of fossil fuels as a result of increased fertilizer efficiency.	↑in revenues 0.6% as a result of the fertilizer substitution credit. ↓ Need for synthetic fertilizers, due to better nitrogen retention. Profitability was maintained at about 0.44 euros per kilogram of pig meat, or 553,460 euros annually. GHG reduction may aid farms avoid future carbon pricing.	Improved respiratory health for farm workers, due to of lower H_2S and NH_3 emissions in barns. Increased safety due to reduced exposure to dangerous gases and safer slurry handling systems. Possibility of collaborative implementation, encouraging teamwork, mutual education, and improved interpersonal relationships.

CSA	Costs	Benefits		
		Environmental	Economic	Social
Manure Management	High CapEx 󰀀 lower net profit ~ 0.39 €/kg pig meat, or about €451,876 annually, despite higher revenue. ↑OpEx, from €1.21 to €1.22/kg of pig meat growth, due to biogas processing energy requirement (~ 0.005€/kg) Moderate financial viability, with a payback period <10 years, partially aided by loans from green investment pools. ↑ Social impact by 0.43% in CAP-relevant indicators, mainly due to upstream flows in electricity; key contributors: Fair Salary (54.50 DALYs), Embodied Biodiversity (49.12 DALYs), GHG Footprints (36.39 DALYs), and Unemployment Rate (14.21 DALYs); Global supply chain effects playing a larger-than-expected role.	↓ GWP, 9% through reduction of CH_4 emissions and substitution credits from the use of digestate as a fertilizer. ↓ Fossil resource scarcity, 16.1%, due to the avoidance of synthetic fertilizers.	↑Revenues, 1.74 €/kg of pig meat growth. through biogas sale (average methane content 57–58% v/v) to CHP installation for 0.8€/m3 & partial use of digestate in place of synthetic fertilizers.	Low direct social impact of biogas production.

CSA	Costs	Benefits		
		Environmental	Economic	Social
Green Protein for Feed	Green protein concentrate was assumed to be sourced externally at a market price of €5/kg → higher feed costs, due to the early-stage, small-scale nature of green protein production. ↓Net profit to 0.35 € per kg of pig meat growth. Net environmental impact stayed relatively constant, due to upstream effects related to the energy and inputs used in the biorefining process.	↓ GWP, 3.4% through reduction of transport-related emissions due to partial replacement of soya by local protein sources. Similarly, ↓ in terrestrial acidification potential (1.9%), freshwater eutrophication potential (1.9%) terrestrial & freshwater ecotoxicity potential (3.1 & 1.9%, respectively), fossil resource scarcity potential (0.8%).	Enhanced feed self-sufficiency and decreased reliance on global markets. Potential future benefits from subsidy programs supporting sustainable feed alternatives or from decreased susceptibility to supply chain disruptions.	↓ Overall social impact, 0.1%, due to reduced worker time per kg of pig meat produced. ↓ CAP-related footprint, 0.16%.

CSA	Costs	Benefits		
		Environmental	Economic	Social
Ventilation Technologies	Total CapEx = ~500 k€ (Chemical air purification unit: 270 k€, Ventilation ducts (spot system) : 230 k€) → annualized CapEx: 0.03 €/kg of pig meat growth OpEx are not significantly affected, remain at 1.21 €/kg of pig meat growth	↓ NH3 emissions, through spot extraction and chemical scrubber ↓ Odor emissions , through spot extraction and chemical scrubber ↓ Terrestrial acidification 53%, due to substantial decrease in NH3 emissions ↓ Fossil resource scarcity 1.4%, due to improved energy systems Reuse of ammonia extracted (~6.7 tons NH_3-N/year in the current scenario) as fertilizer, offsetting industrial fertilizer use.	Fertilizer substitution credit 0.01€/kg pig meat growth ↑Revenues to 1.69€kg of pig meat growth	Major improvement in worker/livestock air quality +0.004% (marginal increase) in DALYs

Table 23: Summary of Cost – Benefit Analysis for the CSA practices studied in the Danish UC

The biogas production scenario represents a more transformative investment, requiring upwards of €3.6 million in CapEx, but offering the dual benefit of renewable energy generation and improved nutrient recycling. The environmental gains include a 9% reduction in GWP and significant improvements in fossil resource use due to digestate reuse. While OpEx increased minimally, net profit per kg dropped to €0.39, though annual profit remained high (~€451,876), indicating economic viability under long-term planning and supportive policies. Socially, impacts increased only slightly, primarily due to upstream energy demands rather than the biogas system itself, making this a strong option for cooperatives or farms with access to green financing.

Green protein feed substitution, though still in its early stages, showed modest environmental improvements—such as a 3.4% reduction in GWP and slight reductions in ecotoxicity and eutrophication potentials—by reducing reliance on imported soy. However, higher feed costs (5 €/kg) lowered net profit by ~0.35 €/kg, making it the least economically favorable scenario. Nevertheless, the potential for future cost reductions via economies of scale, and eligibility for feed-related subsidies, indicates longer-term promise. Social sustainability improved slightly due to reduced incineration of waste and better feed efficiency, highlighting the feed strategy's strategic value in increasing food system resilience.

Lastly, ventilation technologies like chemical air purification and spot extraction offer a practical balance between economic and environmental performance. With a moderate CapEx of ~€500,000 and no increase in OpEx, this strategy significantly reduces ammonia emissions (by ~53%) and acidification potential. Though profitability declines slightly due to amortized investment, enhanced nitrogen recovery creates small revenue offsets and improves long-term nutrient management. The social benefits are clear, particularly in barn air quality and worker well-being, making this approach well-suited for regions with stringent environmental regulations or where emission-reduction incentives are available.

In summary, frequent slurry discharge and ventilation technologies provide accessible, cost-effective solutions with solid environmental and social returns. In contrast, slurry acidification and biogas production offer deeper emission cuts but require substantial upfront investment and policy support. Green protein feed holds potential for feed independence and sustainability, though cost barriers must be addressed through innovation and scaling. Each practice offers unique trade-offs, and their suitability depends on farm size, access to subsidies, and long-term sustainability goals.

3.5. Use Case Pilot #5: Onions & Potatoes, The Netherlands

3.5.1. Description of the CSA practices

Biodiversity | Description

Biodiversity plays an important role in the stability and productivity of agricultural ecosystems. It directly contributes to yield stability and environmental health by supporting vital ecological processes like nutrient cycling, pest control, and soil structure maintenance. Monoculture methods and heavy chemical input frequently degrade biodiversity in arable systems, such as potato or onion farming, by lowering the number of beneficial organisms and interfering with ecosystem processes.

Enhancing biodiversity is not always sought as a stand-alone intervention in the Dutch potato and onion use case; rather, it arises as a co-benefit of more comprehensive agroecological techniques, like cover crops, composting, and input reduction. These methods lessen ecotoxicity, restore microbial populations, and enhance soil life. The system becomes more robust, biologically active, and functionally balanced as a result. Implementing intercropping techniques, preserving natural habitats in less productive areas, and boosting field-level biodiversity by adding floral strips or nesting locations to support beneficial species are examples of on-farm tactics. The best results are frequently obtained by combining several strategies that preserve a high level of biodiversity throughout the landscape. It's crucial that biodiversity conservation strategies are context-specific, considering regional environmental factors and possible compromises like the possibility of invasive species spreading or increased pest pressure (Muller et al. 2017; Crowther et al. 2024).

Sustainable Irrigation System | Description

Particularly considering growing climatic variability and water shortage, water management is essential to sustainable agriculture. Irrigation is frequently necessary for yield stability in intensive cropping systems used to grow potatoes and onions, however these practices can result in water overconsumption, fertilizer leaching, and inefficient energy use.

The goal of a sustainable irrigation system is to minimize environmental effects while maximizing water use efficiency. This covers methods like automated moisture monitoring, drip irrigation, pressure control, and irrigation scheduling based on soil sensors or meteorological data. These devices facilitate targeted nitrogen supply, stop soil deterioration, and minimize water loss. Sustainable irrigation serves two purposes in this instance. First of all, it lessens the production's water footprint. Secondly, it lowers the possibility of nitrogen leaching, which is one of the biggest environmental stresses on the system. Sustainable irrigation enhances the agricultural system's overall climate-smart performance when paired with integrated fertilization techniques and renewable energy (Canaj et al. 2021).

Crop Protection – Integrated Pest Management (IPM) | Description

Because high-value crops like potatoes and onions are vulnerable to a variety of pests and diseases, crop protection is essential to agricultural output. The synthetic pesticides, herbicides, insecticides, and fungicides used in conventional crop protection methods provide temporary control but are frequently linked to detrimental effects on the environment and human health, such as contaminated soil and water, biodiversity loss, and pest resistance. By using ecological principles, sustainable crop protection aims to lessen reliance on chemical inputs. One of the main principles that directs the use of pesticides is integrated pest management, or IPM. IPM's primary goal is to maximize pesticide inputs while avoiding overuse (Pecenka et al. 2021). IPM is the careful consideration of all available pest management approaches and the subsequent implementation of appropriate measures to inhibit the establishment of pest populations. It integrates biological, chemical, physical, and crop-specific (cultural) management tactics and practices growing healthy crops while lowering or limiting pesticide dangers to human health and the environment, resulting in sustainable pest management (FAO, retrieved 6/2025).

In this instance, cutting back on pesticide use is especially crucial because, according to LCA evaluations, plant protection products have a significant impact on freshwater ecotoxicity and terrestrial acidification. In addition to enhancing environmental performance, switching to more sustainable protection techniques promotes long-term system resilience and adherence to EU policy objectives on pesticide reduction.

Green Energy | Description

In agriculture, green energy refers to the use of low- or zero-emission sources in place of fossil fuel-based inputs. This could involve integrating energy-efficient technologies, utilizing wind- or solar-powered irrigation pumps, or mounting photovoltaic panels on sheds or storage buildings in arable systems like Dutch potato and onion farming. Over time, these actions can minimize energy costs and drastically cut both direct and indirect CO_2 emissions (Kumar et al., 2021).

Renewable energy supports climate mitigation, boosts agricultural self-sufficiency, and supports EU energy decarbonization objectives within the context of Climate Smart Agriculture. Green energy solutions are technically possible and environmentally beneficial in this setting with well-developed infrastructure and legislative backing, particularly when combined with precision irrigation and cooling systems (Pastore & Masera, 2024).

Soil management | Description

An essential part of agricultural systems, soil acts as a reservoir for water, nutrients, and biological activity in addition to being the substrate for plant growth. However, conventional farming practices have resulted in extensive soil degradation, decreased fertility, and diminished microbial diversity. They are characterized by large chemical inputs, intensive tillage, and poor organic matter return.

The goal of sustainable soil management is to maintain and improve soil health using agroecological techniques like composting, cover crops, organic fertilizer, and reduced tillage. These techniques enhance water retention, boost microbial activity, improve soil structure, and raise the amount of organic carbon. Long-term productivity depends on healthy soils' ability to withstand erosion, drought, and nutrient loss.

In the context for potato and onion farming, soil management is especially important due to the system's sensitivity to compaction, nutrient leaching, and high fertilizer dependency. Practices like compost use and the reduction of synthetic nitrogen inputs not only improve soil fertility but also reduce environmental pressures such as greenhouse gas emissions and nitrate runoff. Soil health, therefore, acts as a foundation for both agronomic performance and environmental sustainability (Ierna & Distefano, 2024).

3.5.2. Goal and Scope definition

The objective of the assessments conducted (LCA, LCC, and S-LCA) is to evaluate the environmental, economic, and social impact potentials of applying the CSA practices described in subsection 3.5.1. in the Dutch UC scenario.

Product systems

Baseline: The product system was a farm representative of conventional onion and potato farms in the Southwest of the Netherlands, with focus on a clay soil.

Biodiversity: The product system consisted of a Dutch arable farm cultivating potatoes or onions with the integration of biodiversity-supportive practices. These included reduced use of herbicides, fungicides, and insecticides (by 10-30%), establishment of vegetative buffer strips and improvement of soil health indicators. The included processes were: seed planting, soil preparation, fertilization (mineral and organic), pesticide application, irrigation, and harvesting of potatoes or onions.

Sustainable Irrigation System: The product system was a Dutch arable farm utilizing sprinkler-based irrigation with sensor-based automatic management. In this scenario, irrigation system was powered by imported renewable electricity (photovoltaic-sourced). Diesel use remained the same as in the baseline scenario. The core processes included land preparation, seed setting, fertilization, pesticide application, water delivery (sprinkler irrigation), harvesting, and energy use for irrigation.

Crop Protection – Integrated Pest Management (IPM): The product system was a Dutch arable farm that utilized chemical and alternative crop protection agents to prevent yield losses from pests and diseases. Inputs included substances like mandipropamid, lambda-cyhalothrin, and orange oil derivatives, which are commonly used in IPM approaches. The processes included the application of crop protection agents through spraying, including sub-processes such as preparation, dilution, and delivery of active ingredients. These are embedded within broader agricultural activities (sowing, irrigation, fertilization, etc.).

Green Energy: The product system was a Dutch arable farm that integrated renewable electricity, replacing grid electricity with green energy sources (wind powered). According to the Simapro model, 747 kWh of electricity were used per hectare, corresponding to actual Dutch farming practices (KWIN proxy with USLCI/NVUP). The core processes included all agricultural operations related to potato or onion cultivation: land preparation, sowing, irrigation, fertilization, crop protection, and harvesting. These are powered using a combination of diesel and electricity, with the latter origin from renewable energy components.

Soil management: The product system was a Dutch arable farm that applied soil management strategies through the substitution of synthetic fertilizers with compost-based organic fertilizers and improved tillage techniques. The system integrated the use of green amendments, such as compost, to enhance soil fertility and structure, and floral strips to reduce nutrient runoff. The main processes included within the system boundaries were soil preparation, fertilization using organic matter, irrigation, crop protection, mechanical weeding, and harvesting.

System boundaries: A cradle-to-gate approach has been adopted, covering the production cycle from field preparation to crop harvesting. All upstream inputs-including fertilizers, diesel, and plant protection products-are considered in line with ISO-based LCA practice. Post-harvest processes such as storage, packaging, and distribution were excluded.

Allocation procedures: No allocation is needed, as the system produces a single product to each case: potatoes and onions.

Environmental impact assessment methodology: Environmental impacts are assessed using the ReCiPe 2016 (H, midpoint) method, which allows for conversion of emissions and resource use into midpoint impact categories at regional and global scales. These include terrestrial ecotoxicity, freshwater eutrophication, and climate change indicators. Although the assessment is cradle-to-gate, the characterization factors support consistent cross-scenario comparison.

Data requirements: Data were collected through structured farmer questionnaires and supplemented by secondary sources from Ecoinvent, Agri-footprint, and Agribalyse, all relevant to the EU-28 region. The data reflect the conditions and input levels of the 2023 production year.

Assumptions / Limitations:

Biodiversity: The system reflected a typical arable potato or onion farm in the Netherlands implementing biodiversity-enhancing actions without drastically altering crop type or total output. Reductions in pesticide use and improvements in soil organic matter were used as proxies for biodiversity gains. A reduction of 10-30% in pesticides application due to effective pest management was assumed. No direct measurement of species richness or ecological indicators is available; results were interpreted based on input reductions and established literature values. Moreover, the establishment of vegetative buffer strips along field margins for biodiversity enhancement was assumed to reduce nutrient runoff by approximately 53% for nitrogen and 62% for phosphorus (Aguiar et al. 2015).

Sustainable Irrigation: The system reflected a Dutch potato or onion farm operating under average irrigation demand conditions with sensor-based automatic management, leading to 38% reduced water consumption and 38% reduced energy consumption (Canaj et al., 2021).

Photovoltaic electricity was assumed to substitute the conventional electricity mix (Kumar et al., 2021). The exact energy efficiency of the system was held constant to isolate the impact of the renewable share.

Crop Protection – Integrated Pest Management (IPM): The modeled system reflected standard Dutch potato or onion production on 1 ha, applying IPM with a focus on insecticide reduction through monitoring and preservation of natural enemies. A 95% reduction in insecticide use was assumed (Pecenka et al. 2021).

Green Energy: The analysis assumed substitution of a share of conventional grid electricity with renewable power (wind powered) without altering other farming practices. No additional infrastructure or economic cost data were included.

Soil management: The analysis assumed full replacement of synthetic nitrogen, phosphorus, and potassium with compost-based organic inputs. Moreover, the establishment of vegetative buffer strips along field margins was assumed to reduce nutrient runoff by approximately 53% for nitrogen and 62% for phosphorus (Aguiar et al. 2015).

3.5.3. Life Cycle Inventory

Tables 24 & 25 summarize the Life Cycle Inventory (LCI), which was created using information gathered from stakeholder interviews and backed up by pertinent research. One hectare of farmed potato or onion land is used as the reference flow for aggregating all flows. Baseline values are shown in the second column, and the following columns show the absolute or percentage changes brought about by each Climate-Smart Agriculture (CSA) technique used in the case study of the Netherlands. The functional unit for this analysis is one kilogram of harvested potatoes or onions, and the results are reported per kilogram.

Based on Nemecek et al. (2019), emission distribution fractions to air, soil, and water for agrochemical emissions were calculated using compound-specific emission factors that corresponded to the category of temperate crops. The IPCC (2019) standards were followed in calculating fertilizer (N,P,K) emissions, taking leaching and volatilization pathways into consideration.

Parameter	Baseline	Biodiversity	Sustainable Irrigation System	Green Energy	Soil Management	Crop Protection
INPUTS						
Land use (ha)	1	1	1	1	1	1
Potato seed (kg)	2700	2700	2700	2700	2700	2700
Inorganic nitrogen fertilizer (kg)	250	250	250	250	-	250
Inorganic phosphorus fertilizer (kg)	83.3	83.3	83.3	83.3	-	83.3
Inorganic potassium fertilizer (kg)	300	300	300	300	-	300
Organic nitrogen fertilizer (kg)	-	-	-	-	250	-

Organic phosphorus fertilizer (kg)	-	-	-	-	83.3	-
Organic potassium fertilizer (kg)	-	-	-	-	300	-
Herbicides (kg)	7.4	5.1-6.6	7.4	7.4	7.4	7.4
Insecticides (g)	263	184-236	263	263	263	13.2
Fungicides (kg)	13.7	9.6-12.3	13.7	13.7	13.7	13.7
Mineral oils (kg)	16.6	16.6	16.6	16.6	16.6	16.6
Irrigation (l)	300000	300000	186000	300000	300000	300000
Diesel (MJ)	10159	10159	10159	10159	10159	10159
Electricity, low voltage (kWh)	747	747	-	-	747	747
Electricity, low voltage, renewable energy sources (kWh)	-	-	463	-	-	-
Electricity, low voltage, wind power	-	-	-	747	-	-
OUTPUTS						
Potatoes (Kg)	48200	48200	48200	48200	48200	48200
Emissions to air						
Emissions from fungicides (kg)[19]	1.4	1.0-1.2	1.4	1.4	1.4	1.4
Emissions from insecticides (g)[1]	26	18-23	26	26	26	1.3
Emissions from herbicides (kg)[1]	0.74	0.52-0.67	0.74	0.74	0.74	0.74
Nitrogen monoxide (kg)[20]	3.93	1.84	3.93	3.93	1.84	3.93
Ammonia (kg)[2]	30.36	14.27	30.36	30.36	14.27	30.36
Emissions from mineral oil (kg)	1.38	1.38	1.38	1.38	1.38	1.38
Emissions to water						
Emissions from fungicides (g)[1]	3.0	2.1-2.7	3.0	3.0	3.0	3.0

[19] Nemecek et al., 2019
[20] (IPCC, 2019)

Emissions from herbicides (g)[1]	2.0	1.4-1.8	2.0	2.0	2.0	2.0
Phosphate (kg)[2]	110.71	42.07	110.71	110.71	42.07	110.71
Nitrate (kg)[2]	0.63	0.30	0.63	0.63	0.30	0.63
Emissions from mineral oil (g)	0.17	0.17	0.17	0.17	0.17	0.17
Emissions to soil						
Emissions from fungicides (kg)[1]	2.5	1.8-2.3	2.5	2.5	2.5	2.5
Emissions from insecticides (g)[1]	48	34-43	48	48	48	2.4
Emissions from herbicides (kg)[1]	5.6	3.8-5.0	5.6	5.6	5.6	5.6
Nitrate (kg)[2]	75	35.3	75	75	35.3	75
Emissions from mineral oil (kg)	6.75	5.74	6.75	6.75	6.75	6.75

Table 24: Life Cycle Inventory for the potato farming – Dutch UC. The values are given per ha per year (reference flow). "-" indicates zero value.

Parameter	Baseline	Biodiversity	Sustainable Irrigation System	Green Energy	Soil Management	Crop Protection
INPUTS						
Land use (ha)	1	1	1	1	1	1
Onion seed (units)	3.8	3.8	3.8	3.8	3.8	3.8
Inorganic nitrogen fertilizer (kg)	630	630	630	630	-	630
Inorganic phosphorus fertilizer (kg)	93	93	93	93	-	93
Inorganic potassium fertilizer (kg)	300	300	300	300	-	300
Organic nitrogen fertilizer (kg)	-	-	-	-	630	-

Parameter	Baseline	Biodiversity	Sustainable Irrigation System	Green Energy	Soil Management	Crop Protection
Organic phosphorus fertilizer (kg)	-	-	-	-	93	-
Organic potassium fertilizer (kg)	-	-	-	-	300	-
Herbicides (kg)	11	7.7-9.9	11	11	11	11
Insecticides (kg)	1.15	0.81-1.04	1.15	1.15	1.15	0.06
Fungicides (kg)	3.4	2.4-3.1	3.4	3.4	3.4	3.4
Mineral oils (kg)	3.8	3.8	3.8	3.8	3.8	3.8
Irrigation (l)	288000	288000	179000	288000	288000	288000
Diesel (MJ)	8994	8994	8994	8994	8994	8994
Electricity, low voltage (kWh)	1600	1600	-	-	1600	1600
Electricity, low voltage, renewable energy sources (kWh)	-	-	992	-	-	-
Electricity, low voltage, wind power	-	-	-	1600	-	-
OUTPUTS						
Onions (Kg)	50000	50000	50000	50000	50000	50000
Emissions to air						
Emissions from fungicides (kg)[21]	0.34	0.24-0.31	0.34	0.34	0.34	0.34
Emissions from insecticides (g)[1]	115	80.5-103.5	115	115	115	5.8
Emissions from herbicides (kg)[1]	1.1	0.77-0.99	1.1	1.1	1.1	1.1

[21] Nemecek et al., 2019

Parameter	Baseline	Biodiversity	Sustainable Irrigation System	Green Energy	Soil Management	Crop Protection
Nitrogen monoxide (kg)[22]	9.89	4.65	9.89	9.89	4.65	4.65
Ammonia (kg)[2]	76.46	35.94	76.46	76.46	35.94	35.94
Emissions to water						
Emissions from fungicides (g)[1]	3.0	2.1-2.7	3.0	3.0	3.0	3.0
Emissions from herbicides (g)[1]	1.0	0.7-0.9	1.0	1.0	1.0	1.0
Phosphate (kg)[2]	278.84	105.96	278.84	278.84	105.96	278.84
Nitrate (kg)[2]	0.70	0.33	0.70	0.70	0.33	0.70
Emissions to soil						
Emissions from fungicides (g)[1]	620	434-558	620	620	620	620
Emissions from insecticides (g)[1]	210	147-189	210	210	210	2.4
Emissions from herbicides (kg)[1]	8.4	5.9-7.6	8.4	8.4	8.4	8.4

Table 25: Life Cycle Inventory for the onion farming – Dutch UC. The values are given per ha per year (reference flow). "-" indicates zero value.

3.5.4. Environmental Life Cycle Impact Assessment (e-LCIA)

ReCiPe 2016 (H, hierarchist) was applied for the conversion of the LCI data presented in Tables 24 & 25 into a set of environmental impact potential scores. The results of the baseline scenario have been updated due to database updates, with the revised values of the 18 midpoint indicators being presented in Tables 26 & 27. The main midpoint indicators that resulted from life cycle impact assessment of the various product systems and differentiate among these systems are presented in Figures 10 & 11.

Impact category	Unit	Value
Global warming	kg CO2 eq	0.089
Stratospheric ozone depletion	kg CFC11 eq	2.39E-07
Ionizing radiation	kBq Co-60 eq	4.35E-03
Ozone formation, Human health	kg NOx eq	3.01E-04
Fine particulate matter formation	kg PM2.5 eq	8.33E-04

[22] (IPCC, 2019)

Impact category	Unit	Value
Ozone formation, Terrestrial ecosystems	kg NOx eq	3.93E-04
Terrestrial acidification	kg SO2 eq	3.12E-03
Freshwater eutrophication	kg P eq	2.34E-04
Marine eutrophication	kg N eq	6.57E-05
Terrestrial ecotoxicity	kg 1,4-DCB	1.46
Freshwater ecotoxicity	kg 1,4-DCB	0.007
Marine ecotoxicity	kg 1,4-DCB	0.017
Human carcinogenic toxicity	kg 1,4-DCB	0.006
Human non-carcinogenic toxicity	kg 1,4-DCB	0.208
Land use	m2a crop eq	0.014
Mineral resource scarcity	kg Cu eq	4.11E-04
Fossil resource scarcity	kg oil eq	0.026
Water consumption	m3	0.007

Table 26: Dutch UC Baseline scenario – midpoint impact indicators (FU: 1 kg of potatoes per year)

Impact category	Unit	Value
Global warming	kg CO_2 eq	0.107
Stratospheric ozone depletion	kg CFC11 eq	2.26E-07
Ionizing radiation	kBq Co-60 eq	5.39E-03
Ozone formation, Human health	kg NO_x eq	1.63E-04
Fine particulate matter formation	kg $PM_{2.5}$ eq	1.79E-03
Ozone formation, Terrestrial ecosystems	kg NO_x eq	3.70E-04
Terrestrial acidification	kg SO_2 eq	6.88E-03
Freshwater eutrophication	kg P eq	1.60E-05
Marine eutrophication	kg N eq	4.89E-04
Terrestrial ecotoxicity	kg 1,4-DCB	0.353
Freshwater ecotoxicity	kg 1,4-DCB	0.001
Marine ecotoxicity	kg 1,4-DCB	0.004
Human carcinogenic toxicity	kg 1,4-DCB	0.001
Human non-carcinogenic toxicity	kg 1,4-DCB	0.099
Land use	m^2a crop eq	0.003
Mineral resource scarcity	kg Cu eq	3.88E-04
Fossil resource scarcity	kg oil eq	0.034
Water consumption	m^3	0.007

Table 27: Dutch UC Baseline scenario – midpoint impact indicators (FU: 1 kg of onions per year)

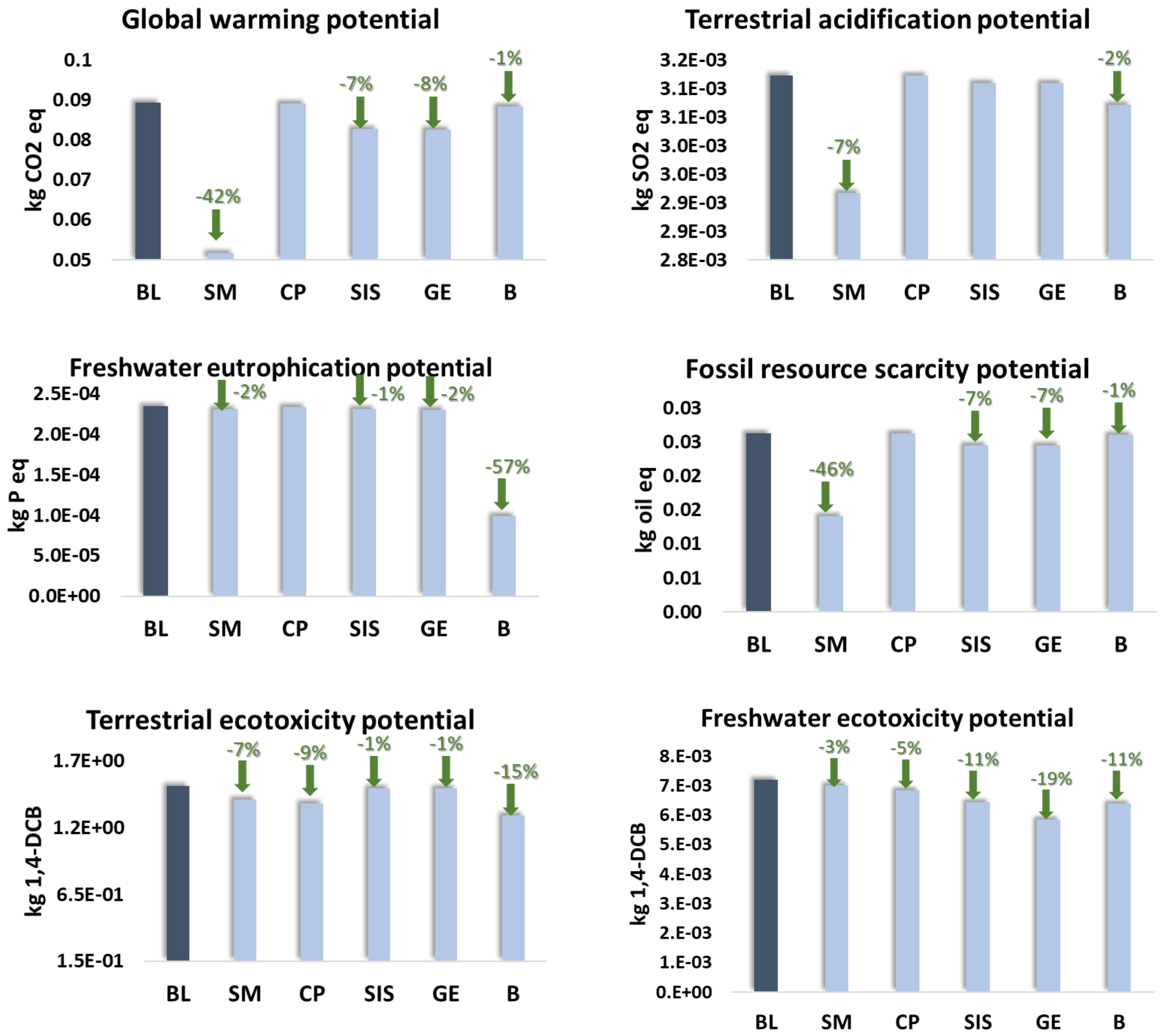
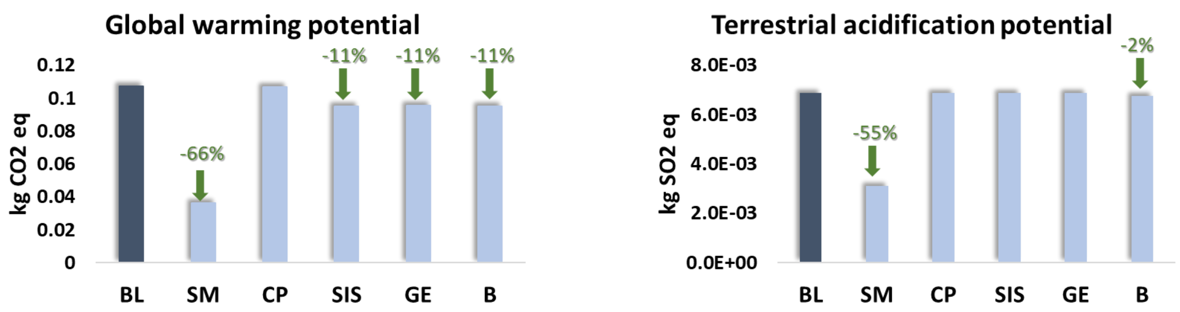


Figure 10: Environmental impact potential comparison of the Dutch baseline scenario vs. the different scenarios of the application of CSA practices – selected midpoint impact indicators are shown per ha of cultivated land per year (Dutch UC - potatoes). [Scenarios include: BL – Baseline, SM – Soil Management (IPM), CP – Crop Protection measures, SIS – Sustainable Irrigation Systems, GE – Green Energy, and B – Biodiversity measures].



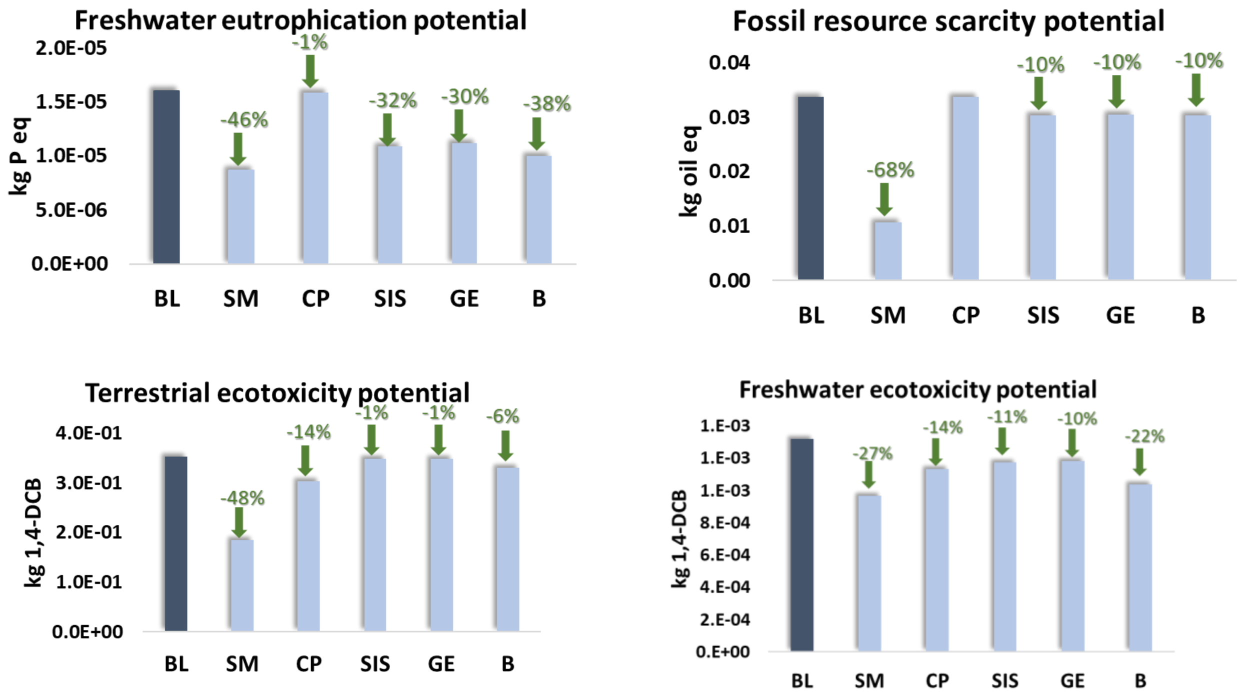


Figure 11: Environmental impact potential comparison of the Dutch baseline scenario vs. the different scenarios of the application of CSA practices – selected midpoint impact indicators are shown per ha of cultivated land per year (Dutch UC - onions). [Scenarios include: BL – Baseline, SM – Soil Management (IPM), CP – Crop Protection measures, SIS – Sustainable Irrigation Systems, GE – Green Energy, and B – Biodiversity measures].

The LCA conducted for the five different CSA practices applied in potato and onion farming demonstrated differentiated environmental performance across these scenarios. Each practice contributes uniquely to reducing environmental impact potentials, with some delivering substantial improvements across several midpoint impact categories.

Biodiversity measures, like flower strips and vegetative buffer zones, produce a variety of ecological advantages. These actions can enhance resilience at the landscape level, provide habitat for natural enemies and pollinators, and physically capture pesticide and nutrient runoff. The ability of vegetated strips to hold onto nitrogen and phosphorus that would otherwise end up in water bodies was demonstrated by the 38% (onion farming) and 57% (potato farming) decrease in freshwater eutrophication in the scenarios studied. Because of habitat buffering or a decreased need for chemical control, a 11-22% decrease in freshwater ecotoxicity indicated less chemical exposure in aquatic ecosystems. Although less significant, the decreases in global warming (1-11%) and the use of fossil fuels (1-10%) were probably the result of indirect efficiencies like less dependence on artificial inputs.

Significant environmental benefits resulted from **soil management** techniques, particularly the complete replacement of synthetic fertilizers for nitrogen, phosphorus, and potassium with organic amendments derived from compost. The removal of high-emission synthetic fertilizers, whose production involves intensive fossil fuel inputs, was the main factor responsible for the 42% (potato farming) and 66% (onion farming) reduction in global warming potential and the 46% (potato farming) and 68% (onion farming) decrease in the scarcity of fossil resources in the current scenario. In addition to lowering emissions, organic inputs improved soil organic carbon sequestration, which improved climate outcomes even more. Decreases in terrestrial ecotoxicity (48%) and freshwater eutrophication (46%) were a result of the reduced chemical leaching and increased nutrient use efficiency assumed in the studied scenario for onion farming. Compared to synthetic fertilizers, compost binds nutrients more effectively, lowering runoff and the possibility of contaminating neighboring ecosystems.

The ecological burden of pesticide use was lessened with the implementation of **Integrated Pest Management** (IPM). This scenario improved toxicity-related indicators, despite not altering fertilizer or energy inputs, which explains why global warming and the use of fossil fuels have not changed. The local fauna, soil microorganisms, and aquatic ecosystems benefit from reducing synthetic chemical applications, as evidenced by a 14% decrease in both terrestrial and freshwater ecotoxicity in onion farming. Similar results were obtained in the scenario of potato farming, with 9% and 5% decrease in terrestrial and freshwater ecotoxicity, respectively. IPM may not provide great changes when applied on its own, but it is essential for enhancing ecosystem health and reducing unanticipated environmental consequences of crop protection.

By combining automated irrigation sensors with solar-powered pumps, **sustainable irrigation systems** enable farmers to precisely adjust watering schedules to plant requirements. Due to less nutrient leaching and runoff, there were noticeable decreases in water-related effects, such as a 32% reduction in freshwater eutrophication in the potato farming scenario. The transition from diesel or grid-based irrigation systems to renewable power sources was reflected in the 7-10% decrease in the use of fossil resources and the 7-11% decrease in the potential for global warming in both scenarios. The effectiveness of sensor-based irrigation, which avoids overwatering and lowers the amount of fertilizer lost through drainage, amplified these benefits. As fertilizer and pesticide compositions didn't change, ecotoxicity reductions in these scenarios were only slight (1–11%). However, when combined with more comprehensive regenerative techniques, it can be a potent step toward low-carbon, resource-efficient water use.

Adoption of **green energy**, such as the use of wind power to power machinery, storage facilities, and irrigation systems, produced improvements across the board. The use of renewable energy instead of diesel or grid electricity in the current scenarios reduced CO_2 emissions by 8-11% and fossil resource scarcity by 7-10%. More stable power availability for precision systems (such as irrigation), which allowed for more consistent nutrient delivery and minimized runoff, was indirectly responsible for the 30% decrease in eutrophication in the scenario of potato farming. Although green energy lowered indirect emissions, it didn't directly replace harmful agricultural inputs, according to the comparatively tiny decreases in ecotoxicity indicators.

The scenarios represent a realistic entry point for integrating low-carbon energy solutions into Dutch agricultural systems with clear emission reduction potential. The results clearly demonstrated that the integration of CSA practices into potato and onion farming can significantly reduce environmental burdens. Each different CSA practice has its own distinct benefits and sometimes drawbacks; a combined application would have the potential to provide improved benefits, supporting the broader sustainability goals in potato and onion farming.

3.5.5. Life Cycle Cost Analysis (LCC)

A comparative LCC analysis was conducted for the different scenarios, taking into account annual operating costs, annual revenues, any subsidies provided, and any additional capital expenses required for the adoption of CSA practices. The main outputs of the LCC analysis are presented in Tables 28 & 29. At all cases, any prior 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 among the different scenarios under the same conditions. This approach aligns with the cradle-to-gate system boundaries and minimizes uncertainties associated with multi-year projections. The adoption of **biodiversity measures** is supported through eco-schemes under the EU's Common Agricultural Policy, providing an average subsidy of 106€/ha per year. No specialized equipment was required; thus no additional CapEx were included in the LCC analysis. Moreover, flower strips were assumed to be established on non-productive field margins, resulting in no loss of arable land. At the studied product system, the cost for the purchase of plant protection products was assumed to be decreased by 20%, as the need for pest management was addressed through more environmentally friendly approaches. The extra work needed for the establishment and maintenance of the vegetative strips was considered negligible and therefore not reflected in the labor costs. Since biodiversity measures are not directly yield-oriented, annual production volumes remained unchanged. Thus, the reduction in OpEx contributed to an estimated 8% profit increase in both scenarios, reaching above 3 k€ per year. The establishment of **innovative and sustainable irrigation systems** is supported through eco-schemes under the EU's Common Agricultural Policy, providing an average subsidy of 106€/ha per year. For the establishment of such a system, equipment including soil moisture sensors, automated controllers, data logging, and IoT platforms was assumed to be obtained. The purchase cost for the smart irrigation system was estimated at about 220€ per ha for a medium-scale farm. Applying straight-line depreciation over a 10-year lifespan, the annual CapEx was estimated at 22€/ha. Any other equipment used is considered to have been depreciated, with only its maintenance costs considered. Conventional electricity was assumed to be replaced with green energy, provided by a larger renewable energy grid (regional green electricity mix) free of charge, since it came from renewable sources and was acquired through a cooperative subsidized program. Thus, the farm was not subject to any additional capital or operating costs. Regarding the OpEx, as a result of more effective irrigation scheduling, the conventional electricity replacement and the lower water consumption, they marginally dropped to approximately €6,650 per ha per year. The slightly lower OpEx offset most of the CapEx in the current scenarios, whereas revenues stayed the same. This resulted in a slight increase in annual profit of roughly 3% over the baseline scenario, reaching 2960€-3180€ per ha per year. The adoption of **IPM** is supported through eco-schemes under the EU's Common Agricultural Policy, providing an average subsidy of 106€/ha per year. Reliance on natural pest enemies, decreased insecticide use, and monitoring-based decision-making were all features of the IPM scenario. The 20% reduction in pesticide-related expenses had a moderate impact on profit, which was 4% increased compared to the baseline and demonstrated that environmentally friendly pest control can be profitable. In the **green energy** scenario, it was assumed that renewable energy sources, primarily wind energy supplied via the regional grid, would partially power on-farm energy requirements like irrigation. The farm paid a standard rate, comparable to that of conventional electricity. The use of green energy is also supported through eco-schemes under the EU's Common Agricultural Policy, providing an average subsidy of 106€/ha per year. Electricity costs were comparable to those in the baseline scenario, as renewable energy was sourced through certified grid-based suppliers. No significant changes were observed in OpEx, whereas a modest increase in revenues (attributed to subsidies) resulted in a 3-4% increase in overall profit. **Soil management** techniques are incorporated into the system to improve soil fertility and structure and are usually supported through eco-schemes under the EU's Common Agricultural Policy, providing an average subsidy of ~110€/ha per year. Due primarily to reduced synthetic fertilizer inputs and improved field operations, these adjustments resulted in a decrease of ~260-330€/ha per year in OpEx. Because the soil was better at retaining water and nutrients, production levels stayed constant. Thus, at 3,300-3,500 €/ha/year, a 12-15% increase over the baseline, the scenarios were the most profitable of all the options.

	Cost category (€/ha/year)	Baseline	Biodiversity	Sustainable Irrigation System	Green Energy	Soil Management	Crop protection (IPM)
EXPENSES	Annualized CapEx	€ -	€ -	€ 22	€ -	€ -	€ -
	Seeds	€ 1,296	€ 1,296	€ 1,296	€ 1,296	€ 1,296	€ 1,296
	Energy	€ 447	€ 447	€ 447	€ 447	€ 447	€ 447
	Fertilizers	€ 332	€ 332	€ 332	€ 332	€ -	€ 332

	Cost category (€/ha/year)	Baseline	Biodiversity	Sustainable Irrigation System	Green Energy	Soil Management	Crop protection (IPM)
	Plant protection products	€ 1,036	€ 900	€ 1,036	€ 1,036	€ 1,036	€ 1,036
	Water	€ 30	€ 30	€ 19	€ 30	€ 30	€ 30
	Maintenance	€ 33	€ 33	€ 33	€ 33	€ 33	€ 33
	Labor	€ 2,838	€ 2,838	€ 2,838	€ 2,838	€ 2,838	€ 2,838
	Rent	€ 600	€ 600	€ 600	€ 600	€ 600	€ 600
	Other (taxes, admin, etc)	€ 148	€ 148	€ 148	€ 148	€ 148	€ 148
	Total	€ 6,761	€ 6,625	€ 6,771	€ 6,761	€ 6,428	€ 6,761
	Change over BL:		-2%	0.2%	0%	-4.9%	0%
REVENUE	Potatoes	€ 9,640	€ 9,640	€ 9,640	€ 9,640	€ 9,640	€ 9,640
REVENUE	Subsidies	€ -	€ 106	€ 106	€ 106	€ 106	€ 106
REVENUE	Total	€ 9,640	€ 9,746	€ 9,746	€ 9,746	€ 9,746	€ 9,746
REVENUE	*Change over BL:*		1.1%	1.1%	1.1%	1.1%	1.1%
	Profit	€ 2,879	€ 3,121	€ 2,975	€ 2,985	€ 3,318	€ 2,985

Table 28: Comparative LCC analysis (annual basis) of the baseline scenario and the different CSA practices for the Dutch UC (potatoes).

	Cost category (€/ha/year)	Baseline	Biodiversity	Sustainable Irrigation System	Green Energy	Soil Management	Crop protection (IPM)
EXPENSES	Annualized CapEx	€ -	€ -	€ 22	€ -	€ -	€ -
EXPENSES	Seeds	€ 1,824	€ 1,824	€ 1,824	€ 1,824	€ 1,824	€ 1,824
EXPENSES	Energy	€ 535	€ 535	€ 535	€ 535	€ 535	€ 535
EXPENSES	Fertilizers	€ 267	€ 267	€ 267	€ 267	€ -	€ 267
EXPENSES	Plant protection products	€ 200	€ 138	€ 200	€ 200	€ 200	€ 200
EXPENSES	Water	€ 29	€ 29	€ 18	€ 29	€ 29	€ 29
EXPENSES	Maintenance	€ 34	€ 34	€ 34	€ 34	€ 34	€ 34
EXPENSES	Labor	€ 2,838	€ 2,838	€ 2,838	€ 2,838	€ 2,838	€ 2,838
EXPENSES	Rent	€ 600	€ 600	€ 600	€ 600	€ 600	€ 600
EXPENSES	Other (taxes, admin, etc)	€ 148	€ 148	€ 148	€ 148	€ 148	€ 148
EXPENSES	Total	€ 6,474	€ 6,412	€ 6,485	€ 6,474	€ 6,208	€ 6,474
EXPENSES	*Change over BL:*		-0.95%	0.17%	0.00%	-4.12%	0.00%
REVENUE	Onions	€ 10,000	€ 10,000	€ 10,000	€ 10,000	€ 10,000	€ 10,000
REVENUE	Subsidies	€ 106	€ 106	€ 106	€ 106	€ 106	€ 106
REVENUE	Total	€ 10,106	€ 10,106	€ 10,106	€ 10,106	€ 10,106	€ 10,106
REVENUE	*Change over BL:*		1.1%	1.1%	1.1%	1.1%	1.1%
	Profit	€ 3,526	€ 3,694	€ 3,621	€ 3,632	€ 3,898	€ 3,632

Table 29: Comparative LCC analysis (annual basis) of the baseline scenario and the different CSA practices for the Dutch UC (onions).

3.5.6. Social Life Cycle Impact Assessment (s-LCIA)

General | s-LCIA

The production flows and relevant inventory data of all the examined Dutch CSA scenarios were taken from the resulting LCIAs shown in previous Tables 24 & 25. According to the received questionnaire, the data inputs for most of the impact factors were similar with the baseline scenario for all the examined CSAs, and thus were directly taken from Table 35 of the previous D3.1. These included the impact factors with their associated risk levels. The only exceptions were the “Sector average wage, per month”, “Women in the sectoral labor force”, “Men in the sectoral labor force”, “Gender wage gap”, “Certified Environmental Management Systems”, “Embodied agricultural area footprints”, “Embodied water footprints”, “Embodied CO2eq footprints” and “Embodied value added” impact factors, for which their values were reassessed, according to the received questionnaire data for each CSA. The changes to the data inputs, with regards to the baseline scenario described in previous D3.1, are summarized in Tables 30 & 31 below:

Input	Baseline	Soil management	Biodiversity	Crop protection	Sustainable irrigation	Green energy
Worker hours[6]	0.0448	0.0448	0.0448	0.0448	0.0448	0.0448
Sector average wage, per month	High	Medium	Medium	Medium	Medium	Medium
Women in the sectoral labor force	Very High	Medium	Medium	Medium	Medium	Medium
Men in the sectoral labor force	No Risk	Medium	Medium	Medium	Medium	Medium
Gender wage gap	Very High	No Risk	No Risk	No Risk	No Risk	No Risk
Certified Environmental Management Systems	Very High	Very Low	Very Low	Very Low	Very Low	Very Low
Embodied agricultural area footprints	High	High	High	High	High	High
Embodied water footprints	Very Low	Very Low	Very Low	Very Low	Very Low	Very Low
Embodied CO2eq footprints	Medium	Medium	Medium	Medium	Medium	Medium
Embodied value added	Medium	Medium	Medium	Medium	Medium	Medium

Table 30: Changes of the data inputs of s-LCIA, from the Dutch baseline scenario, shown in previous D3.1 – potato production (the impact factors not shown were not changed and thus were taken directly from the baseline scenario, as presented in Table 35 of the previous D3.1).

Input	Baseline	Soil management	Biodiversity	Crop protection	Sustainable irrigation	Green energy
Worker hours[6]	0.0432	0.0432	0.0432	0.0432	0.0432	0.0432
Sector average wage, per month	High	Medium	Medium	Medium	Medium	Medium
Women in the sectoral labor force	Very High	Medium	Medium	Medium	Medium	Medium
Men in the sectoral labor force	No Risk	Medium	Medium	Medium	Medium	Medium
Gender wage gap	Very High	No Risk	No Risk	No Risk	No Risk	No Risk
Certified Environmental Management Systems	Very High	Very Low	Very Low	Very Low	Very Low	Very Low
Embodied agricultural area footprints	High	Medium	Medium	Medium	Medium	Medium
Embodied water footprints	Very Low	Very Low	Very Low	Very Low	Very Low	Very Low
Embodied CO2eq footprints	Medium	Medium	Medium	Medium	Medium	Medium
Embodied value added	Medium	Medium	Medium	Medium	Medium	Medium

Table 31: Changes of the data inputs of s-LCIA, from the Dutch baseline scenario, shown in previous D3.1 – onion production (the impact factors not shown were not changed and thus were taken directly from the baseline scenario, as presented in Table 35 of the previous D3.1).

The results from the s-LCIA analyses for all the examined CSA scenarios are shown in Figures 12 & 13 below. Along with the studied CSAs, the results of the baseline scenario have also been updated due to database updates (ILO, WHO etc.) that changed the risk levels of some impact factors. A more detailed analysis of each CSA examined is given below. Generally, the results were in line with the changes of the LCI. However, some of the impact factors resulted in high social footprints, despite the fact that they had very low-medium risks. This was found for all examined CSAs and the baseline scenario as well, and was attributed to impacts from upstream flows. More specifically, for the baseline scenario, most impactful flows were the ones related with the use of inorganic fertilizers on global scale, followed by production of potato seeds and production and use of electricity and diesel. Any CSA that contributed a positive change to the above resulted in reduced impacts.

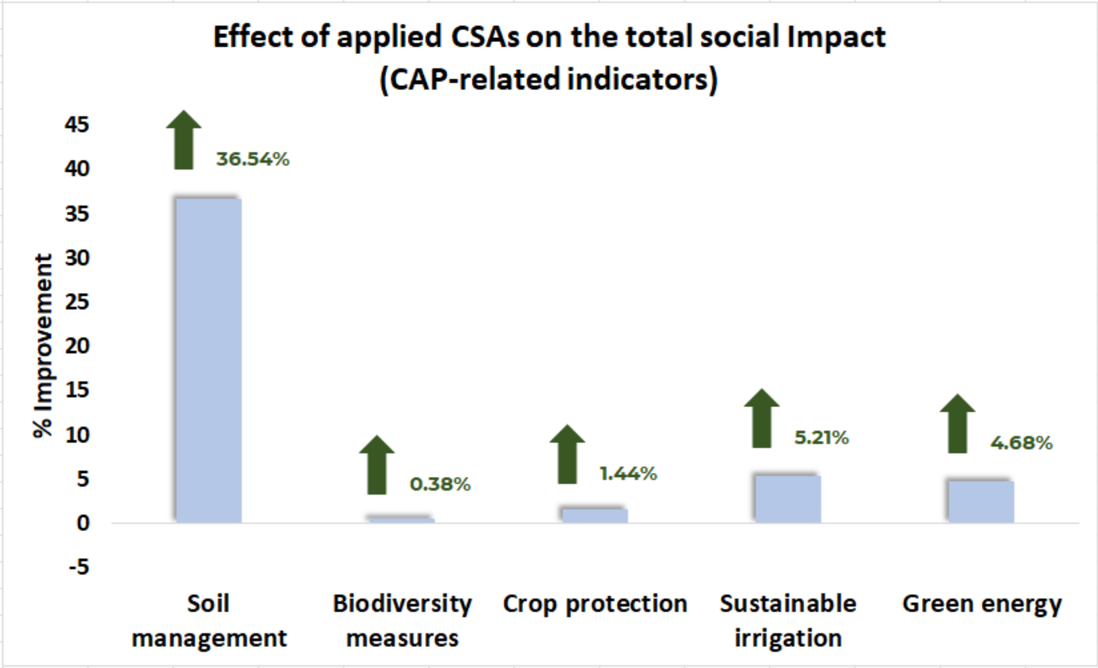


Figure 12: Comparison of the changes in the social impacts from the investigated CSAs, regarding the EU CAP-relevant social indicators – impacts for potatoes production per year (Dutch UC) (0 value represents the baseline).

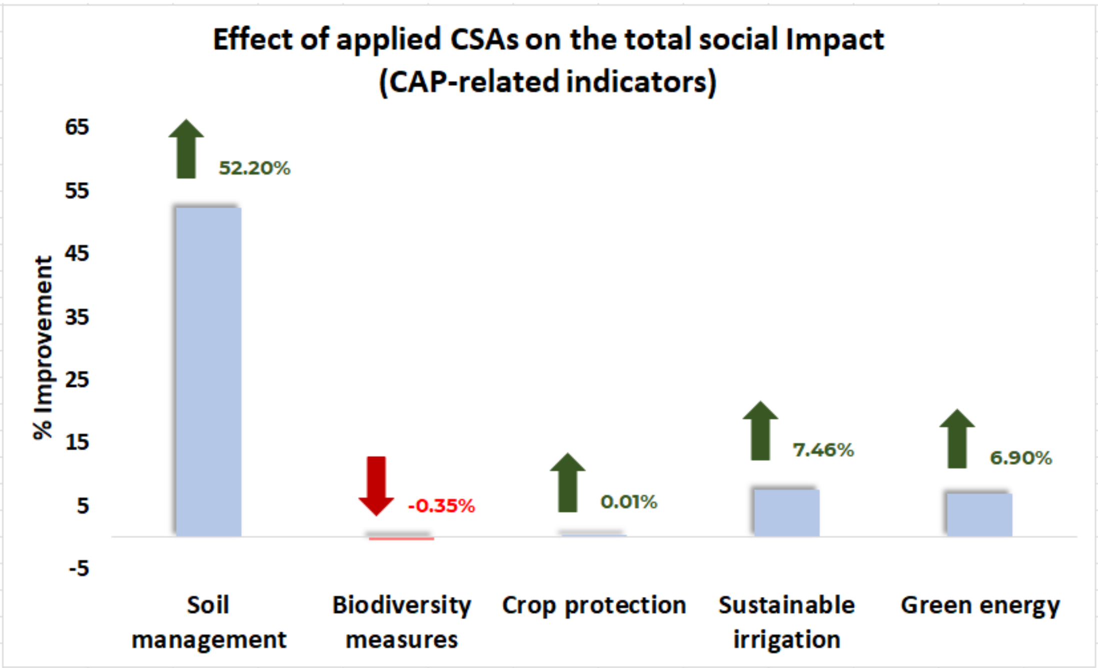


Figure 13: Comparison of the changes in the social impacts from the investigated CSAs, regarding the EU CAP-relevant social indicators – impacts for onions production per year (Dutch UC) (0 value represents the baseline).

Soil management | s-LCIA

Beginning with the soil management scenario, this one performed better than the baseline scenario. For potatoes production, it resulted in a 49% decrease in total DALYs, while for onions production, it resulted in a 75% decrease, respectively. This result was expected, as the anticipated changes were mostly based on changes in the LCI, as well as on the improvement of some impact factors (Tables 24 & 25). Focusing on the CAP-relevant indicators that are more in accordance with the BEATLES project, the soil management scenario resulted in 37% and 52% reduced social footprints for potatoes and onions production respectively. The 4 most important factors were the Fair Salary, followed by Embodied Biodiversity Footprints, GHG Footprints and Unemployment rate. As a result, the soil management scenario resulted in reduced social impacts than the baseline scenario, due to the changes associated with the fertilizers used.

Biodiversity | s-LCIA

Moving on to the biodiversity scenario, this one performed very close to the baseline scenario, with very marginal differences. For both potatoes and onions production, it resulted in a <1% decrease in total DALYs. This result was expected, as the anticipated changes were mostly based on changes in the LCI, as well as on the improvement of some impact factors (Tables 24 & 25). Focusing on the CAP-relevant indicators that are more in accordance with the BEATLES project, the biodiversity scenario resulted in <1% reduced social footprints for potatoes production and in <1% increased social footprints for onions production respectively. The 4 most important factors were the Fair Salary, followed by Embodied Biodiversity Footprints, GHG Footprints and Unemployment rate. Notably, the biodiversity scenario included only slight changes in less impactful flows, and as a result it performed close to the baseline scenario.

Crop protection | s-LCIA

Subsequently for the crop protection scenario, this one performed very close to the baseline scenario, with very marginal differences. For potatoes production, it resulted in a 1% decrease in total DALYs, while for onions production, it resulted in a <1% decrease, respectively. This result was expected, as the anticipated changes were mostly based on changes in the LCI, as well as on the improvement of some impact factors (Tables 24 & 25). Focusing on the CAP-relevant indicators that are more in accordance with the BEATLES project, the crop protection scenario resulted in 1% and <1% reduced social footprints for potatoes and onions production respectively. The 4 most important factors were the Fair Salary, followed by Embodied Biodiversity Footprints, GHG Footprints and Unemployment rate. Notably, the crop protection scenario included only slight changes in less impactful flows, and as a result, it performed close to the baseline scenario. Additionally, compared with the previous quite similar biodiversity scenario, it seems that the changes in the chemicals used in crop protection scenario were slightly more beneficial (much reduced amounts of insecticides only, compared to a smaller reduction for all the chemicals used).

Sustainable irrigation system | s-LCIA

Moving on to the sustainable irrigation scenario, this one performed slightly better than the baseline scenario. For potatoes production, it resulted in a 2% decrease in total DALYs, while for onions production, it resulted in a 3% decrease, respectively. This result was expected, as the anticipated changes were mostly based on changes in the LCI, as well as on the improvement of some impact factors (Tables 24 & 25). Focusing on the CAP-relevant indicators that are more in accordance with the BEATLES project, the sustainable irrigation scenario resulted in 5% and 7% reduced social footprints for potatoes and onions production respectively. The 4 most important factors were the Fair Salary, followed by Embodied Biodiversity Footprints, GHG Footprints and Unemployment rate. As a result, the sustainable irrigation scenario resulted in slightly reduced social impacts than the baseline scenario, due to the reduced demands of electricity.

Green energy | s-LCIA

Finally, for the green energy scenario, this one performed slightly better than the baseline scenario. For potatoes production, it resulted in a 2% decrease in total DALYs, while for onions production, it resulted in a 3% decrease, respectively. This result was expected, as the anticipated changes were mostly based on changes in the LCI, as well as on the improvement of some impact factors (Tables 24 & 25). Focusing on the CAP-relevant indicators that are more in accordance with the BEATLES project, the green energy scenario resulted in 5% and 7% reduced social footprints for potatoes and onions production respectively. The 4 most important factors were the Fair Salary, followed by Embodied Biodiversity Footprints, GHG Footprints and Unemployment rate. As a result, the green energy scenario resulted in slightly reduced social impacts than the baseline scenario, due to the use of electricity from renewable sources.

Conclusions | s-LCIA

According to the results from the s-LCIA analyses, from the social impact perspective, the best results were acquired from the soil management scenario (37% and 52% reduced footprints for potato and onion production respectively), followed by sustainable irrigation and green energy (5% and 7% reduced footprints for both). Crop protection and biodiversity scenarios performed very close to the baseline one (up to 1% reduced footprints) and can be considered in case the improvement of the social footprints is a secondary objective of the transition-to-CSA strategy.

3.5.7. Cost-Benefit Analysis

The comparative cost-benefit analysis of the five sustainability scenarios—Biodiversity, Sustainable Irrigation, Integrated Pest Management (IPM), Green Energy, and Soil Management—reveals diverse paths to improved environmental, economic, and social performance in agriculture, each with varying levels of investment, operational change, and impact.

From a cost perspective, Soil Management emerged as the most economically advantageous scenario, requiring no CapEx and delivering the greatest OpEx savings by replacing synthetic fertilizers with compost. Similarly, Biodiversity and IPM scenarios were low-cost to implement, as they used existing infrastructure and integrated measures into routine operations. Green Energy required no direct investments but relied on cooperative power purchasing, and while Sustainable Irrigation involved moderate CapEx (220€/ha), its cost was offset over time through energy and water savings.

In terms of environmental outcomes, Soil Management again led with dramatic reductions in global warming potential (42–66%) and fossil fuel use (46–68%). Biodiversity and IPM both notably reduced pesticide-related ecotoxicity, while Sustainable Irrigation decreased eutrophication and contributed to climate-smart agriculture by switching to renewable energy. Green Energy contributed to lower emissions and resource use but had limited impact on ecotoxicity due to unchanged chemical inputs, highlighting the need for coupling with other interventions.

Economically, all scenarios demonstrated improved profitability, aided by CAP eco-scheme subsidies of 106€/ha/year. Soil Management showed the highest profit increase (12–15%), followed by Biodiversity (8%), IPM (4%), Green Energy (3–4%), and Sustainable Irrigation (3%). Yield stability across all scenarios ensured that sustainability did not come at the cost of productivity, which is crucial for scalability and farmer adoption.

CSA	Costs	Benefits		
		Environmental	Economic	Social
Biodiversity	No additional CapEx, as no specialized equipment was required. Slight increase in labor intensity (but negligible cost impact), due to additional handling for buffer zones. Time investment in planning and maintenance Limited direct market reward; no observed premium price for biodiversity	↓freshwater eutrophication, 38–57%, as buffer strips captured nitrogen and phosphorus runoff effectively ↓freshwater ecotoxicity, 11–22%, due to reduced pesticide usage. ↓GWP & fossil fuel use, 1–11%, due to lower input reliance (e.g., pesticides). Enhanced habitat and landscape resilience, as floral bands provide food and shelter for pollinators and natural enemies	20% reduction in plant protection product costs, due to reduced need for chemical pest control. No yield reduction or land loss, as measures were implemented on non-productive field margins. +106 €/ha/year from CAP eco-schemes 8% increase in annual profit (~3,000 €/year), due to reduced OpEx and provided subsidies.	Enhanced awareness of sustainable practices, as farmers engaged in biodiversity measures develop knowledge and skills relevant to CSA. Chain shortening and certification (e.g., Planet Proof) add indirect social value. Slight improvement or neutrality in social footprint indicators. Potatoes ↓0.38% in social footprint, onions ↑0.35%, reflecting minimal net social impact overall.

CSA	Costs	Benefits		
		Environmental	Economic	Social
Sustainable Irrigation System	CapEx: 22€/ha/year (depreciated over 10 years) → Cost of smart irrigation systems (soil moisture sensors, automation, IoT tools) estimated at 220€/ha; amortized over 10 years.	↓freshwater eutrophication, 32%, as smart scheduling reduces nutrient leaching, preventing phosphorus and nitrogen from contaminating water bodies. ↓GWP, 7–11% due to replacement of conventional electricity/diesel with green energy. ↓fossil fuel use, 7–10%, due to shift to renewable-powered irrigation systems (e.g., solar pumps, green grid). ↓freshwater ecotoxicity, 1–11% as mproved water efficiency lowers runoff, reducing chemical exposure to aquatic ecosystems.	+106 €/ha/year from CAP eco-schemes ↑annual profit (~3000 €/ha/year), 3%, as lower OpEx and provided subsidies help offset CapEx. ↓OpEx to ~€6,650/ha/year, due to lower water and electricity use, and use of subsidized green energy. No change in yields Smart irrigation improved efficiency without sacrificing productivity.	↓DALYs, 2-3%, due to improved environmental conditions. ↓Social footprint (CAP indicators),5-7.5%, due to lower energy use and better labor/resource allocation. Medium risk only in Fair Salary and GHG Footprints. All other indicators (Biodiversity Footprint, Unemployment) were low or no-data risk, suggesting overall social responsibility improved. Knowledge transfer and digital skill enhancement Farmers gain experience with smart agri-tech, improving employability and digital literacy.

CSA	Costs	Benefits		
		Environmental	Economic	Social
Crop Protection – Integrated Pest Management (IPM)	No additional CapEx, as IPM relies on existing equipment. Slight increase in labor costs, as more time required for pest monitoring. Neglible costs compared to the total annual OpEx that remained at 6760€ (potatoes) and 6900€ (onions) per ha. Farmers may need guidance on implementing biological control and scouting, but no structural investment was needed. No change in GWP or fossil fuel use, as fertilizer and energy inputs remained constant; IPM focused strictly on pest control practices.	↓Terrestrial and freshwater ecotoxicity, 14%, due to less insecticide use in onions cultivation. ↓Terrestrial and freshwater ecotoxicity, 5-9%, due to less insecticide use in potatoes cultivation. More modest benefits for potatoes but still significant improvements in soil and water health. Enhanced local biodiversity and soil life through reduction in pesticide application.	+106 €/ha/year from CAP eco-schemes ↑Annual profit, 4%, through a 20% reduction in pesticide costs. Low operational disruption; IPM was integrated into existing farming systems without major reorganization or cost burdens.	↓DALYs (1.26% in potatoes and 0.01% in onions), due to reduced exposure to toxic chemicals. ↓Social footprint (1.44% in potatoes and 0.01% in onions). Medium risk in Fair Salary and GHG Footprints. All other social risks were rated Low or No Data, and changes remained marginal but in a positive direction. Supports farmer skills and ecological awareness.

CSA	Costs	Benefits		
		Environmental	Economic	Social
Green Energy	No additional CapEx, as the farm did not install its own wind turbine or infrastructure; renewable energy was sourced through the cooperative grid. Electricity costs comparable to baseline, as power from the regional green energy grid is priced similarly to conventional electricity. No direct control over supply; the wind turbine is owned by a nearby company within a cooperative.	↓CO_2 emissions 8–11%, due to fossil-based electricity replacement with wind power. ↓ Fossil resource use, 7–10% ↓ Freshwater eutrophication (potatoes), 30% Small (1–5%) decrease in ecotoxicity indicators, as fertilizers and pesticides were unchanged	+106 €/ha/year CAP eco-scheme subsidy ↑profit, 3–4%, driven by subsidies, not energy cost savings. No change in operational complexity, as energy sourcing was through an existing grid connection	1.70% and 2.50% reduction in DALYs (potatoes, onions), due to use of clean energy reduced emissions and health-related externalities. 4.68% and 6.90% reduction in social footprint (potatoes, onions) Medium risk in Fair Salary and GHG Footprints Cooperative energy sharing among farmers builds local solidarity and mutual benefit.

CSA	Costs	Benefits		
		Environmental	Economic	Social
Soil Management	No additional CapEx, as no specialized equipment was required. ↓OpEx 260 to 330 €/ha/year, due to replacement of synthetic fertilizers with organic compost.	↓GWP, 2% (potatoes) and 66% (onions) due to replacement of synthetic fertilizers with compost. ↓ fossil resource scarcity, 46% (potatoes) and 68% (onions) due to avoidance of high-energy fertilizer inputs. ↓ terrestrial ecotoxicity 7-48%, as nutrient binding in compost minimized chemical leaching and contamination of soil ecosystems. ↓ freshwater eutrophication 46% decrease (onions), due to more efficient nutrient use and less runoff.	+106 €/ha/year CAP eco-scheme subsidy ↑Profit, 12–15% (3,300–3,500 €/ha/year), due to reduced OpEx and retained yields. Stable yields due to improved nutrient retention.	↓DALYs, 48.93% (potatoes) and 75.25% (onions) due to lower emissions and chemical exposure. ↓ social footprint, 36.54% (potatoes) and 52.20% (onions), driven by environmental gains and fairer production flows. Medium risk for Fair Salary and GHG Footprints Enhanced long-term farm resilience, nutrient cycling, and carbon capture, contributing to both environmental and social sustainability.

Table 32: Summary of Cost – Benefit Analysis for the CSA practices studied in the Netherlands UC.

Socially, Soil Management had the most profound impact, with DALY reductions of nearly 49% (potatoes) and 75% (onions), along with the largest improvements in social footprint metrics. Green Energy also showed strong social gains due to cleaner energy inputs. While IPM and Biodiversity offered modest social benefits, they supported farmer education and long-term ecosystem resilience. Sustainable Irrigation showed balanced social improvements, largely from reduced chemical exposure and better resource management.

In conclusion, while all scenarios contribute to sustainability, Soil Management stands out for its high environmental impact and economic returns, with significant social co-benefits. Biodiversity and IPM offer low-cost, easily adoptable strategies with strong environmental returns. Green Energy and Sustainable Irrigation, though requiring more systemic infrastructure or partnerships, provide steady gains across all dimensions. An integrated approach combining elements of each scenario could maximize the sustainability of future cropping systems.

4. Theory of Change of BEATLES

The overall status of the ToC of BEATLES in terms of the established short/mid-term outcomes as outlined in the ToC strategy, is presented for all completed activities in Figure 14. Current completion rate is around 23%, nevertheless, it is expected that ongoing/upcoming activities and events will significantly contribute to the established targets (e.g. Lab 4-8 experiments, Field 1-2 experiments etc.). The present section updates the corresponding one in the previous D3.1 deliverable with the results from the completed relevant activities of this year. These included the EU multi-actor working groups 1 & 2, the webinars 2, 3 & 4, as well as the 3rd Co-creation workshops. More details are presented in below sections for each activity.

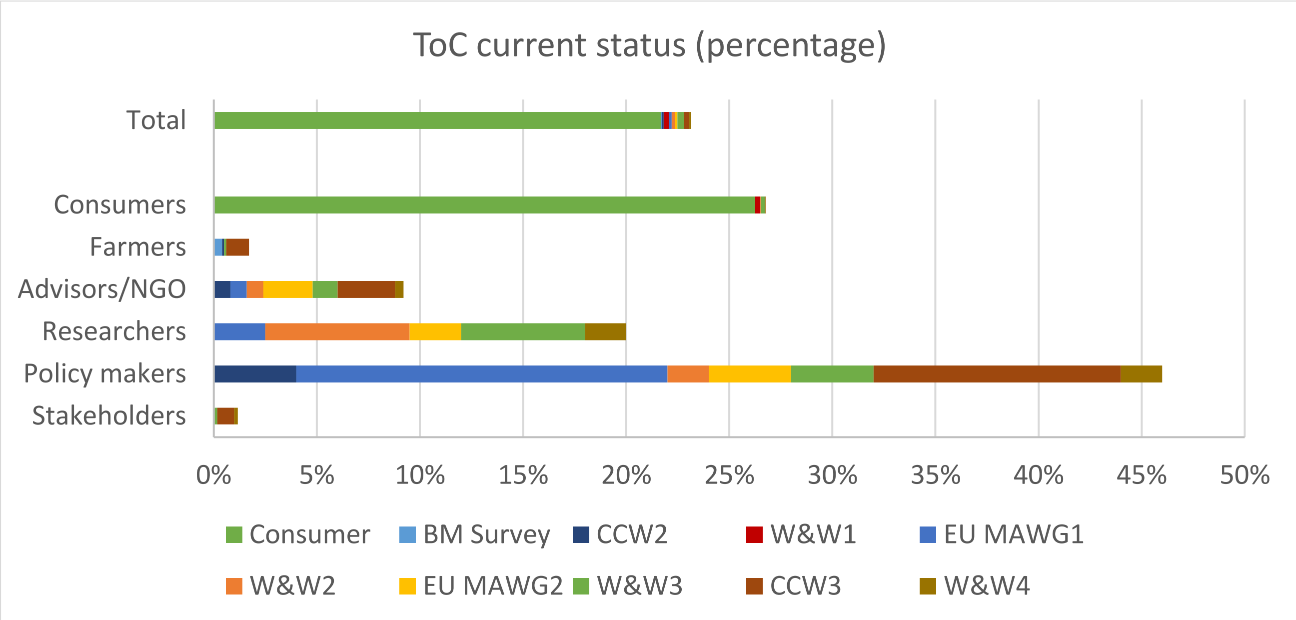


Figure 14: Current status of completion of short/mid-term outcomes of the ToC strategy

4.1. EU Multi-actor working group 1 (EU MAWG1)

The EU Multi-actor working group 1 questionnaire included two ToC-relevant questions, involving the increase of awareness regarding policy aspects for the transition to CSA. The ToC-relevant results from the EU MAWG1 questionnaire are presented below (Figure 15). Overall, the questionnaire got a total of 16 responses, out of which 12 were positive and 3 neutral, meaning that most of the participants increased their awareness regarding policy aspects for the transition to CSA.

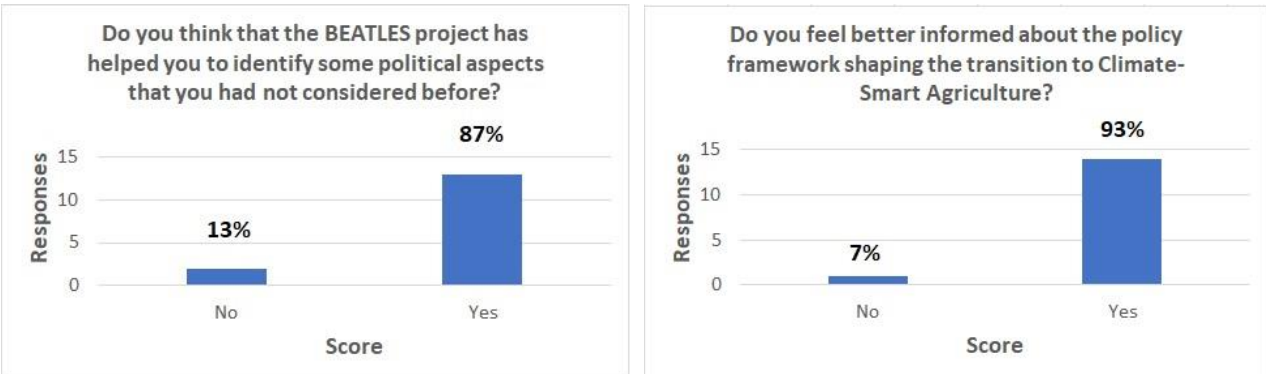


Figure 15: ToC results from the EU multi-actor working group 1 questionnaire.

4.2. Webinar & workshop 2 (W&W2)

The Webinar 2 questionnaire included 2 ToC-relevant questions, involving the increase of awareness regarding the decision-making factors for transition towards CSA, as well as two questions about satisfaction of the event and recommendation of the project. The ToC-relevant results from the W&W2 questionnaire are presented below (Figure 16). Overall, the questionnaire got a total of 21 responses, out of which 19 were positive and 2 neutral, meaning that most of the participants increased their awareness regarding the important levers and challenges for the transition to CSA and were satisfied from the event and the project.

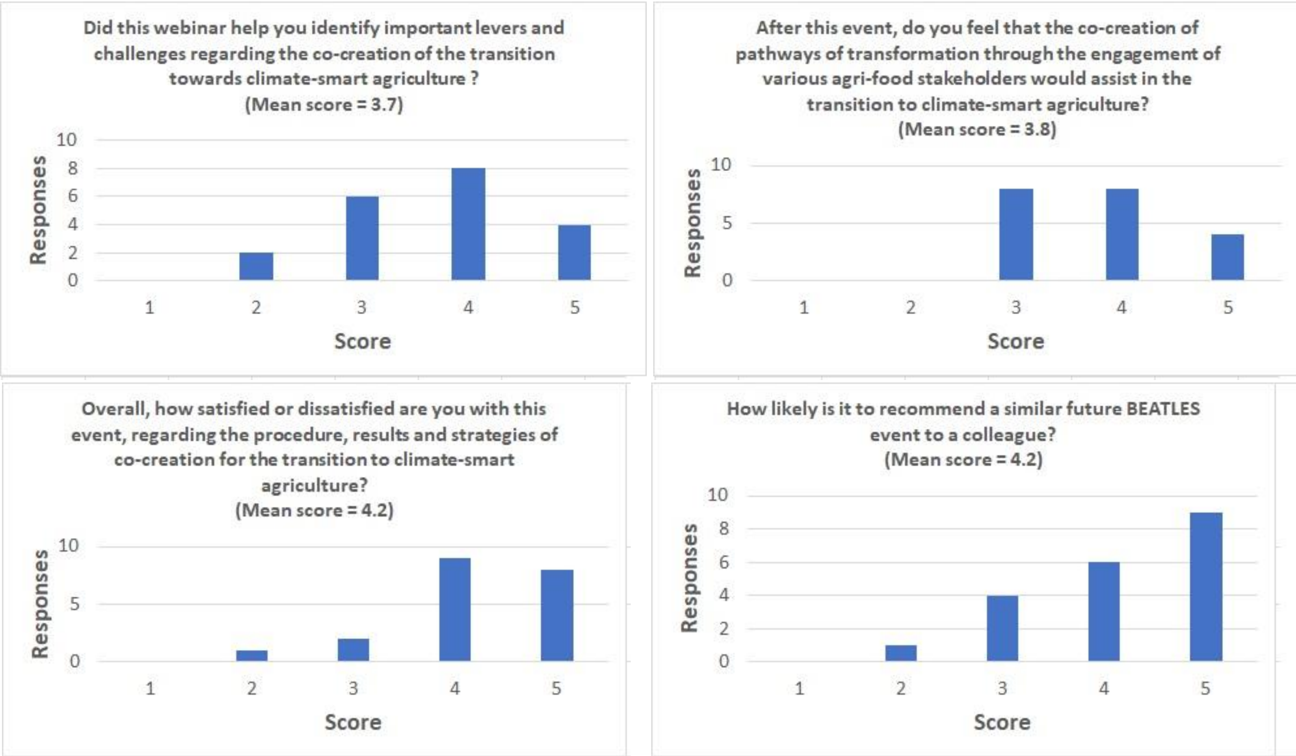


Figure *16*: ToC results from the webinar & workshop 2 questionnaire.

4.3. EU Multi-actor working group 2 (EU MAWG2)

Similar with the previous EU MAWG1, the EU MAWG 2 questionnaire included two ToC-relevant questions, involving the increase of awareness regarding policy aspects for the transition to CSA. The relevant results from the EU MAWG2 questionnaire are presented below (Figure 17). Overall, the questionnaire got a total of 13 positive responses, meaning that most of the participants increased their awareness regarding policy aspects for the transition to CSA.

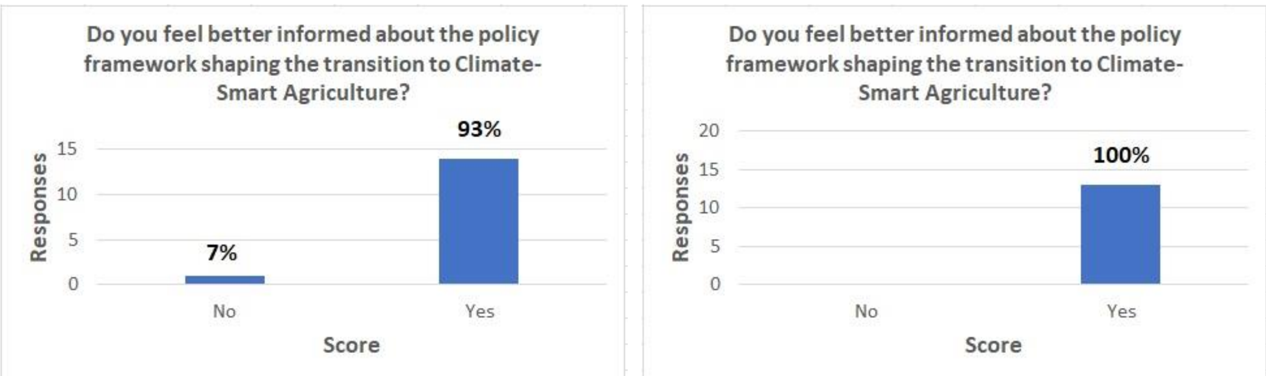


Figure 17: ToC results from the EU multi-actor working group 2 questionnaire.

4.4. Webinar & workshop 3 (W&W3)

The Webinar 3 questionnaire included 2 ToC-relevant questions, involving the willingness to pay for products manufactured in an environment-friendly way, the increase of awareness regarding the decision-making factors for transition towards CSA, as well as two questions about satisfaction of the event and recommendation of the project. The ToC-relevant results from the W&W3 questionnaire are presented below (Figure 18). Overall, the questionnaire got a total of 20 responses, out of which 19 were positive and 1 negative, meaning that most of the participants agree to pay more if necessary for environment-friendly products, increased their awareness regarding the important levers and challenges for the transition to CSA and were satisfied from the event and the project.

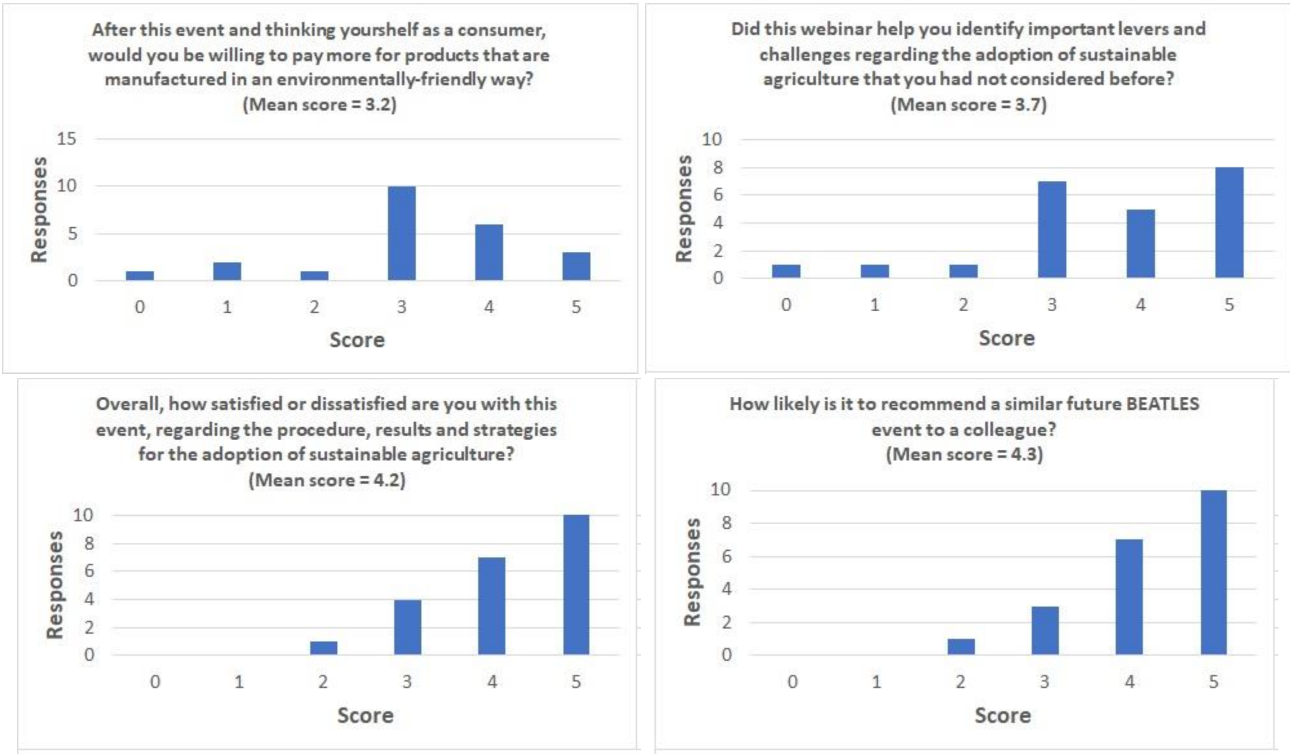


Figure 18: ToC results from the webinar & workshop 3 questionnaire.

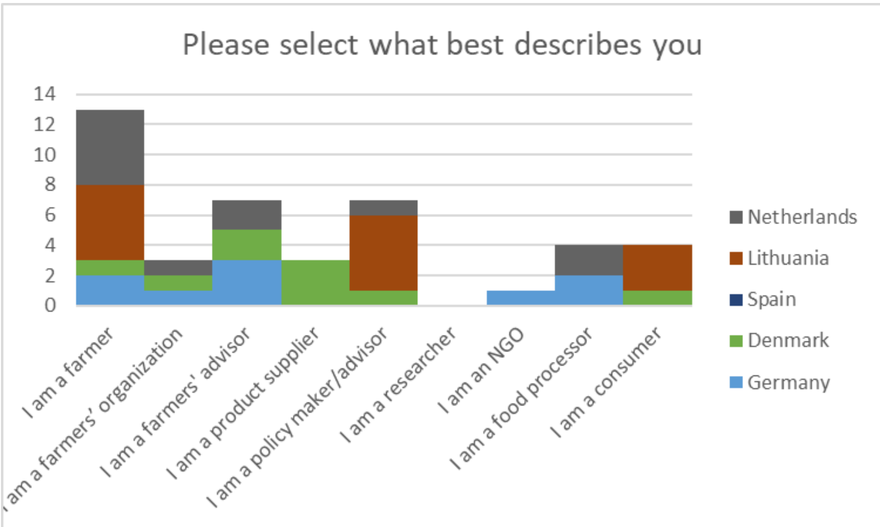
4.5. 3rd Co-creation workshop (CCW3)

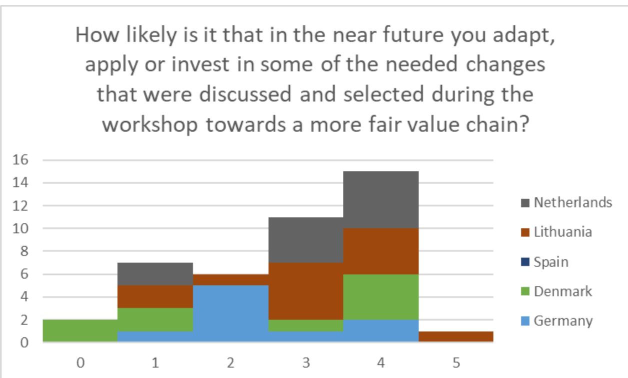
The 3rd co-creation workshop questionnaire included in total 10 ToC-relevant questions for farmers, organizations, advisors, product suppliers, policy makers, researchers, NGOs and consumers, across the studied Use Cases. The questions were focused on the three main topics of the workshop, namely the fairness of the value chains, the applied business models and the sustainability frameworks. Overall, the questionnaires got a total of 42 responses, out of which 32 were positive (76%). The first questions identified the participant and investigated the perception of fairness of the value chains (Figure 19). Most participants were identified as farmers (13), farmers' advisors (7), or policy makers (7).

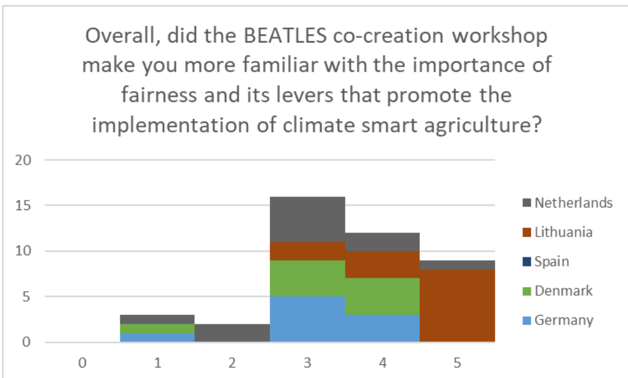
Beginning with the fairness of the value chains, the intension to apply changes towards more fair value chains, as well as the increase of awareness varied between the use cases studied, with the Lithuanian and Dutch use cases being more positive (mean scores 3.77 and 3.05 respectively).

Among the various identities of the participants, most positive responses were taken from policy makers, followed by consumers, NGOs, farmers and food processors (mean scores 3.64, 3.63, 3.50, 3.27, 3.00). Regarding the applied business models, the Lithuanian use case was the most positive for both applying the suggested changes, as well as becoming more aware, followed by the Dannish and German use cases (mean scores 3.35, 2.67 and 2.67 respectively). Among the various identities of the participants, most positive responses were taken from policy makers, followed by consumers, farmers, food processors and product suppliers (mean scores 3.36, 3.25, 2.77, 2.63 and 2.33 respectively). Finally, for the suggested sustainability frameworks, the Lithuanian, Dutch and German use cases were more positive for both applying the suggested changes, as well as becoming more aware (mean scores 3.45, 3.05 and 3.00 respectively). Among the various identities of the participants, most positive responses were taken from farmers' advisors, followed by consumers, farmers, policy makers and food processors (mean scores 3.43, 3.25, 3.23, 3.21 and 2.88 respectively).

The final questions regarding the satisfaction of the event and recommendation of the project received most positive responses from the Lithuanian and Danish use cases (mean scores 4.54 and 3.44 respectively). Among the various identities of the participants, most positive responses were taken from consumers, followed by policy makers, farmers, product suppliers, farmers' organizations and farmers' advisors (mean scores 4.25, 4.14, 3.42, 3.17, 3.17 and 3.14 respectively). Additionally, for the negative responses, there was a follow-up question examining the reasons for the overall dissatisfaction, for which the main reason was that more aspects needed to be included in the event, which have hardly been discussed, or not at all (Table 33).







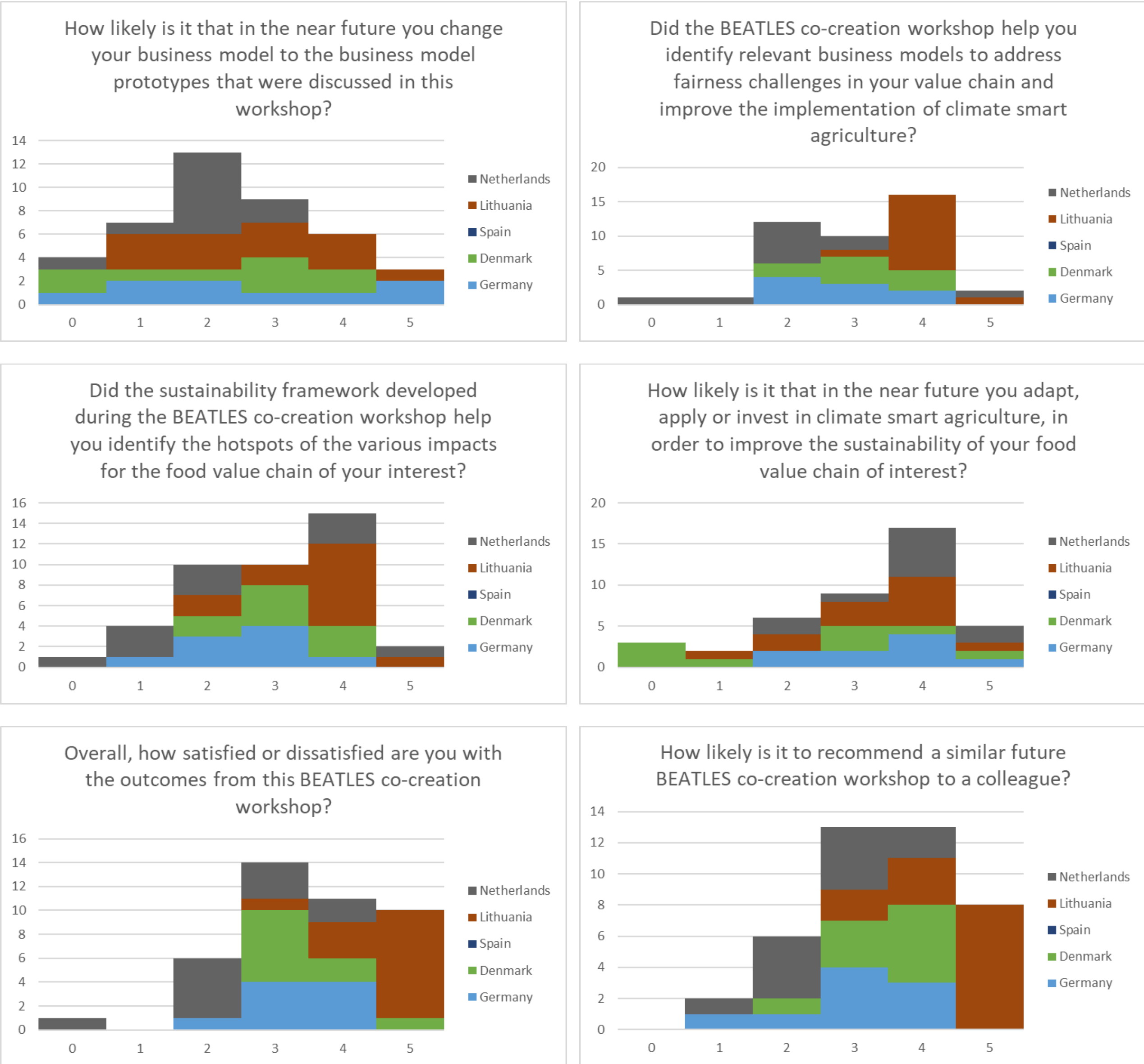


Figure 19: ToC results from the 3rd co-creation workshop questionnaire.

Reason for dissatisfaction	Responses
The suggested changes do not sufficiently align participant's needs	2
The suggested changes are too ambitious and unrealistic	1
More relevant information & solutions were expected	1
More applied examples were expected and the impact that these created	2
More aspects need to be taken into account that have hardly been discussed or not at all	3
The discussion was too long, without producing satisfying outcomes	1

Table 33: Reasons for dissatisfaction from the 3rd co-creation workshop.

4.6. Webinar & workshop 4 (W&W4)

The Webinar 4 questionnaire included 1 ToC-relevant question, involving the willingness to adapt or invest in climate-smart agriculture, as well as two questions about satisfaction of the event and recommendation of the project. The ToC-relevant results from the W&W4 questionnaire are presented below (Figure 20). Overall, the questionnaire got a total of 12 responses, out of which 10 were positive and 2 negative, meaning that most of the participants plan to apply or invest in CSA, and were satisfied from the event and the project.

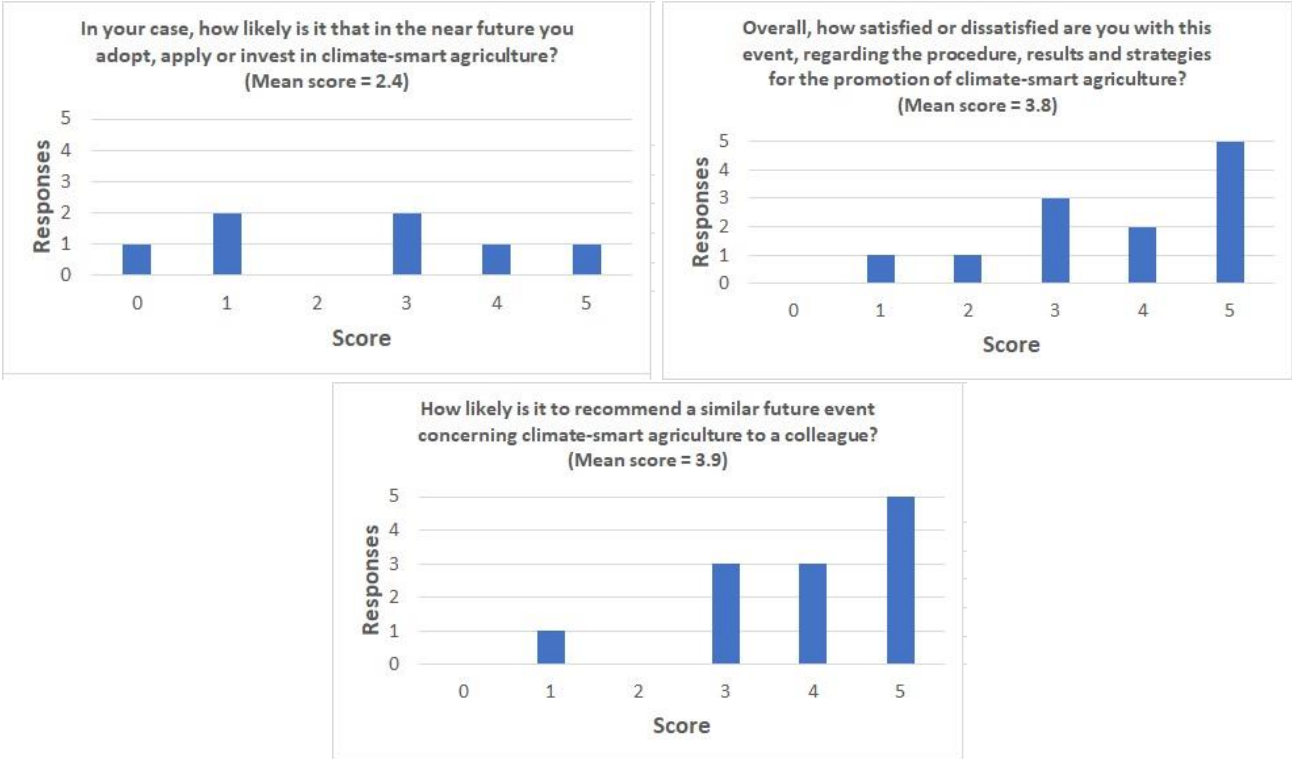


Figure *20*: ToC results from the webinar & workshop 4 questionnaire.

4.7. Feedback from attendees

The findings across the present ToC surveys indicate a strong interest in climate-smart agriculture among policy makers, consumers, researchers and farmer's advisors, as well as a mixed but cautiously optimistic response from farmers regarding business model and sustainability changes and the BEATLES project recommendations. The EU Multi-actor working group events were particularly effective in attracting policy makers, researchers and advisors, increasing their awareness and exchange views and ideas with researchers, while the webinars attracted various stakeholders, particularly consumers and researchers, allowing for exchange of views and ideas and increase of awareness. The 3rd co-creation workshops were particularly effective in increasing awareness and understanding of fairness, business models and sustainability in value chains, attracting farmers, policy makers, advisors and agri-food industries. Nevertheless, a considerable number of responses pointed the need to include more targeted and localized information and examples, including further aspects to address specific concerns and increase engagement. The limited response rates in some areas highlight the need for broader participation to ensure more robust conclusions.

Finally, a lot of respondents provided their feedback regarding both the events and the project (Figure 21). Some interesting responses were the need to look deeper into policy aspects and how they influence decisions, the need for increased awareness across the different stakeholders, the need for more relevant information and concrete examples for farmers and the need to consider and attract other relevant identities, such as producers of sustainable technologies.

"Provide more information and tools to create the space for farmers to adopt strategies that work for them."

"Less general questions, more concrete cases."

"Systemic and practical view on the challenges at hand. Transitions are only realised when all stakeholders are aware and willing to change."

"Change of mindset is more necessary than ever!"

"The political aspects are quite clear in several member states and I do hope participants in these projects come to a swift conclusion that climate change and farmer practices are not getting into a transition by political aspects. We must act more and above all, set the example of the change we want and need ourselves."

"I am inspired to implement some part of this project in Georgia and would like to ask for such cooperation and networking on regional and subregional scale."

"The questions were not relevant to me/producer of environmental technology for pig production."

"How policies are created and who influences the policies are key to understand as a researcher seeking to perform valuable research that has an impact on society."

"The LFL's carbon footprint calculator leads to gross distortions and false statements. Therefore, it cannot be recommended."

"Hearing from a southern European experience was excellent to help with my understanding of climate smart solutions."

"More focus on practical perspectives from farmers and independent advisors through a systemic approach."

"For me it was sad to see that policy frameworks still mainly focus on technological solutions in Climate Smartness, where a transition of overall mindset is necessary to engage into the future. Techniques are there already, but are too expensive to apply on farm level when the food chain is not going to embrace fair value and consumers do not get their priorities straight."

"The statements are often formulated too broadly."

"The end users are missing, even though they represent a very relevant part of the chain."

Figure *21*: Feedback responses from all the aforementioned events.

5. Conclusions

The analysis of the different agricultural and livestock systems and the various CSA practices applied, revealed significant impacts attributable to specific practices and inputs. Across the five studied UCs and their CSA practices, key contributors to environmental, economic and social burdens and advantages have been identified. An overall CBA for each CSA practice revealed the relative trade-offs between implementation costs and sustainability gains, demonstrating which practices provide the most well-rounded advantages in terms of social, economic, and environmental aspects. This evaluation offers practical advice for setting priorities for CSA practices that optimize benefits and reduce drawbacks.

In line with the outcomes of the 2024 D3.1, synthetic fertilizers and pesticides, along with diesel consumption were the primary contributors to environmental drawbacks. Therefore, CSA practices with a focus on reducing the reliance on the above chemicals or fossil fuels, can provide significant benefits by reducing the environmental impact potential. The benefits and the trade-offs of each CSA practice varies depending on the region, the resources available, the assumptions made per scenario and the viability of implementation.

In **wheat cultivation (Lithuanian UC)**, extensive wetland management, variable rate fertilization, and no-tillage scenarios stand out as excellent practices. No-tillage was a low-cost, high-return method that had significant social and economic advantages while lowering emissions, fuel, water, and labor inputs. By optimizing resource use through precision agriculture, variable rate fertilization also reduced environmental impacts while boosting farm profitability and social well-being. Wetland management, on the other hand, provided ecosystem resilience and natural nutrient buffering, which is in line with more general policy goals for sustainable land use.

The most promising CSA practices for the **organic dairy farming case (German UC)** were the “naturland” approaches to dairy farming, longevity breeding, and regional feed protein sourcing. In addition to producing modest environmental and social benefits, breeding scenarios significantly improved farm economics by prolonging the lifespan of productive animals and enhancing their welfare. Although there were some social trade-offs that needed more consideration, using local sources in livestock protein feed lessened the reliance on imported inputs, promoting ecological and economic sustainability. Sustainable livestock production was also supported by the “naturland” farming approaches, which use even stricter criteria than organic farming for dairy farms, and successfully balanced lower synthetic inputs with better animal welfare and overall system viability.

Organic farming, cover crops, and grazing methods were particularly prominent as scenarios in the **organic apple farming (Spanish UC).** Despite initial yield issues, organic farming improved social conditions, had long-term environmental benefits, and fetched higher market prices, which raised farm income. Cover crops were beneficial for the environment and the economy because they enhanced soil health, sequester carbon, and controlled pests with little increase in operating costs. A holistic approach to sustainability was also promoted by the scenarios of grazing, a low-investment technique that could increase biodiversity, decrease chemical inputs, lower greenhouse gas emissions, and improve community ties.

Regular slurry discharge, biogas generation, and cutting-edge ventilation technologies were recognized as key solutions in **pig farming (Danish UC)**. Regular slurry discharge was an economical way to improve barn air quality and reduce greenhouse gas emissions without increasing operating expenses. When backed by legislative frameworks, biogas systems can offer a climate-smart pathway that reduces greenhouse gas emissions and recycles nutrients, even though they require a larger initial investment. By lowering ammonia emissions and improving air quality, advanced ventilation technologies offered a workable balance between environmental benefits and financial viability.

Finally, the most sustainable scenarios among those studied in the **potato and onion farming (Dutch UC)** were biodiversity enhancement, sustainable irrigation, and soil management through compost application. Using compost offered financial savings and social health advantages while significantly reducing greenhouse gas emissions and nutrient runoff. Subsidies for sustainable irrigation systems increased economic viability and environmental benefits, while optimizing water and energy use. Although targeted innovation may further strengthen the social benefits, biodiversity-focused management improved farm profitability, decreased pesticide and nutrient runoff, and increased ecosystem resilience.

In conclusion, the selected CSA practices serve as excellent examples of the various avenues for promoting locally specific sustainable agriculture. Their application can improve social outcomes, increase economic returns, and lessen environmental footprints, essential elements for creating robust and sustainable agri-food systems. Nonetheless, certain trade-offs highlight the necessity of supportive policies, capacity building, and ongoing innovation, especially those pertaining to initial investments, upstream supply chain impacts, and social externalities. Farmers, legislators, and other stakeholders can steer toward more sustainable, lucrative, and socially conscious agricultural futures by supporting such CSA practices within their respective UCs.

Last, but not least, the ToC results revealed that stakeholders are very interested in climate-smart agriculture, and that policymakers, researchers, and advisors have been effectively engaged through webinars and workshops. Farmers, on the other hand, expressed cautious optimism. To improve relevance, comprehension, and engagement, responses highlighted the need for more focused, localized information as well as wider stakeholder inclusion, especially for farmers and technology producers.

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