Deliverable 5.9: Environmental assessment (LCA)

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Contents

Tables

Figures

Abbreviations

ASC	Agroecological service crop
BAU	Business-as-usual cropping system
CFCs	Chlorofluorocarbons
FM	Fresh matter
ILCD	International Reference Life Cycle Data System
INN	Innovative cropping system
ISO	International Organization for Standardization
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
NMVOC	non-methane volatile organic compounds
PPP	Plant protection products

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1. Summary

The use of agroecological practices in intensive organic greenhouse production systems represents an innovative approach for improving resilience, soil health and the fertility of these systems. Practices of interest include, for example, diversified crop rotations, agroecological service crops (ASC), local composts, flower strips, and transfer mulches. Yet, for these practices to be adopted, they must, in addition to securing the approval of farmers, also clearly demonstrate competitive or superior levels of environmental sustainability.

The aim of this study, therefore, was to assess the potential environmental impacts of agroecological innovative vegetable cropping systems, relative to business as usual and for a range of environmental indicators and geographic settings. This resulted in data collection, inventory analyses and life cycle impact assessments of 75 unique cultivations belonging to 13 cropping systems of five experimental project sites: Belgium, Denmark, France, Italy, and Switzerland. Collected data for each site represented, in aggregate, an entire crop rotation which allowed for results to be compared at both the product and cropping system level. System boundaries included farm stage production and all main upstream activities associated with key production inputs. A wide set of agriculturally relevant environmental indicators assured the identification of trade-offs between and within systems.

Results of the LCA showed that agroecological innovative (INN) cropping strategies across project sites did not always outperform the business as usual (BAU) counterparts with respect to some or, at times, all environmental indicators. In Belgium, there was a noticeable exchange of impacts associated with fertilization in BAU for impacts of ASC and transfer mulch in INN, resulting in mixed performance between systems. At the Denmark project site, the reduced and targeted use of climate control exhibited a large impact reduction potential, yet at varying costs to yield. In France, additional impacts from the use of transfer mulches in INN were more than the impact reductions realized via reduced fertilization, thereby favoring the BAU system in nearly all indicators. The use of ready-made commercial fertilizers in the Italy BAU system was a key factor for its higher impacts. In contrast, INN systems made use of ASC and/or locally produced composts. Lastly, the mixed performance of Switzerland came down to higher heat energy inputs of one BAU system, as well as the use of transfer mulch and/or ASC in the two INN systems. Here, energy use impacts dominated indicators based on resource management decisions, like energy use and global warming potential, whereas, the use of innovative practices dominated nutrient management indicators, like aquatic eutrophication-N and -P and acidification.

Observed differences in performance often came down to the presence of select innovative practices which required the use of different types and/or quantities of production material and energy inputs. Other sources of variation included yields and methodological decisions regarding, for example, allocation rules, the choice of functional units, and system boundary exclusions. Further, it was not always possible to ascertain contributions of a particular practice, e.g., intercropping, to overall environmental performance. This was compensated by the reporting and interpretation of impact results at both product and cropping system level.

In summary, the following conclusions could be drawn:

- Impact reduction potential exists via reducing material and energy inputs, but at varying costs to yield performance.
- Mechanistic knowledge on how intercropping, companion cropping, and flower strips influence yields and production flows is needed to more precisely determine the environmental performance of these practices.
- High impacts related to the use of transfer mulch could be lowered with more targeted use and if the sourced materials were considered as wastes.
- If ASCs substitute a portion of fertilizer inputs, then there is potential for both decreases and increases in impacts across environmental indicators, thereby suggesting the need to strike a balance between fertilizer and ASC use.
- The environmental superiority of using one fertilization strategy over another was largely inconclusive. Drawing a clearer distinction could have been helped with the inclusion of direct emissions, accompanied by the necessary data for modelling these.

The mixed environmental performance results, both between and within project sites, suggests the potential for further design options, including combinations of BAU and INN strategies. Results of this study contribute to understanding this design potential, and yet this is hampered by a general lack of similar investigations to corroborate with, thereby exemplifying the need for more inter-disciplinary assessments to find solutions that achieve a win-win in terms of both agronomic and environmental performance. Additional investigations into combinations of innovative practices are required to fully understand the wider option space for improving both the environmental and agroecological performance of protected organic vegetable production systems.

2. Introduction

Agroecology has been identified as a tool to re-design the entire food production system, and it comprises a wide range of interventions and practices to improve its sustainability. Whilst the concepts are widely acknowledged, how can they be applied to the intensive organic greenhouse production systems prevalent in Europe? This intensity of production has been identified as a threat to their sustainability and even the public trust in organic greenhouse production. Nevertheless, the implementation of more resilient production systems, based on low energy consumption, appropriate crop rotation, use of agroecological service crops (ASCs) and local organic amendments, is possible at almost any latitude in Europe. The challenge is to design resilient, sustainable and local systems for year-round production of high quality and tasty vegetables in unheated and low-energy greenhouses or polytunnels for different European areas, while at the same time maintaining soil health and improving soil fertility.

The Core Organic Co-funded GreenResilient project was set up to demonstrate the potential and feasibility of an agroecological approach to organic greenhouse production. This allowed for locally adapted and robust agroecosystems of different European areas to be assessed with regard to both productivity and sustainability and from an agronomic and environmental point of view. The main objective of the project was to demonstrate the feasibility of such systems. The redesign of cropping systems based on the integration of concepts from both ecology and agronomy and their application to agricultural systems was expected to improve the ecological functions. In practice this includes mixed cropping of species and varieties, ASCs cultivation, crop rotation, green manuring, compost utilization, introduction of flower strips, and reduced tillage practices, all of which can be combined differently and according to the targeted objectives. Although the efficacy of these agricultural practices, alone or in combination, have been proven under open field conditions, they are not commonly implemented in protected cultivation. The use of agroecological practices in intensive organic greenhouse production systems represents an innovative approach to a traditionally intensive and mainly conventionalised system of organic production. However, their adoption relies not only on farmers acceptance, but also on a clear demonstration of improved environmental sustainability.

The build-up of robust agroecosystems has always been intended as a prerogative of open field agriculture. Under protected conditions (greenhouse, polytunnel), some of the agroecological practices outlined above are not taken sufficiently into account because they are considered as economically non-sustainable. Life cycle assessment (LCA) allows for the quantitative environmental impact assessment along the entire life cycle of product. Therefore, LCA is one of the most comprehensive tools for environmental impact assessment and its life cycle approach helps to prevent problem shifting from one life phase of a product to another. However, in the context of using LCA for the assessment of agricultural products and processes there are still several limitations. For example, land use related impacts on biodiversity and soil quality aspects, though highly relevant in an agricultural context, are not included in standard LCAs. Therefore, it is still difficult to use LCA for comparative analyses of different farming systems such as organic and conventional agriculture. Nevertheless, in the context of the GreenResilient project, where different management approaches within the “same” vegetable production system were assessed, LCA is ideal to identify the practices associated with the lowest environmental impacts.

Therefore, environmental impacts of differing business as usual (BAU) and agroecological innovative (INN) strategies were assessed from cradle to farm gate, including all upstream processes across the five experimental sites of the project.

3. Methods

The LCA approach was used to assess the environmental sustainability of the INN and BAU cropping systems for each of the five experimental sites belonging to the GreenResilient project. This was undertaken in accordance with ISO norms and PAS 2050 guidelines (ISO, 2006a; ISO, 2006b; BSI, 2012). As such, the four primary phases of LCA were observed: (i) goal and scope definition, (ii) life cycle inventory analysis, (iii) life cycle impact assessment, and (iv) interpretation of results.

3.1 Goal

The goal of this LCA study was to assess the potential environmental impacts of agroecological innovative vegetable cropping systems, relative to business as usual and across a range of environmental indicators and geographic settings. Results are intended to contribute to a more complete understanding of the contexts in which these systems and practices contribute or might contribute to improved system and product environmental profiles. Such a knowledge base is a prerequisite to the design and further development of agroecological cropping systems that are environmentally superior and is therefore a key motivator for carrying out this study.

Despite the above expected outcomes, the following study limitations exist: (1) the lack of trial replications, as well as the uniqueness of cropping systems and settings provided little to no basis for capturing variability in results; (2) as this was an attributional LCA, indirect environmental impacts resulting from, for example, the substitution of conventional inputs with innovative inputs were not observed, thereby limiting the ability to draw conclusions about wider system implications of adopting these innovative practices; (3) as it was not necessary or preferable to include all aspects of the cropping production systems, the use of results as benchmarks outside of this work is limited. Additional limitations which surfaced during the LCA work are identified in the methodological steps in which they occurred.

3.2 Scope

The objects of assessment are the BAU and INN cropping systems and crops at experimental sites in Belgium, Denmark, France, Italy, and Switzerland for production years 2018 to 2020. This time span allowed for the observation of a complete crop rotation and served as the basis for the cropping system level assessment. As each site had its own unique cultivation strategy and setting (**Table 1**), comparisons were only possible within sites and not between them. Furthermore, at the crop level of assessment, not every crop had at least one like-crop for which to compare with; these occurrences were few and therefore did not restrict the breadth of the comparative analysis in any meaningful way.

To support comparison, two functional unit types were employed, one based on land-use, “m^2 of harvested area”, and the other based on production-output,” kg fresh matter (FM) marketable product”. At the cropping system level, the reference flow for each functional unit was one entire crop rotation (i.e., total kg FM marketable product of crop rotation), whereas, at the crop level, each crop was observed independently and using the reference flow value of “1” (e.g., 1 m^2 of harvested tomato).

Table 1. Characterization of cultivation strategies and settings for each project site and cropping system.

	Climate control	Growing media	Climate 1)	Agroecological practices 2)
Belgium				
BAU	none	soil	temperate, warm summer	-
INN				ASC, companion and intercropping, local compost, flower strips
Denmark				
BAU	heated	soil	temperate, warm summer	-
INN	frost free			ASC, flower strips
France				
BAU	none	soil	temperate, hot summer	-
INN				companion and intercropping, flower strips, transfer mulch
Italy				
BAU	none	soil	temperate, hot summer	-
INN-bd				ASC, local compost
INN-ae				ASC
Switzerland				
BAU-h	heated	soil	cold, cold summer *(locally hot)*	-
BAU-ff	frost-free			-
INN-m				transfer mulch
INN-am				ASC, transfer mulch

ASC: agroecological service crop
BAU: business as usual (h: heat, ff: frost-free)
INN: innovative (bd: biodynamic, ae: agroecological, m: transfer mulch, am: ASC & transfer mulch)
1) According to the Köppen-Geiger climate classification scheme **may not represent the CH location well*
2) Select occurrences of agroecological practices were accompanied by no or a reduced use of fertilization, plant protection products and energy use, not shown here

The system boundary of this study extends from cradle to farm gate and did not differ between the levels of assessment and from site to site. Included within the boundary is the upstream production of main farm inputs and their use in the farm-stage production of a final marketable product. These were organized into the following input groups: seed and seedlings, tillage, fertilization, plant protection, irrigation, heat energy, electricity, ASC, and mulching material. Items excluded from the system boundary were field emissions, manual labor, and infrastructure. Here, infrastructure is comprised of greenhouse structures, climate control and irrigation equipment, and maintenance. Justifications for these exclusions varied. The presence of infrastructure did not differ between systems and therefore was not a decisive factor in discerning the relative environmental performance of tested innovations. Field emissions, on the other hand, play a more significant role; however, there was no empirical measurements or suitable proxies to support their inclusion. Lastly, as methods for factoring in manual labor are still largely underdeveloped in LCA, its inclusion was not called for in the planning of this work. It is possible that additional exclusions were needed at a later stage, due, for example, to missing or partial records, failed crops, etc.

For the allocation of impacts, the exclusion of field emissions from the system boundary, as well as the absence of by-products, meant that impacts could be allocated completely to the main product in most situations. Exceptions to this occurred when observing innovative practices which dealt with shared production space (i.e., co-production) and carrying-over of nutrients from one crop to the next. For shared production spaces, crops were allocated impacts based on the portion of area which it occupied. For example, an intercropped tomato at 50% of the production area was allocated 50% of the impacts associated with all system inputs and processes for the entire intercropped area. Such an allocation rule was not needed at the cropping system level since all crops were equivocated on the basis of fresh marketable mass. Moreover, any crop-specific treatments that took place were allocated to the respective crop, e.g., targeted applications of plant protection products.

For practices which resulted in the carry-over of nutrients, associated impacts were allocated based on the modelled availability of nitrogen over time (Riley et al., 2003; Båth et al., 2006). For example, with the use of alfalfa-grass transfer mulch in tomato cultivation, it was assumed that 50% of nitrogen was unavailable (i.e., lost in some form to the environment), while the remaining 50% would be made available to crops via natural processes and mechanical incorporation into the soil. Amounts were assumed to be taken up over the next three successive growing periods or at most 60 weeks, whichever occurred first. Allocation between crops was proportional to each crops' growing period.

As for coverage of environmental issues in this study, impact indicators were selected in accordance with recommendations found in the International Reference Life Cycle Data System (ILCD) handbook (European Commission, 2011) and with consideration of methodological advancements made since release of that publication. This resulted in a selection of nine system-relevant midpoint impact categories, as implemented in the recently updated IMPACT World+ LCIA methodology set (Bulle et al., 2019). This included energy demand, global warming potential (over a 100-year timeframe), ozone formation and depletion, water scarcity, aquatic ecotoxicity and acidification, and aquatic eutrophication due to both N- and P-related emissions. Categories are explained further in **Appendix A**. This wide selection of indicators also ensured detection of possible trade-offs and problem shifting within and between cropping systems and environmental indicators. This was also supported by contribution analyses, based on the predefined input groups.

3.3 Life cycle inventory analysis

Primary data for all crop cultivations and cropping systems was submitted by each project site in the form of a completed Excel data protocol, and this served as the blueprint for constructing each life cycle inventory (LCI). This work was carried out using the SimaPro 9.1.1 LCA software, together with the ecoinvent 3.6 LCI database (Wernet et al., 2016). In total, 18 cultivars were observed for the characterization of 75 unique crop cultivations and 13 unique cropping systems (**Table 2**). Due to missing data, 11 crop cultivations could not be observed. Four of these were found in Belgium, with the remaining seven in Denmark; these are not reflected in the above total nor in Table 2.

Data submitted by project partners was not always able to satisfy all LCI data requirements. For this, additional desktop research took place and resulted in select uses of standard agronomic values, modeled values and basic proximation techniques. These occurrences and their locations within the inventory (i.e., foreground or background product system data; input group) are described below:

	BE	CH	DK	FR	IT	Total
Cropping system						
Business as usual (BAU)	1	2	1	1	1	**6**
Innovative (INN)	1	2	1	1	2	**7**
Cropping system, total	**2**	**4**	**2**	**2**	**3**	**13**
Cultivation						
Butternut Squash					3	**3**
Cherry Tomato	2					**2**
Cucumber	1			3		**4**
Eggplant				2		**2**
Kohlrabi		1		1	3	**5**
Lamb's Lettuce	1	8		2		**11**
Lettuce		2		4	3	**9**
Melon		2				**2**
Mizuna	1					**1**
Oak Leaf Lettuce		2				**2**
Plantago		1				**1**
Purslane	2	1				**3**
Radish	2	1				**3**
Rocket					3	**3**
Spinach		2		2		**4**
Sweet Pepper				1		**1**
Swiss Chard	1					**1**
Tomato	2	6	4	3	3	**18**
Cultivation, total	**12**	**26**	**4**	**18**	**15**	**75**

Table 2. All cultivars (common names), cultivations, and cropping system instances observed in the LCA study, listed for each project site (country code).

Foreground data

(1) Nutrients supplied by transfer mulches and in the use of agroecological service crops as green manures required that carry-over effects be modeled in order to allocate impacts proportionate to shared benefits. This was carried out as described in section 3.2.

(2) For some fertilizer and plant protection products, not all ingredients could be identified, for example, due to this information being proprietary; in these cases, the predominant ingredient was scaled to fill the gap, which was typically no more than 10%. In a few cases, animal-based products had unknown portions larger than 10%, for which dried chicken manure was assumed.

(3) Nutrient contents (N, P and K) of transfer mulches, green manures and composts were not always fully known; here, missing values were supplemented with standard values coming from agronomic references.

(4) For each project site, records for selected items and input groups were missing, and no suitable substitutes could be found, resulting in their exclusion: For all project sites, no information on the nursery phase of seedlings was provided. As a result of this and for the sake of consistency, inventories for sourced seed materials were also excluded. However, as the use of sourced plant materials for sites was similar, if not identical, between compared systems, this exclusion had no influence on the goal and scope of this study. Further, for Denmark and Italy, irrigation water use records were not available. All greenhouse energy use records for Belgium were unavailable. On-farm electricity values for all France systems and for four crop cultivations of Switzerland were not available. How these omissions influenced results and the ability to draw conclusions on the use of agroecological practices is explored in the discussion.

Background data

Although ecoinvent is the most expansive of all available LCI databases, it is still commonplace for unit processes to be missing, especially when dealing with innovative inputs and processes. This was the case for several of the biocontrol agent and organic amendment products used in this project. These gaps were addressed with the use of proxies. Proxies were chosen based on their degree of similarity to the missing item and with respect to, for example, substance, function, energy profile, production technology, and chemical structure.

4. Results

Results of the LCA are shown by country and begin with an overview of the observed key production parameters. This is followed by the life cycle impact assessment (LCIA) results.

Production parameters are related to the reference flow and functional units, as described in the methods. All values exhibit the primary data submitted by partners unless otherwise noted, e.g., the use of modelled carry-over effects.

For the LCIA, results represent potential impacts and are provided in increasing detail, starting at the cropping system level and then proceeding to the product level. Interpretation is supported by contribution analysis by input group. Cropping system results are reported across all environmental impact categories, with a view on the relative difference between systems, as well as the contribution of each input group within each system.

At the product level, and depending on the completeness of LCI data, up to four impact categories were selected for further comparison; these are energy demand, global warming potential, aquatic eutrophication-N, and water scarcity. Product level results were reported on an absolute basis. This was done with respect to both functional units (i.e., two vertical axes), but with contributions by input group only visible for the production output functional unit (left vertical axis). Products were grouped by season, cultivar, and the system to which they belonged. For the sake of maintaining simplicity, all cultivations were grouped into either Winter or Summer seasons, even if some were clearly cultivated between these seasons. Additional results for environmental indicators which were not selected are available in **Appendix B**.

In general, results of the LCA showed that INN cropping strategies did not always outperform BAU counterparts with respect to some or, at times, all environmental indicators. For Denmark and Italy project sites, the environmental superiority of INN strategies over BAU was clearly demonstrated. In contrast, at the France site, the BAU strategy outperformed INN across nearly all indicators. At Belgium and Switzerland sites, performance outcomes were mixed between the two strategies, suggesting the presence of trade-offs.

In Belgium, there was a noticeable exchange of impacts associated with fertilization in BAU for those of ASC and transfer mulch in INN. At the Denmark project site, the reduced and targeted use of climate control exhibited a large impact reduction potential, yet at a slight cost to Tomato yields. Again, in France, impacts from the use of transfer mulches in INN replaced those of fertilizer in the BAU system. The use of ready-made commercial fertilizers in the Italy BAU system was a key factor in its higher impacts relative to both INN systems. Here, INN systems made use of ASC and/or locally produced composts. Lastly, the mixed performance of Switzerland came down to higher heating of one BAU system, as well as the use of transfer mulch and/or ASC of the two INN systems. Here, energy use impacts dominated resource management indicators, like energy use and global warming potential, whereas, the use of innovative practices dominated nutrient management indicators, like aquatic eutrophication-N and -P and acidification.

4.1 Belgium

Due to a crop failure in Winter 2019, which effected both BAU and INN systems only four of the five Belgium production cycles for each system could be observed. For BAU, this included Purslane, Radish, Tomato, Corn Salad (failed), and Cherry Tomato. The INN system made use of companion cropping and intercropping, with Purslane accompanied by Mizuna and Swiss Chard, Corn Salad (failed) accompanied by Spinach (failed) and Batavia Lettuce, and, lastly, Tomatoes accompanied by Cucumbers. Due to the failure of the INN Corn Salad companion cropping, Batavia Lettuce was also excluded from results. Additional agroecological practices included the use of local compost, ASCs, and flower strips. At the crop level, only the four crops which occurred in both systems were compared. Key production parameters for the compared crops and systems are outlined in **Table 3**.

Overall, fresh marketable yields were slightly higher in the INN system, except for the Cherry Tomatoes. The INN yields were not influenced by the use of flower strips, as these strips occurred strictly on non-production areas (e.g., outer edges of the greenhouse). In addition, associated impacts of the flower strips were excluded due to their negligible impacts, consisting only of a small amount of seed material. Nutrient inputs via fertilization were much higher in INN due to a sizable application of nutrient-rich local compost at the outset of the rotation (5.71 kg FM/m^2, with N/P/K at 2.2/5.1/22.3). The modelled carry-over effects of using ASC as a green manure in the INN system resulted in only a small amount of N being shared throughout the rotation. Lastly, use of plastic mulches for Summer 2019 Tomato in BAU was replaced in INN with the use of straw. No carry-over effects were modelled for straw due to its targeted use and insignificant nutrient values.

The results in **Table 3** show results for BAU and INN comparable crops and for the complete rotation. Please note that the rotation results can include crops that are not shown due to lack of a comparative crop; as such, column totals may not equal the summed values of shown individual crops.

Table 3. Key production parameters observed in the environmental assessment of Belgium crops and rotation.

Production parameters, per m^2 and production cycle		BAU	INN	BAU	INN	BAU	INN	BAU	INN	BAU rotation	INN rotation
Crop		Purslane		Radish		Tomato		Cherry Tomato		complete project rotation [c]	
Season		Winter 2018		Summer 2019		Summer 2019		Summer 2020			
Total yield [a]	kg FM	3.0	3.4	0.9	0.9	7.1	8.2	7.4	7.0	18.5	22.6
Tested practice [b]	codes	-	ASC, C, CC	-	-	-	C, F, I	-	ASC	-	
Tillage											
Number of passes	#	1	1	1	1	1	1	1	1	4	4
Fertilization											
Total N	g	40	17	0	0	57	87	36	28	140	469
N from green manure [1]	g	0	2	0	0	0	1	0	0	0	4
P_2O_5	g	17	8	none		12	173	13	14	43	960
K_2O	g	34	23			37	547	41	19	115	3938
Plant-based product	kg	none		none		0.31	none	0.05	0.05	0.42	0.12
Animal-based product	kg					none		0.06	0.06	0.06	0.06
Compost	kg FM	5.71	2.17			3.80	5.73	4.06	4.82	13.57	27.72
Green manure [1]	kg DM	0.00	0.12	0.00	0.06	0.00	0.11	0.00	0.05	0.00	0.34
Plant protection											
Number of applications	#	none		1	1	6	6	none		7	7
Total active ingredients	g			0.04	0.04	1.30	1.30			1.34	1.34
Irrigation - *none*											
Energy - *not available*											
Additional inputs											
Organic-based mulching [2]	kg	none		none		0.0	0.9	none		0.0	0.9
Plastic-based mulching	g					13.8	0.0	13.8	13.8	27.6	13.8

a) Represents marketable portion

b) For crop-level comparisons with intercropping or companion cropping, values reflect an equivalent harvested area of the listed crop

c) For the rotation-level comparison, totals represent shared production areas, as well as crops not previously shown due to their single occurrences (for INN: two unique ASCs)

1) Modelled values for green manure carry-over; comprised here entirely of ASCs

2) Comprised entirely of straw and assumed to not contribute to meeting nutrient demand

Tested practice codes: ASC - agroecological service crop introduced, C - locally produced compost, CC - companion cropping, F - flower strips, I - intercropping

Belgium cropping system LCIA results

The INN system impacts were between 1% and 15% lower than BAU totals in five of nine environmental impact categories. This was partly due to the use of higher-impact plant-based fertilizer products in BAU, as well as associated impacts being spread over slightly lower yields. Only for acidification and both forms of aquatic eutrophication did the BAU system notably outperform INN (**Figure 1**). One reason for this was the larger quantity of straw mulching material needed compared to mulching with plastic. Although, the embedded impacts per unit mass of straw are lower than those of plastic, much more straw material is needed to reach a similar effect. Higher performance in BAU was also a result of the additional impacts introduced with cultivation and incorporation of the ASCs. The contribution of straw and ASC to eutrophication potential was also observed due to the fertilization involved in either cultivation.

For each impact category except ozone formation, the use of ASC resulted in contributions of between 38% and 65% of total impacts. The burden of ASCs is mostly a result of the fertilizers applied during the first of the two cultivations. For the remaining indicators, the PPP input group contributed the least.

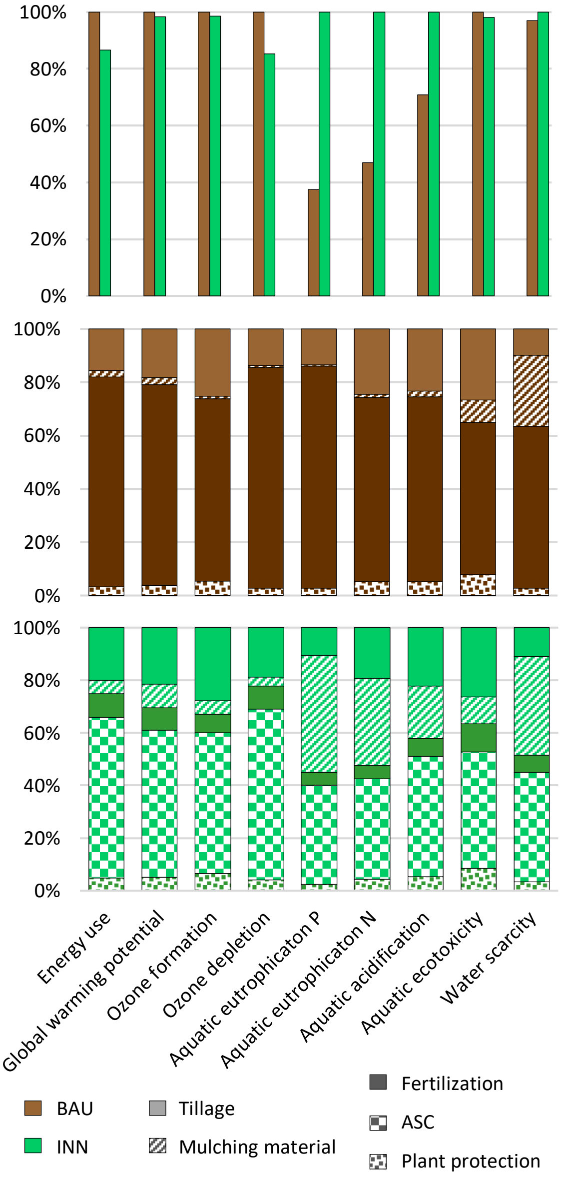

Figure 1. Potential environmental impacts of Belgium cropping systems (above) and contributions of each input group to overall impacts (below).

Belgium crop product LCIA results

For both energy demand and global warming potential, and regardless of the functional unit, each crop except for Radish and Cherry Tomato had lower impacts in the INN system (**Figure 2, top and middle**). Without access to primary data on direct energy use for either production system, results for the energy demand impact category included indirect energy use only, i.e., energy required for production of sourced inputs. The lower performance of INN Radish was explained by the large application of local compost in the cultivation of ASC and its subsequent incorporation into the soil, all of which proceeded the Winter 2018 Purslane. Modelled carry-over effects extended the burdens of ASC cultivation to the INN crops next in the rotation and in increasingly smaller amounts. The lower performance of INN Cherry Tomato was a result of lower yields as well as a small portion of the impacts carried over via the second ASC.

With respect to the eutrophication-N environmental indicator, impacts were mixed, with BAU Radish, Tomato and Cherry Tomato all having lower impacts. The reason for the difference in impacts between BAU and INN Radish was due to the inclusion of ASC in INN, which increased the nitrate leaching potential profile of INN crops. This increased nitrate leaching potential is a result of fertilization of the ASC and the modelled carry-over effect of associated benefits/impacts. In contrast, ASC contributed much less for INN Tomatoes, having received smaller residues. Yet, here, impacts associated with use of straw (i.e., fertilization step in the production of the cereal and straw material) increased impacts far beyond BAU Tomatoes.

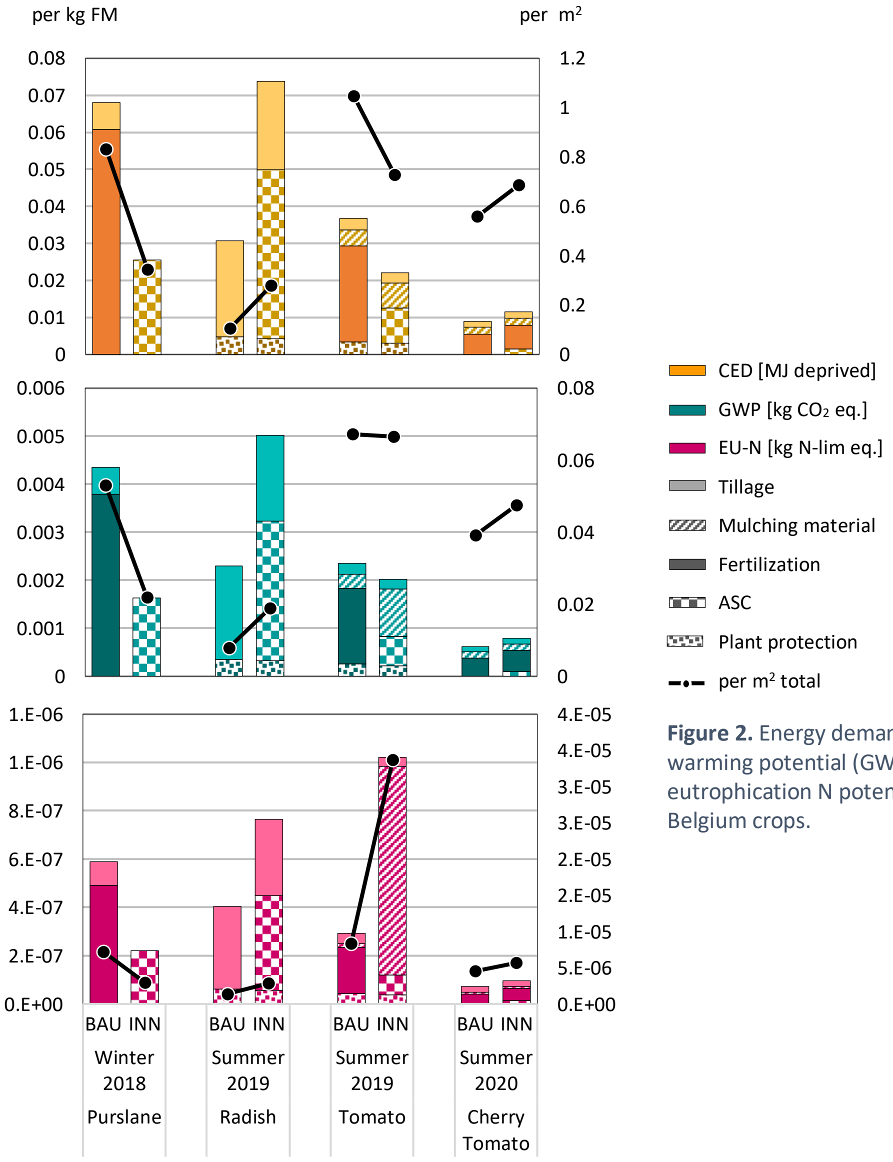

Figure 2. Energy demand (CED) (top), global warming potential (GWP) (middle) and aquatic eutrophication N potential (EU-N) (bottom) for Belgium crops.

4.2 Denmark

Due to limited data, only two production cycles at the Denmark project site were observed, one in Summer 2019 and one in Summer 2020. As such, the ability to draw conclusions as to the environmental performance of the innovative cropping system was not possible and was therefore omitted.

Product level comparisons were made for two instances of Summer-grown Tomatoes. Innovations included the use of ASC, flower strips on non-production areas, and reduced energy via targeted use of heating and ventilation climate control. Neither system made use of tillage processes and machine implementations. Furthermore, there were no plant protection measures reported.

Relative to BAU, total yields were lower for each production cycle in the INN system, 38% lower for 2019 Tomatoes and 30% lower in 2020. This was accompanied in INN by a doubling of fertilizers applied (of the same types) and a 100% decrease in heating, relative to BAU. All observed production parameters in the Denmark LCA are summarized in **Table 4**.

Table 4. Key production parameters observed in the environmental assessment of Denmark crops.

Production parameters, per m^2 and production cycle		**BAU**	**INN**	**BAU**	**INN**
Crop		Tomato			
Season		Summer 2019		Summer 2020	
Total yield	kg FM	41.9	25.8	29.3	20.5
Tested practice [a]	codes	-	ASC, F, rE	-	ASC, F, rE
Tillage - *none*					
Fertilization					
N	g	5	97	90	116
P_2O_5	g	3	55	51	65
K_2O	g	2	32	30	39
Animal-based product	kg	0.16	3.22	3.00	3.85
Plant protection - *none*					
Irrigation - *not available*					
Energy					
Heating	kWh	3.0	0.0	5.0	0.0
Electricity	kWh	0.3	0.3	0.4	0.3
Additional inputs - *none*					

a) Contributions by ASC (e.g., nutrient carry-over) not observed due to lack of data

Tested practice codes: ASC - agroecological service crop introduced, F - flower strips, rE - reduced energy via heating only below 4°C and ventilating only >20°C

Denmark crop product LCIA results

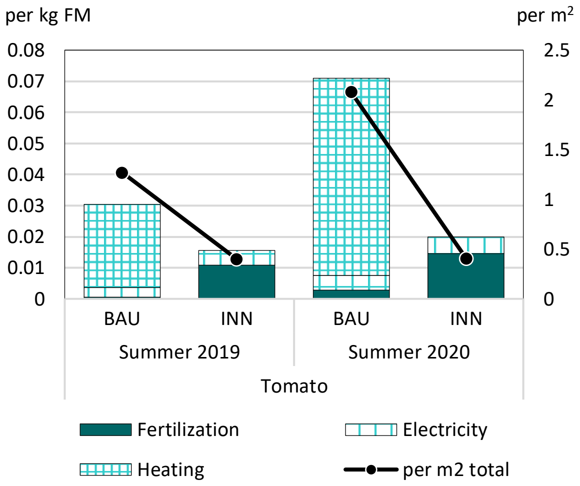

Figure 3. Global warming potential (GWP) [kg CO_2 eq.] of Denmark crops.

As both cultivation strategies made use of the same inputs and there were no modelled values for carry-over effects of ASC, it was enough to observe performance for just global warming potential, as the performance pattern would have been the same for all other indicators (**Figure 3**). Higher yields of BAU Tomatoes were not able to absorb enough of the additional impacts of heating and ventilation so as to make impacts per kg product comparable to INN crops. Furthermore, the doubling of fertilization in INN Tomatoes resulted in a much higher global warming potential, relative to BAU. Here, it is important to note that surplus nutrients from previous crops in the rotation were not modelled due to limited data. If it were possible to have included this, then impacts of fertilization between systems would have been likely much closer. Overall, the use of targeted climate control was the primary reason for improved performance in the INN system.

4.3 France

All production cycles were observed at the French project site. This consisted of eight unique cultivars across three systems. Also, due to reoccurrences of select crops in the INN rotation, comparisons of like-cultivars were possible both between systems and within the INN system itself. Common cultivars of both BAU and INN systems were Lettuce, Tomato, Eggplant and Cucumber. Within the INN system, there were reoccurrences of Lettuce, Lamb’s Lettuce, Spinach, Tomato, and Cucumber. Compared to BAU, the INN rotation was more diverse, largely due to the use of intercropping and companion cropping. Intercropping took place for Eggplant/Sweet Pepper and two separate occasions of Tomato/Cucumber. In Winter 2018, Kohlrabi was paired with Lettuce, Lamb’s Lettuce and Spinach. Lastly, in Winter of 2019, three items were paired with each other, Lettuce, Lamb’s Lettuce and Spinach. Additional agroecological practices included use of flower strips throughout the entire crop rotation, only on non-production areas, as well as two applications of alfalfa hay transfer mulch in the earlier intercropped cycles. Modelled values for carry-over effects of transfer mulches resulted in residues, of up to 600 grams per m2, being transferred to succeeding crops.

Over the entire crop rotation of both systems, total inputs were largely similar, with the exception of INN having 25% more applied active ingredients and 21% less applied fertilizers (transfer mulch not included), relative to BAU totals. This was accompanied by an overall 36% increase in fresh marketable production output in the INN system. Yields, however, were not always higher on a crop-by-crop basis. Overall, yields were mixed for Lettuce and Tomato, similar for Lamb’s Lettuce and Spinach, and higher for INN Eggplant and Cucumbers (**Table 5 and 6**).

Table 5. Key production parameters observed in the environmental assessment of France winter crops.

Production parameters, per m^2 and production cycle		**BAU**	**INN**	**BAU**	**INN**	**INN**	**INN**	**INN**	**INN**
Crop		Lettuce				Lamb's Lettuce		Spinach	
Season		Winter 2018		Winter 2019		W18	W19	W18	W19
Total yield [a]	kg FM	3.9	3.4	3.6	3.8	0.9	1.0	2.3	2.3
Tested practice [b]	codes	-	CC, F	-	CC, F	CC, F		CC, F	
Tillage									
Number of passes	#	3	3	4	3	3	3	3	3
Fertilization									
Total N	g	6	4	6	5	4	5	4	5
N from organic-based mulching (1)	g	0	4	0	5	4	5	4	5
P_2O_5	g	2	0	2	0	1	2	1	2
K_2O	g	1	0	1	0	8	10	8	10
Mineral product	kg	none				none		none	
Plant-based product	kg	0.12	0.00	0.12	0.00				
Animal-based product	kg	none							
Plant protection									
Number of applications	#	none				none		none	
Total active ingredients	g								
Irrigation									
Externally sourced water	l	143	143	111	111	130	91	143	91
Energy - *heating: none; electricity: not available*									
Additional inputs									
Organic-based mulching (1)	kg	0.0	0.5	0.0	0.6	0.5	0.6	0.5	0.6
Plastic-based mulching	g	23.7	23.7	23.7	23.7	23.7	23.7	23.7	23.7

a) Represents marketable portion

b) For crop-level comparisons with intercropping or companion cropping, values reflect an equivalent harvested area of the listed crop

1) Modelled values for organic-based mulching material carry-over (i.e., transfer mulch)

Tested practice codes: CC - companion cropping, F - flower strips, I - intercropping, M - transfer mulch introduced

The results in **Table 5** and **Table 6** show results for BAU and INN comparable crops and for the complete rotation. Please note that the rotation results can include crops that are not shown due to lack of a comparative crop; as such, rotation totals may not equal the sum of shown crops.

Table 6. Key production parameters observed in the environmental assessment of France summer crops and rotation.

Production parameters, per m^2 and production cycle		**BAU**	**INN**	**INN**	**BAU**	**INN**	**BAU**	**INN**	**INN**	**BAU rotation**	**INN rotation**
Crop		Tomato			Eggplant		Cucumber			complete project rotation c)	
Season		Summer 2018		S20	Summer 2019		Summer 2020		S18		
Total yield a)	kg FM	8.9	10.2	4.2	6.8	10.6	4.0	6.2	4.9	27.2	37.1
Tested practice b)	codes	-	F, I, M		-	F, I, M	-	F, I, M		-	
Tillage											
Number of passes	#	3	3	3	3	3	3	3	3	16	15
Fertilization											
Total N	g	43	54	24	26	46	18	24	54	98	132
N from organic-based mulching 1)	g	0	14	10	0	26	0	10	14	0	59
P_2O_5	g	14	19	16	14	21	22	16	19	54	58
K_2O	g	27	47	42	13	63	33	42	47	75	169
Mineral product	kg	0.09	0.09	0.12	none		0.12	0.12	0.09	0.20	0.20
Plant-based product	kg	0.93	0.82	0.14	0.80	0.70	0.14	0.14	0.82	2.10	1.66
Animal-based product	kg	0.08	0.08	0.15	none		0.15	0.15	0.08	0.23	0.23
Plant protection											
Number of applications	#	6	10	5	3	3	5	5	10	14	18
Total active ingredients	g	13.5	21.3	4.5	13.0	13.0	4.5	4.5	21.3	31.0	38.8
Irrigation											
Externally sourced water	l	excluded		n/a	507	478	not available		excl.	761	741
Energy - *heating: none; electricity: not available*											
Additional inputs											
Organic-based mulching 1)	kg	0.0	0.9	0.8	0.0	1.8	0.0	0.8	0.9	0.0	4.7
Plastic-based mulching	g	13.8	0.0	23.7	23.7	0.0	23.7	23.7	0.0	108.5	71.0

a) Represents marketable portion

b) For crop-level comparisons dealing with intercropping or companion cropping, values reflect an equivalent harvested area of the listed crop

c) For the rotation-level comparison, totals represent shared production areas, as well as crops not previously shown due to their single occurrences (for INN: Kohlrabi)

1) Modelled values for organic-based mulching material carry-over (i.e., transfer mulch)

Tested practice codes: CC - companion cropping, F - flower strips, I - intercropping, M - transfer mulch introduced

France cropping system LCIA results

Impacts of the INN cropping system were higher for all indicators except water scarcity. This exception was a direct result of less irrigation water being sourced. Among the remaining eight indicators, the largest performance differences between systems occurred for indicators relating to nutrient management, aquatic eutrophication-N and -P and acidification, with BAU impacts at 42%, 11% and 26% of INN totals, respectively (**Figure 4, top**). The reason for these higher impacts can be traced back to the embedded impacts of the alfalfa hay as well as the initial quantities applied. Although plastic-based mulches have higher impacts than the transfer mulch per unit of equivalent mass, the much smaller amount of plastic-based material needed to reach a similar mulching effect resulted in an overall lower impact with use of the plastic-based material. In fact, the sizable application of transfer mulch in the INN system amounted to it contributing at least 50% of impacts in each indicator, except for in water scarcity (**Figure 4, bottom**). Though higher yields were achieved in INN, they were not high enough to absorb these additional impacts.

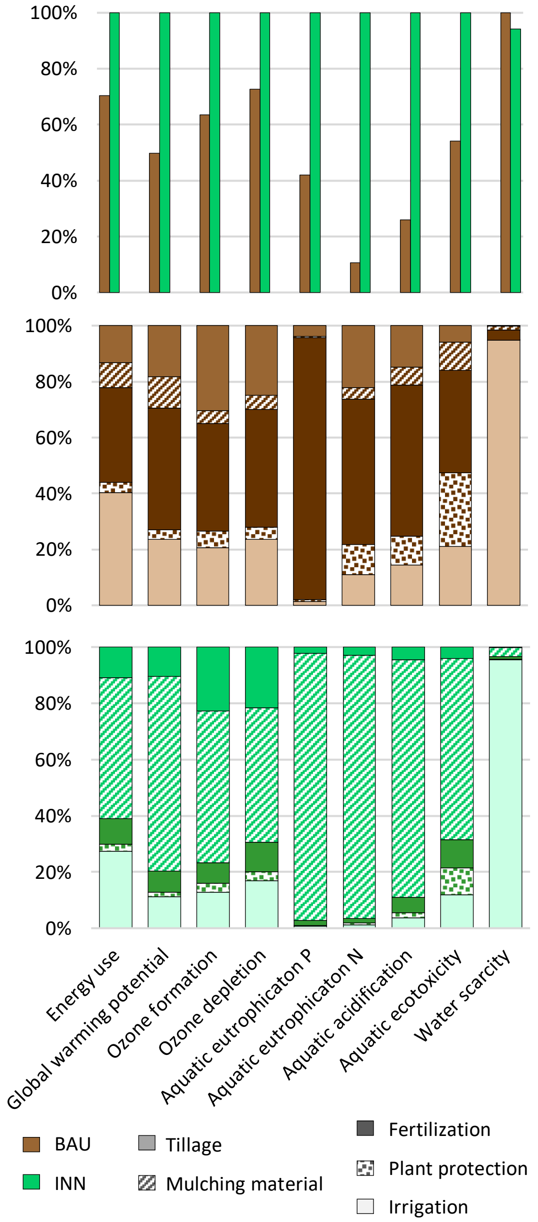

Figure 4. Potential environmental impacts of France cropping systems (above) and contributions of each input group to overall impacts (below).

France crop product LCIA results

Crop level results for the four selected indicators are depicted in **Figure 5**. As was observed at the cropping system level, the introduction and subsequent carry-over effects of transfer mulches was largely responsible for the higher impacts for each INN crop, without exception. With respect to energy use, electricity for pumping irrigation water was the second largest contributor for INN crops and the primary contributor for BAU crops, followed by fertilization. Here it is important to note that data on irrigation use in Tomato cultivations was missing.

For global warming potential and eutrophication-N, fertilization contributed the most to BAU crop impacts. If it were not for the large portion of nuclear energy in France, then the electricity sourced for irrigation water would have contributed more to global warming potential and possibly to water scarcity, via hydroelectricity.

For between-system comparisons at the crop level, higher performance only occurred for Cucumbers in the intercropped Cucumber/Tomato production cycle of 2020. Moreover, this was the case only when the production output functional unit was observed. Here, it is important to note that only the Cucumber portion of the intercropped system was used to compare with the pure Cucumber cultivation in BAU, with use of an equivalent area. As production was nearly identical between Cucumber product systems, aside from a small addition of carried-over burdens from transfer mulches, the lower impacts of INN were therefore largely a result of Cucumber yields being 55% higher in INN than in BAU.

Within-system comparisons were only possible for the INN crop rotation due to reoccurrences of select cultivars. Here, it is worth noting that differences in growing conditions between years were not factored into any assessment calculations. For reoccurring crops involved in both instances of companion cropping (Lettuce, Lamb's Lettuce and Spinach), there was a notable difference in the impacts associated with transfer mulch carry-over effects. This was a result of the 2019 companion cropping receiving more mulch residues from the proceeding crop (due to a higher application rate), relative to 2018. The influence of crop cultivation periods, though observed in modelled values, did not play a role here, as both crop sequences followed a near-similar schedule.

As for the differences observed in transfer mulch impacts between the two Tomato/Cucumber intercroppings, differences were more influenced by the location of each intercropping in the rotation, rather than the differences in application rates. Here, the 2020 instance was the furthest from the application of any mulch, making it a recipient of less material in comparison to 2018, which was the recipient of a fresh application. These differences, however, were hidden in per kg results (**Figure 5, left vertical axis**) due to the sizeable differences in intercropping yields. Here, there was clearly a favoring of Tomatoes over Cucumbers in 2018 and Cucumbers over Tomatoes in 2020.

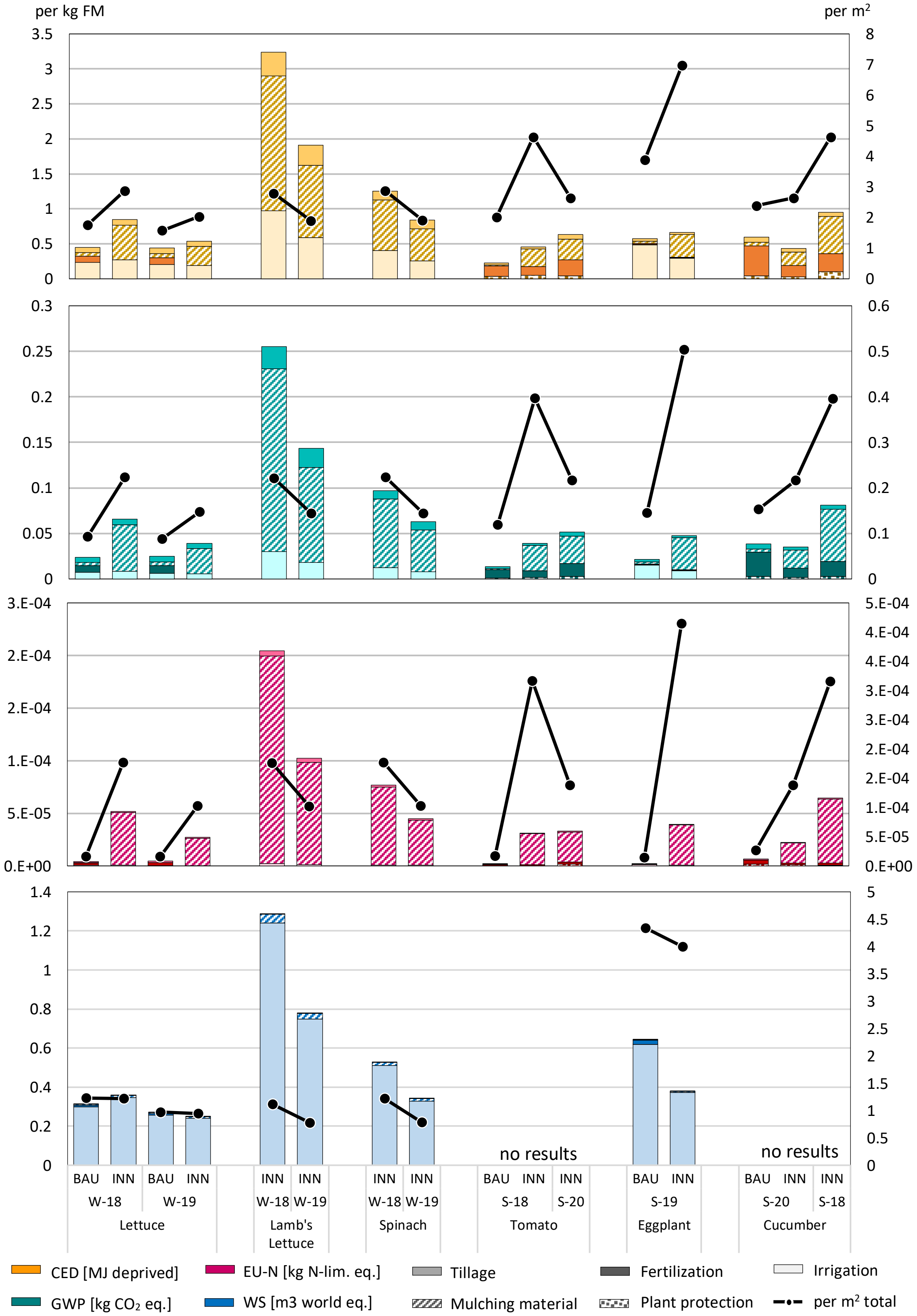

Figure 5. Energy demand (CED) (top), global warming potential (GWP) (middle-top), aquatic eutrophication N potential (EU-N) (middle-bottom) and water scarcity (WS) (bottom) of France crops. W: Winter, S: Summer

4.4 Italy

An identical cropping rotation for three cultivations strategies was observed for the Italy project site. Systems included one BAU and two INN, one described as biodynamic (INN-bd) and the other as agroecological (INN-ae). Between Winter 2018 and Summer 2020, rotations consisted of Rocket, Tomato, Lettuce, Kohlrabi, and Butternut Squash cultivars and in that order. All crops made use of bioplastic foliar as mulching material, with an additional application taking place before BAU Winter cultivations as a solarization treatment. Both INN systems made use of an ASC mix prior to Winter cultivations. The use of a locally produced compost was also considered as an additional agroecological practice in the biodynamic system.

Table 7. Key production parameters observed in the environmental assessment of Italy winter crops.

Production parameters, per m^2 and production cycle		**BAU**	**INN-bd**	**INN-ae**	**BAU**	**INN-bd**	**INN-ae**	**BAU**	**INN-bd**	**INN-ae**
Crop		Rocket			Lettuce			Kohlrabi		
Season		Winter 2018			Winter 2019			Winter 2019		
Total yield [a]	kg FM	2.8	2.3	2.5	3.2	3.1	2.8	4.5	3.4	3.7
Tested practice	codes	-	ASC, C	ASC	-	ASC, C	ASC	-		
Tillage										
Number of passes	#	4	4	4	4	4	4	4	4	4
Fertilization										
Total N	g	15	12	31	12	12	30	9	1	1
N from green manure [1]	g	0	7	8	0	6	7	0	1	1
P_2O_5	g	12	4	12	9	4	12	0	0	0
K_2O	g	0	12	27	0	12	26	0	2	2
Mineral product	kg	0.00	none		0.00	none		0.00	none	
Plant-based product	kg	0.04			0.04			0.00		
Animal-based product	kg	0.40			0.31			0.31		
Compost	kg FM	0.00	0.40	1.00	0.00	0.40	1.00	none		
Green manure [1]	kg DM	0.00	0.33	0.41	0.00	0.38	0.44	0.00	0.10	0.10
Plant protection										
Number of applications [2]	#	5	5	5	2	none		none		
Total active ingredients	g	1.00	0.63	1.00	0.40					
Irrigation - *not available; tractor-pump*										
Energy - *none*										
Additional inputs										
Solarization material	g	45	none		45	none		none		
Plastic-based mulching	g	1	1	1	1	1	1	1	1	1

a) Represents marketable portion

1) Modelled values for green manure carry over; comprised here entirely of ASC

2) Use of hand pump for applying plant protection products

Tested practice codes: ASC - agroecological service crop introduced, C - locally produced compost

Overall, yields were slightly lower in both INN systems, relative to BAU, with biodynamic yield performance being lowest. Applied fertilizers in BAU were ready-made commercial products of mostly plant and animal origins, whereas INN systems made use of only composts and green manures (i.e., the incorporated ASCs). Nutrient delivery from the different fertilization strategies was comparable between systems. INN systems also saw a near halving of pesticide applications. No data for irrigation was made available, but this was not foreseen as contributing in any significant way to differences between systems. **Tables 7 and 8** provide an overview of the key production parameters observed in the LCA. Please note that the rotation results can include crops that are not shown due to lack of a comparative crop; as such, column totals may not equal the summed values of shown individual crops.

Table 8. Key production parameters observed in the environmental assessment of Italy summer crops and rotation.

Production parameters, per m^2 and production cycle		**BAU**	**INN-bd**	**INN-ae**	**BAU**	**INN-bd**	**INN-ae**	**BAU rotation**	**INN-bd rotation**	**INN-ae rotation**
Crop		Tomato			Butternut Squash			complete project rotation [b)]		
Season		Summer 2019			Summer 2020					
Total yield [a)]	kg FM	2.9	2.7	2.4	3.3	2.2	2.9	16.6	13.7	14.3
Tested practice	codes	-	C	-	-			-		
Tillage										
Number of passes	#	6	6	6	4	4	4	22	22	22
Fertilization										
Total N	g	11	9	27	13	1	1	61	35	92
N from green manure [1)]	g	0	4	4	0	1	1	0	19	23
P_2O_5	g	11	3	11	0	0	0	33	12	36
K_2O	g	0	8	22	0	2	2	0	36	77
Mineral product	kg	0.00	none		0.00	none		0.00	none	
Plant-based product	kg	0.00			0.00			0.08		
Animal-based product	kg	0.38			0.42			1.82		
Compost	kg FM	0.00	0.40	1.00	none			0.00	1.20	3.00
Green manure [1)]	kg DM	0.00	0.24	0.29	0.00	0.10	0.10	0.00	1.15	1.35
Plant protection										
Number of applications [2)]	#	4	1	1	2	2	2	13	8	8
Total active ingredients	g	0.80	0.05	0.10	0.60	0.30	0.30	2.80	0.98	1.40
Irrigation - *not available; tractor-pump*										
Energy - *none*										
Additional inputs										
Solarization material	g	none			none			90	none	
Plastic-based mulching	g	1	1	1	1	1	1	5	5	5

a) Represents marketable portion

b) For the rotation-level comparison, INN-bd and INN-ae totals do not include production of ASCs, due to lack of data

1) Modelled values for green manure carry over; comprised here entirely of ASC

2) Use of hand pump for applying plant protection products

Tested practice codes: ASC - agroecological service crop introduced, C - locally produced compost

Italy cropping system LCIA results

Across the three systems and for all environmental indicators, the biodynamic system had the highest performance, with impacts between 8% and 68% to those of BAU (**Figure 6, top**). With only slight differences in cultivation strategies between the INN systems, the agroecological system had similar performance. One exception to this was found with the near tripling of aquatic ecotoxicity impacts.

With a view to contributions by input group, the impact profiles of both INN systems were very similar (**Figure 6, bottom**). Here, impacts were dominated by the tillage input group, which consisted of chiseling, harrowing and hoeing operations. As the number of passes were identical across all systems, the size of tillage contributions in the INN systems relative to that of BAU offers some indication of how minor contributions of the other inputs and processes were in overall INN impacts. The second largest contributor to INN systems was the cultivation and use of ASC. Lastly, the higher aquatic ecotoxicity impacts in the agroecological system were traced back to the PPP input group, namely, to an applied copper formulation which was not present in the biodynamic system.

In contrast, BAU impacts were dominated by both the ready-made fertilizer products and tillage operations. For select indicators, the use of PPP and the polyethylene solarization material were also notable in the BAU system. Like the agroecological system, contributions of PPP in BAU results were a result of multiple copper formulation applications. Lastly, the large contribution of solarization was a result of the amount of polyethylene material applied (45 g/m^2), the production of which depends largely on water use.

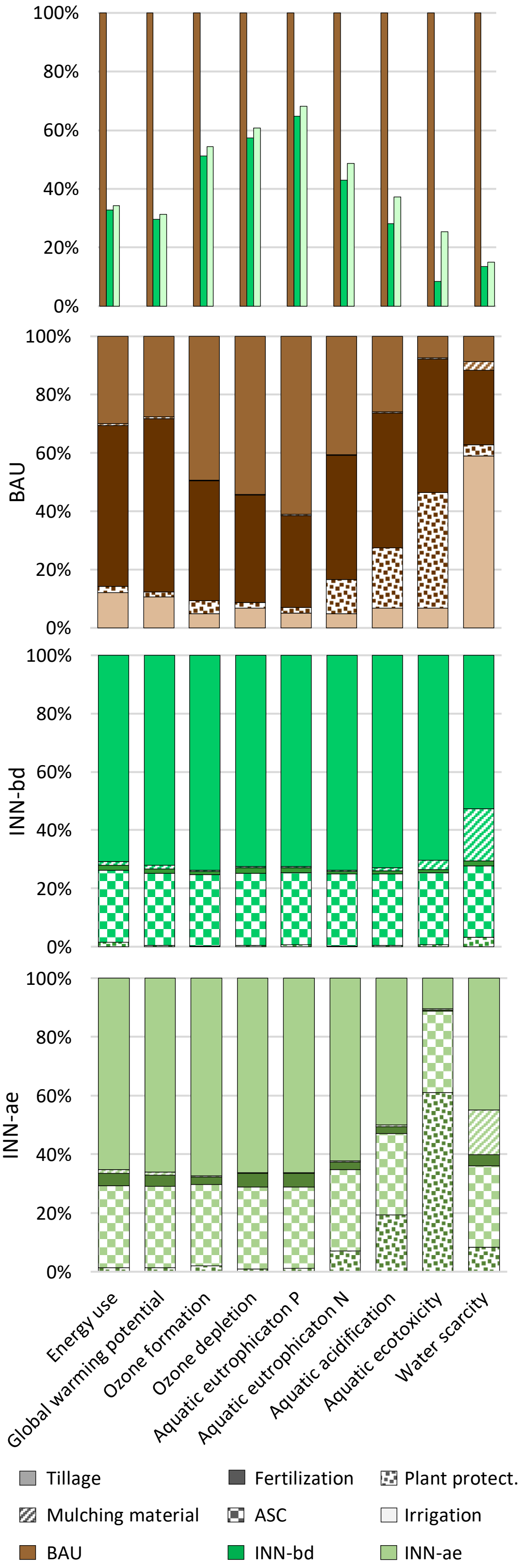

Figure 6*.* Potential environmental impacts of Italy cropping systems (above) and contributions of each input group to overall impacts (below).

Italy crop product LCIA results

The allocation of ASC impacts to other crops was determined via the modelling of nutrient carry-over. In this way, the shared benefits were proportional to the shared burdens. As for the actual impacts associated with ASC cultivations, since production data did not distinguish between ASC and the rest of the rotation, impacts of the total rotation were thus allocated to ASC cultivation based on the portion of ASC dry matter yields relative to the rotation total. This resulted in ASC impact contributions being consistently large across indicators when viewed at the cropping system level (**Figure 6**). Yet, at the crop level of comparison, ASC contributions reflected the differences in modelled values of carried-over nutrients (**Figure 7**).

Here, and with respect to all three indicators, the ASC input group contributed the most to INN product impacts—yet, only for those crops which directly followed incorporation of the ASC into the soil. Crops which were positioned further away in time from this initial incorporation received less nutrients and therefore less impacts. This was the case for Summer crops, for which tillage processes were then the largest contributor to overall impacts.

Although yields were higher for each BAU crop, this was not enough to bring impacts (per unit productional output) down to levels competitive to those of INN crops. Differences in impacts between BAU and INN systems were around 50% or more for each crop. The largest performance difference occurred for Winter crops, Rocket and Lettuce. Further differences at the crop level were observed between the INN systems. For impacts per production output, the differences in yield performances directly correlated with the observed differences in impacts. The Rocket cultivation was the only exception to this, as a result of the additional impacts coming from the applied copper formulation in the agroecological system.

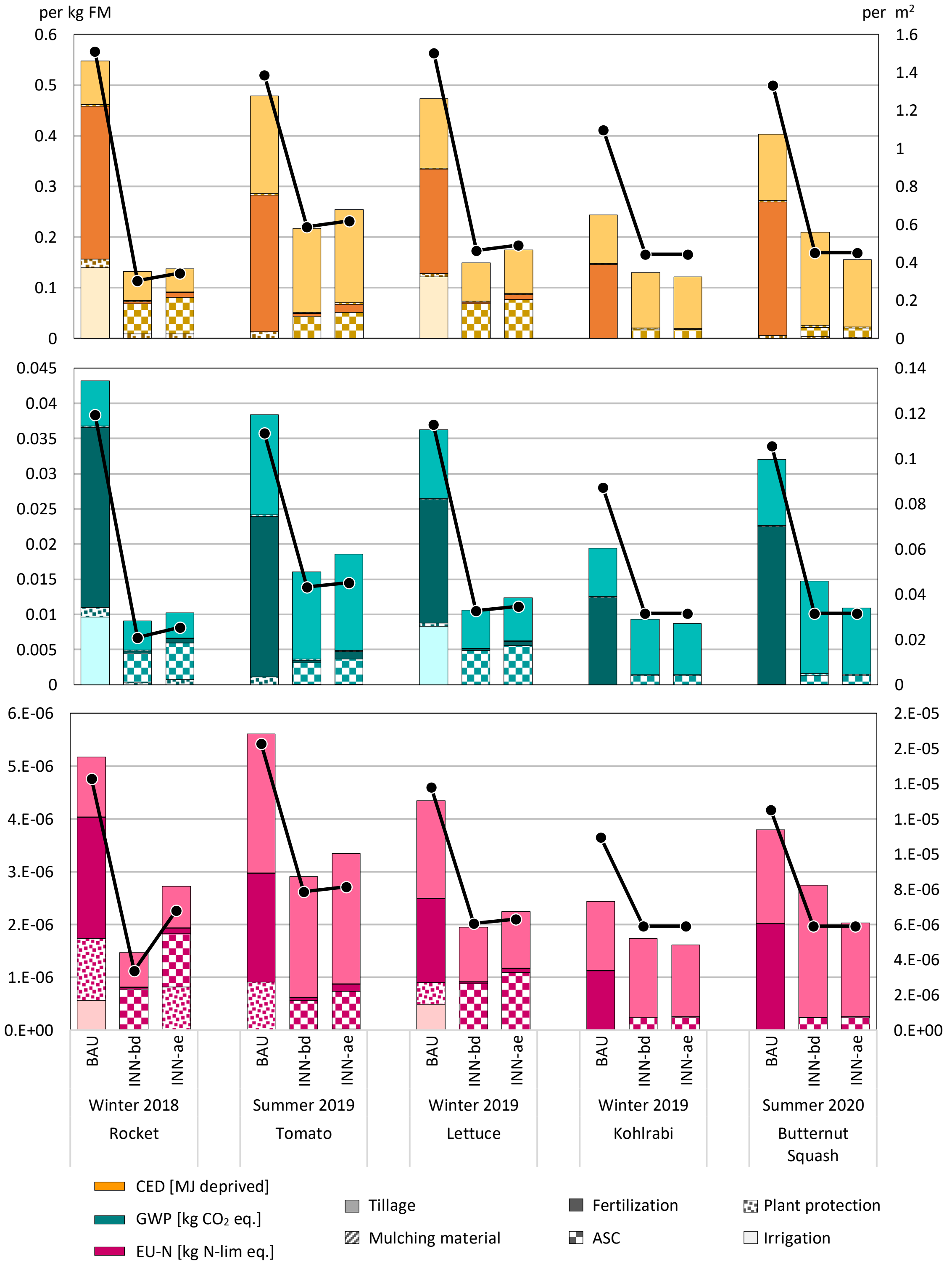

Figure 7. Energy demand (CED) (top), global warming potential (GWP) (middle) and aquatic eutrophication N potential (EU-N) (bottom) of Italy crops.

4.5 Switzerland

All crop production cycles at the Switzerland project site were observed in the LCA study. This included ten cultivars used in 26 cultivations across four cropping systems, two BAU and two INN. Due to multiple occurrences of each system-type, comparisons were also made between like-systems, in addition to between systems.

For BAU systems, a key difference was in the use of climate control, with one heated (BAU-h) and the other managed as frost-free (BAU-ff). Notable differences between INN systems were found in their use of transfer mulch and ASC practices, for which one made use of both (INN-am) while the other used only transfer mulch (INN-m). In addition, crop rotations were also slightly different, so not every INN crop had a like-crop to compare with at the product level. As for inputs, INN systems excluded commercial organic fertilizers and plastic mulches. Here, there was also a reduction of plant protection products to avoid effects on beneficial organisms.

With respect to data completeness, all input groups were observed in the Switzerland LCI dataset, and are summarized both below and in the accompanying **tables 9 and 10**. In general, and from a production input perspective, BAU-h and INN-am were the more intensive variants of the BAU and INN systems, respectively. Overall, fresh matter yields of INN systems were between 11% and 48% lower than those in BAU, with the largest difference observed between BAU-h and INN-am. With respect to the fertilization input group, large differences were found in the quantities of applied fertilizers. Nutrient requirements of INN systems were met entirely with either transfer mulch (INN-m) or the combination of transfer mulch and ASC (INN-am). For plant protection inputs, applied quantities were nearly halved in INN systems. The heating and electricity energy use of INN systems were comparable to those of the BAU-ff system. In contrast, values were much higher for BAU-h, with nearly 29-times more heat energy and nearly double the amount of electricity used for other purposes. Lastly, for irrigation, only minor differences in sourced water quantities were found between systems, with slightly more in INN systems.

Switzerland cropping system LCIA results

The top performer among all systems was BAU-ff, except with respect to the water scarcity indicator. Between the remaining three systems, performance across environmental indicators was mixed (**Figure 8**). INN systems performed similarly in all indicators, making it difficult to identify a clear top-performer between the two. When compared with BAU-h, INN impacts were lower for resource management-based indicators and higher for nutrient and toxicity management indicators. Performance was the most similar between all systems with respect to aquatic ecotoxicity and water scarcity. In addition, performance was also similar between BAU-ff and both INN systems, but only with respect to resource management indicators.

The largest differences in impacts occurred among resource management indicators between BAU-h and other systems. Here, BAU-ff impacts were 9% to 20% of BAU-h and the INN systems were 13% to 34% of BAU-h. There were large differences in respect to nutrient indicators, with BAU systems at near quarter and third of INN impacts for eutrophication-P and -N, respectively. Differences between BAU and INN were smallest for aquatic acidification and ecotoxicity.

The results in **Table 9** and **Table 10** show results for BAU and INN comparable crops and for the complete rotation. Please note that the rotation results can include crops that are not shown due to lack of a comparative crop; as such, rotation totals may not equal the sum of shown crops.

Table 9. Key production parameters observed in the environmental assessment of Switzerland winter crops.

Production parameters, per m^2 and production cycle		BAU-h	BAU-ff	BAU-h	BAU-ff	BAU-h	BAU-ff	INN-m	INN-am	BAU-h	BAU-ff	BAU-h	BAU-ff	INN-m	INN-am
Crop		Lamb's Lettuce								Lettuce		Oak Leaf Lettuce		Spinach	
Season		Winter 2018		Winter 2019		Winter 2020				Winter 2018		Winter 2019		Winter 2019	
Total yield	kg FM	1.4	1.9	1.5	1.7	1.1	1.4	1.5	1.3	2.6	2.6	1.8	1.6	1.8	1.3
Tested practice	codes	-						nF		-		-		-	
Tillage															
Number of passes	#	1	1	2	2	2	2	2	2	1	1	2	1	2	2
Fertilization															
Total N	g	none						4	6	none		770	759	5	11
N from organic-based mulching 1)	g							4	4			none		5	10
N from green manure 1)	g							0	1					0	1
P_2O_5	g							2	2			487	480	2	5
K_2O	g							3	5			1025	1011	3	9
Compost	kg FM	none						none		none		28.0	27.6	none	
Green manure 1)	kg DM							0.0	0.1			none		0.0	0.1
Plant protection															
Number of applications 2)	#	3	3	3	3	none				7	6	8	8	0	6
Total active ingredients	g	0.7	6.0	0.6	0.7					6.2	6.4	8.0	5.2	0.0	5.4
Irrigation															
Externally sourced water	l	52	54	60	55	50	50	50	50	94	97	19	16	66	54
Energy															
Heating 3)	kWh	0.1	0.0	54.0	0.0	0.1	0.0	none		39.2	2.7	51.0	3.5	0.0	3.5
Electricity	kWh	not available		0.9	0.7	0.6	3.0	3.0	3.0	not available		2.0	2.2	0.8	1.9
Additional inputs															
Organic-based mulching 1)	kg	none						0.6	0.6	none		none		0.7	0.9
Plastic-based mulching	g	22.1	22.4	22.1	22.4	22.1	22.4	none		22.1	22.4	22.1	22.4	none	

1) Modelled values for crop carry-over effects 2) Use of hand or electrical pump for applying plant protection products 3) Fuel: methane

Tested practice codes: nF - no fertilizers

Table 10. Key production parameters observed in the environmental assessment of Switzerland summer crops and rotation.

Production parameters, per m^2 and production cycle		**BAU-h**	**BAU-ff**	**BAU-h**	**BAU-ff**	**INN-m**	**INN-am**	**INN-m**	**INN-am**	**BAU-h rotation**	**BAU-ff rotation**	**INN-m rotation**	**INN-am rotation**
Crop		Tomato						Melon		complete project rotation a)			
Season		Summer 2019		Summer 2020				Summer 2019					
Total yield	kg FM	15.8	13.8	19.9	14.3	14.8	14.4	5.5	6.1	44.1	37.3	33.8	23.7
Tested practice	codes	-				M	ASC, M	M	ASC, M	-			
Tillage													
Number of passes	#	1	1	2	1	2	2	1	1	11	9	11	11
Fertilization													
Total N	g	41	22	33	22	24	31	28	36	845	803	70	96
N from organic-based mulching 1)	g	none				24	26	28	32	none		70	83
N from green manure 1)	g					0	5	0	4			0	13
P_2O_5	g	15	3	17	10	10	13	12	15	520	494	30	41
K_2O	g	56	30	46	30	17	25	20	28	1128	1071	50	79
Mineral product	kg	0.46	0.23	0.34	0.27	none		none		0.81	0.50	none	
Animal-based product	kg	0.13	0.07	0.13	0.07					0.26	0.14	none	
Compost	kg FM	none								28.0	27.6		
Green manure 1)	kg DM					0.00	0.28	0.00	0.19	none		0.00	0.75
Plant protection													
Number of applications 3)	#	12	14	9	1	1	1	5	5	42	35	20	22
Total active ingredients	g	6.1	11.3	27.6	5.7	5.7	5.7	8.5	8.5	49.2	35.4	24.2	23.2
Irrigation													
Externally sourced water	l	70.8	75	82	72	80	80	64	64	428	419	494.0	517.0
Energy													
Heating	kWh	none		32.5	0.0	none		none		176.8	6.2	6.3	6.3
Electricity	kWh	2.7	2.3	4.6	11.1	11.1	11.1	2.3	2.3	10.9	19.3	19.6	19.2
Additional inputs													
Organic-based mulching 1)	kg	none				2.0	2.0	1.5	1.7	none		5.6	6.5
Plastic-based mulching	g	28.9	14.4	28.9	14.4	none		none		168.4	141.1	none	

a) For the rotation-level comparison, totals include crops not previously shown due to their single occurrences (INN-m: Purslane, Radis and Plantago; INN-am: Kohlrabi and two ASC crops)

1) Modelled values for crop carry-over effects 2) Use of hand or electrical pump for applying plant protection products 3) Fuel source: methane

Tested practice codes: ASC - agroecological service crop introduced, M - transfer mulch introduced

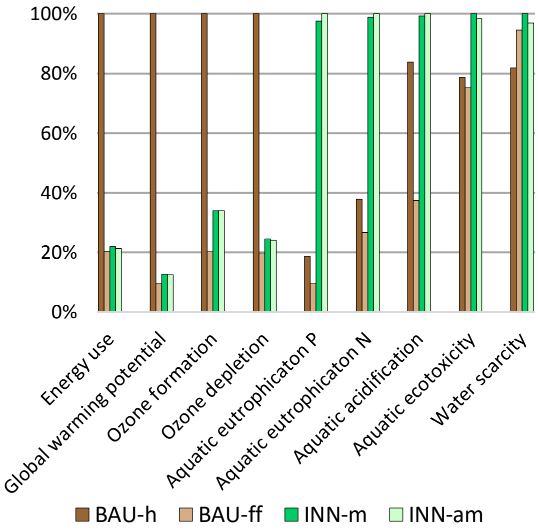

Figure 8. Potential environmental impacts of Switzerland cropping systems.

Regarding input group contributions to overall impacts, many differences were observed between the systems (**Figure 9**), most of which took place between BAU and INN systems as well as between BAU systems. Also here, most similarities in results occurred between INN systems. Over all systems, impacts associated with energy use were often among the largest contributors. In BAU-h, energy impacts dominated totals in all indicators. The same was true in BAU-ff, except in ozone depletion and eutrophication-P indicators. For INN systems, energy related impacts contributed the most but only to four of the nine indicators, energy use, global warming potential, aquatic ecotoxicity and water scarcity. Secondary contributions for BAU systems were notable only for select indicators; this included contributions of PPP to ozone depletion and fertilization to aquatic eutrophication-P.

Contributions of each input group to each indicator were very similar between the INN system. If contributions of ASC and transfer mulch were considered together in the INN-am system, than their contribution would be comparable to that of just transfer mulch in the

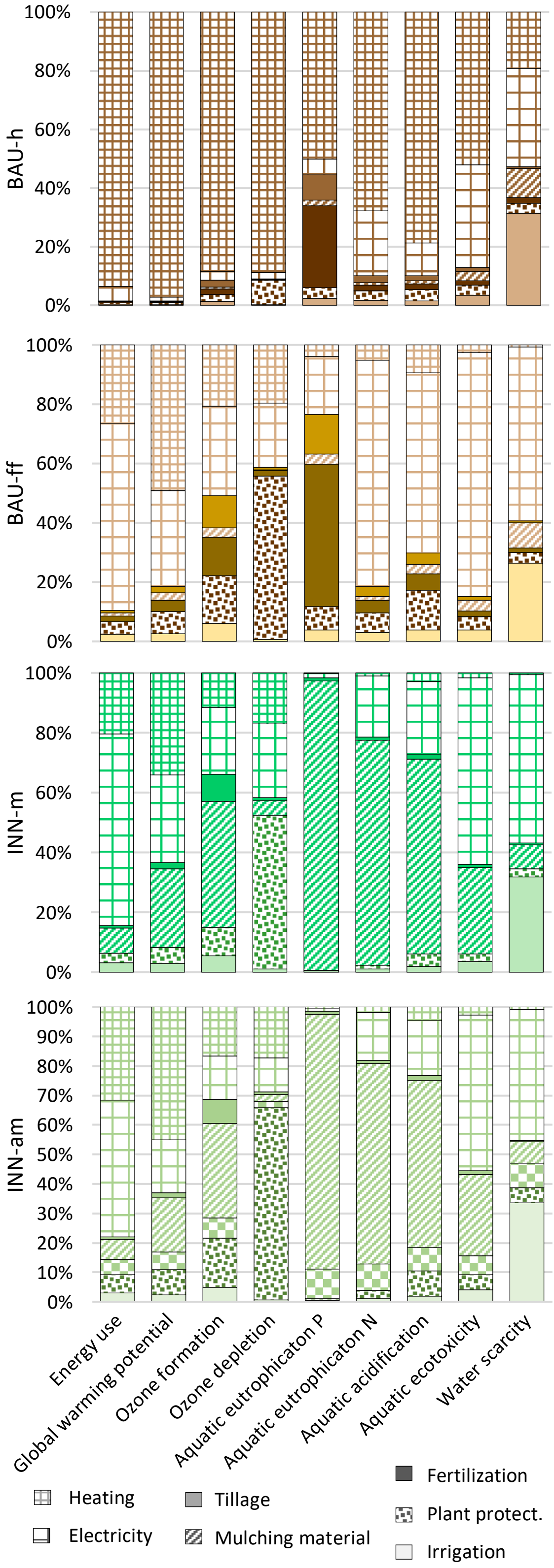

Figure 9. Potential environmental impacts by input group of Switzerland cropping systems.

INN-am system. Either uses of organic materials resulted in similar contributions to energy use and for the indicators not previously mentioned. An exception here is in ozone depletion, where the PPP input group dominated total impacts.

Switzerland crop product LCIA results

At the product level, impacts varied greatly both within and between product groups, seasons, systems, and indicators (**Figure 10**). As was also the case at the cropping system level of comparison, INN products performed favorably with respect to eutrophication-N and water scarcity indicators, whereas BAU products had lower potential impacts for energy use and global warming potential indicators.

For energy use and global warming potential, large difference in total impacts were observed between winter BAU crops, INN Spinach, and between BAU and INN systems with respect to Lamb's Lettuce and Tomatoes. In most cases which involved BAU-h, differences were a result of the added impacts resulting from larger heat energy use. Differences between INN Spinach crops was a result of impacts associated with the presence of PPP, ASC and additional energy use in INN-am. In a select few cases, differences in performance came down to the choice of functional unit (**Figure 10, right versus left vertical axis**), as seen in Lamb's Lettuce of 2020 and Spinach of 2020. In both cases, impacts per unit area were comparable but not when viewed per unit mass.

Observed differences were also similar for eutrophication-N and water scarcity, but these were less pronounced throughout. The sourcing of hydrologically produced electricity within Switzerland explained the electricity input group contributions to water scarcity for irrigated crops. As for eutrophication-N, the use of transfer mulches dominated INN crop impact profiles, due mostly to nitrogen emissions associated with cultivation of the mulching material. The use of ASC, on the other hand, made use of on-site production inputs, which resulted in a sharing of materials between crops and thereby had lower impacts relative to the use of transfer mulch.

Impacts associated with mulch and ASC were allocated to specific crops based on modelled values of carry-over effects. These contributions were visible in crops which received residual nutrients, with amounts generally diminishing the further the crop was from an initial application and/or incorporation of organic material. Therefore, with Summer INN crops as the first to receive the organic materials, and in addition to the length of their production cycles, they received the largest portion of related impacts. Across the four selected indicators, these impacts were most visible in eutrophication-N due to their associated nitrate leaching potential.

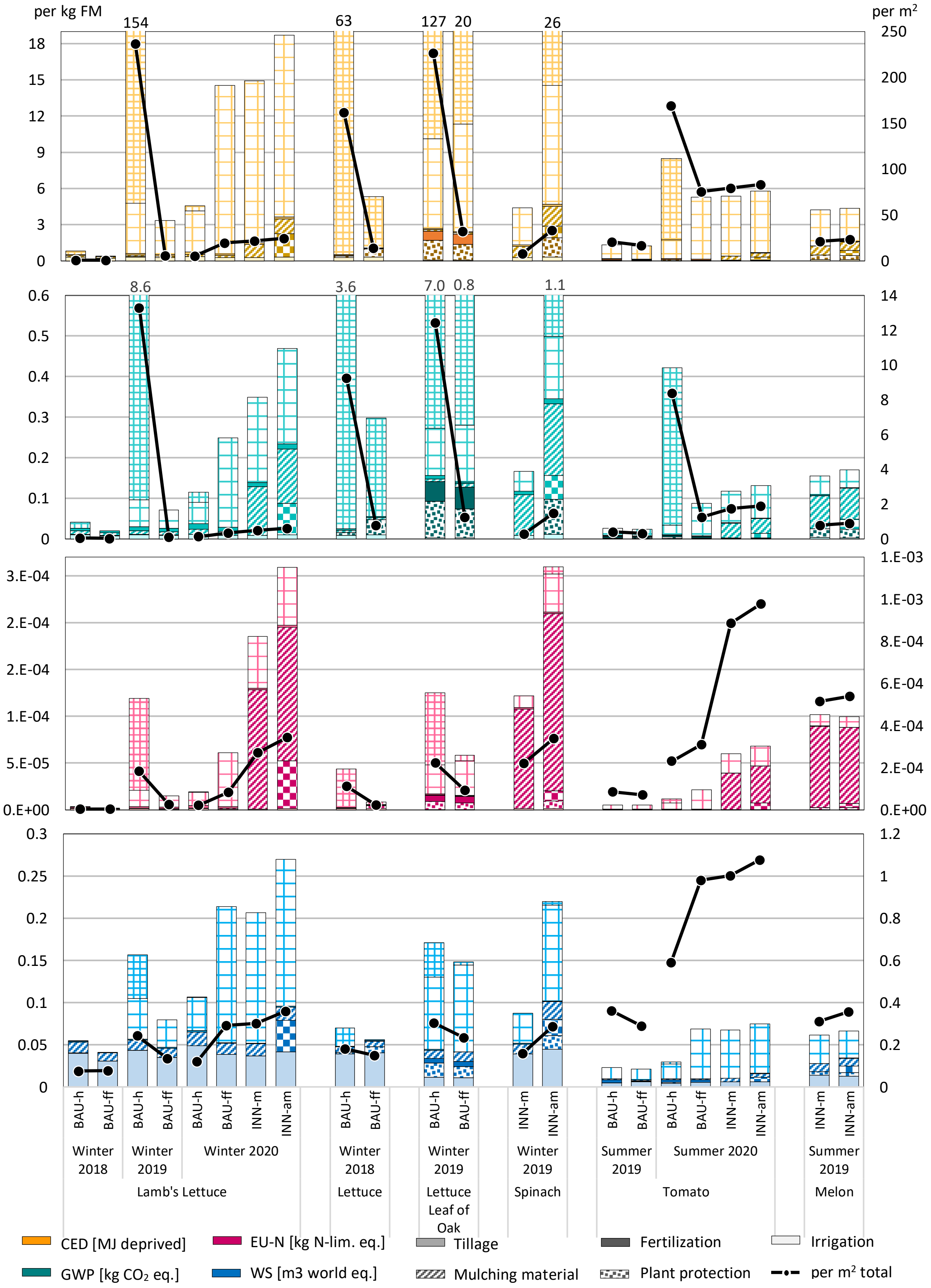

Figure 10. Energy demand (CED) (top), global warming potential (GWP) (middle-top), aquatic eutrophication N potential (EU-N) (middle-bottom) and water scarcity (WS) (bottom) of Switzerland crops.

5. Discussion & Conclusions

The application of LCA to assess and compare potential environmental impacts of BAU and INN cropping strategies at the five project sites revealed a mix of environmental performance, as well as several key factors which contributed to these outcomes. The knowledge and contextual understanding of these is an essential step towards deciding how to best utilize innovative practices involved in reaching favorable agroecological and environmental outcomes. For this, key performance differences and the factors and methodological decisions which contributed to these are explored in detail below. This then serves as a basis for drawing conclusions, practical recommendations, and suggestions for further research.

Observed differences in environmental performance often came down to the presence of select innovative practices which required use of different types and/or quantities of production material and energy inputs. In contrast, intercropping and companion cropping, both of which did not influence observed production input flows, likely contributed to differences in yields, but how they contributed to performance could not be identified in the results. Other sources of variation included yield differences and methodological decisions regarding, for example, allocation rules and system boundary exclusions. For systems with similar performance, differences in yield were often a decisive factor. However, a more complete understanding of the range of variation in production inputs and yields was limited by the lack of experimental replications, as well as a lack of evidence on the correlation between certain practices and yield, both from the project and in literature. This is a common shortcoming in vegetable LCAs (Perrin et al., 2014). Additionally, sources of inherent variability, like those of climate and soil, were expected to have contributed but were not explicitly factored into the assessment.

Environmental performance contexts of tested practices

The practice of reducing energy and/or material inputs always resulted in a proportionate reduction in associated impacts per unit area, i.e., from the land-use perspective. On the other hand, when impacts were viewed from a production output perspective, per unit mass, then reductions were not always proportional due to differences in yield performance. This illustrates the push-pull between intensification and resource-efficiency which is often lacking attention in agricultural LCA studies (Meier et al., 2017). Here, the differences in potential impact reductions relative to yields suggests that there is likely room to lower material and energy inputs, especially with respect to use of heat energy. Similar large contributions of heat to overall impacts were found in a LCA study on protected tomato production in France (Boulard et al., 2011). Authors, however, did not provide an indication of which reduction is achievable without seeing large decreases in yield.

For intercropping and companion cropping practices, environmental (dis)advantages of their use were not discernable in LCA results. It was also not possible to derive this information indirectly, via observed differences in yields, due to the presence of multiple simultaneous treatments at experiment sites. Moreover, without sufficient evidence, also from literature, on the correlation of yields and use of these practices, an indication of their potential performance could not be drawn. A similar situation was found with the use of flower strips, where evidence of their influence on production inputs and yields was missing, rendering it impossible to quantitatively understand their impact reduction potential. Here, it can only be safely said that their use would increase impacts, albeit in an insignificant amount as a result of the upstream production of sourced seed materials.

The use of transfer mulches in all instances was associated with sizeable impacts, far greater than those associated with the use of plastic mulch. This was a result of both the embedded impacts of these materials, stemming from their cultivation, as well as the quantities applied. Indeed, when compared per unit of equivalent mass, plastic mulches have much higher impacts. The large difference in applications between mulching techniques was therefore a matter of the quantity of material applied. This begs the question of whether there is room to optimize transfer mulch application rates. Another important consideration is if only mulches with low to no value could be used, i.e., those with low-opportunity costs, for example, the non-selected material left over by cattle in feed troughs. If the material is considered a waste, then it is possible that little to no impacts shall be allocated to it. However, even if treated as a waste, it is questionable if the benefits of transfer mulch could justify the additional impacts associated with direct emissions from their on-site decomposition.

Indeed, such direct emissions were excluded from the LCA system boundary. This decision was backed by missing values for key emission modelling parameters, such as N-min, as well as a general lack of suitable modelling approaches for vegetable cropping sequences. The latter can be evidenced in the results of an in-depth review of LCA vegetable studies which found that most N-emission modelling methods applied in studies were done so beyond the intended application domain (Perrin et al., 2014). Moreover, due to the complexities of vegetable cropping systems, there is a high data burden if accurate representation is to be achieved (BSI, 2012). Although uncertainties in impact results would likely increase with the inclusion of direct emissions, it would also likely capture additional differences between practices. Indeed, partial consideration of N-emissions was made, but only for the purpose of modelling carry-over effects of ASC and transfer mulch. Here, it was assumed that 50% of total N from materials was not available, as it would be lost to the environmental in some form. However, these emissions were not further distinguished by form and therefore were not included in life cycle inventories of the products or systems. This would have influenced greatly the potential eutrophication-N impacts associated with their use.

Other system boundary exclusions, as well as unresolved gaps in LCI data, also likely influenced the ability to draw conclusions between performance of cultivation strategies. For example, this was the case for transportation. Indeed, its inclusion would have played an important part for select inputs, such as biocontrol agents which rely on unique (sub-)tropical plant extracts, as well as for observing differences between locally produced composts and commercially produced fertilizers. However, the inclusion of transportation also comes with uncertainties; for example, it is often the case that the further back one goes in the supply chain, the less transparent it is where and how materials are sourced. Lastly, although greenhouse infrastructure can contribute a large portion to overall product level impacts (BSI, 2012; Cellura et al. 2012), its exclusion was justified on the basis of both systems making equal use of infrastructure.

Drawing conclusions on the performance of different fertilization strategies was hampered by a lack of data on how local composts were prepared, what components were involved, and how they were stored. Only in the case of Italy could a clear distinction between BAU and INN strategies be observed, and this was a result of BAU relying on energy intensive, commercially produced fertilizers in contrast to the use on-site composts, having lower impacts per mass, in the INN systems. A similar outcome was found in an LCA study comparing the use of organic and mineral fertilizers in a Mediterranean open-field vegetable cultivation setting; here, authors found the lowest impacts with use of composts based on locally sourced household organic waste when compared to industrial composts and mineral fertilizers (Quiros et al., 2015). However, it is important to note a key modelling decision of the authors: The impacts that would have accrued with disposal of household wastes at a waste management facility were deducted from their total impacts, as these were viewed as avoided impacts. As this study made use of the attributional LCA approach, such indirect emissions were not considered. Although its inclusion would have offered valuable insights on possible consequences of increased adoption of innovative practices, it would have also required a great deal of detailed information and assumptions on the different inputs of each system, involving, for example, impacts of suitable substitutes as well as their market shares. All of this is needed to substantiate allocation decisions and impact credits/deductions.

Lastly, with respect to the use of ASC, in general their use was accompanied by an overall increase in production inputs and thus impacts, but when compared with BAU strategies, these impacts were often accompanied by a shifting of burdens away from resource management indicators and towards nutrient management indicators, in INN. This was a result of ASC compensating for a portion of reduced fertilizer inputs. Moreover, the choice to allocate impacts of ASC and transfer mulch based on N-carry-over was because N was assumed to be the most valuable asset, but allocation could also have been based on a different shared benefit. However, this would have required more quantitative evidence as to the other functions that these practices served, such as, improving soil quality or enhancing biodiversity. The necessary methods for properly representing these within LCA studies, however, remains limited (van der Werf et al., 2020). For this, the use of other sustainability assessment tools may be more suitable for drawing conclusions on the potential or achieved benefits of on-farm agroecological practices (Landert et al., 2020).

Outlook

In summary, the following conclusions, practical recommendations, and future research suggestions could be made:

- Impact reduction potential exists via reducing material and energy inputs, but at varying costs to yield performance
- Knowledge of how co-production practices and the use of flower strips influence yields and production inputs would need to supplement LCA results in order to draw conclusions on their environmental reduction potential
    - This would likely require observational data for longer term trials in order to see the influence of, for example, yield-stabilizing effects in LCA results.

- High impacts related to the use of transfer mulch could be lowered with more targeted use and if the sourced materials were considered as wastes
- If ASCs substitute a portion of fertilizer inputs, then there exists potential for both increases and decreases in impacts across environmental indicators.
    - Here, it is important to strike a balance between fertilizer and ASC use.
- The environmental superiority of using one fertilization strategy over another was largely inconclusive. Drawing a clearer distinction could have been helped with the inclusion of direct emissions, accompanied by the necessary data for emissions modelling.

Overall, the mixed environmental performance results, both between and within project sites, suggests the potential for further design options, including combinations of BAU and INN strategies. Results of this study contribute to understanding this design potential, and yet this is hampered by a general lack of similar investigations for which to corroborate with. Additional investigations into combinations of innovative practices are therefore required to understand the wider option space for improving both the environmental and agroecological performance of protected organic vegetable production systems.

6. References

Båth, B., Malgeryd, J., Stintzing, A.R. and Åkerhielm, H., 2006. Surface mulching with red clover in white cabbage production. Nitrogen uptake, ammonia losses and the residual fertility effect in ryegrass. Biological agriculture & horticulture, 23(3), pp.287-304.

Boulard, T., Raeppel, C., Brun, R., Lecompte, F., Hayer, F., Carmassi, G. and Gaillard, G., 2011. Environmental impact of greenhouse tomato production in France. Agronomy for Sustainable Development, 31(4), p.757.

Bulle, C., Margni, M., Patouillard, L., Boulay, A.M., Bourgault, G., De Bruille, V., Cao, V., Hauschild, M., Henderson, A., Humbert, S. and Kashef-Haghighi, S., 2019. IMPACT World+: a globally regionalized life cycle impact assessment method. The International Journal of Life Cycle Assessment, 24(9), pp.1653-1674.

BSI, 2012. PAS 2050-1:2012: Assessment of life cycle greenhouse gas emissions from horticultural products -Supplementary requirements for the cradle to gate stages of GHG assessments of horticultural products undertaken in accordance with PAS 2050. British Standard. London, England.

Cellura, M., Longo, S. and Mistretta, M., 2012. Life Cycle Assessment (LCA) of protected crops: an Italian case study. Journal of cleaner production, 28, pp.56-62.

European Commission, 2011. International reference life cycle data system (ILCD) handbook—recommendations for life cycle impact assessment in the European context, 1st ed. European commission - Joint Research Centre - Institute for Environment and Sustainability, Luxemburg.

International Organization for Standardization (ISO), 2006a. Environmental Management – Life Cycle Assessment – Principles and Framework. EN ISO 14040.

International Organization for Standardization (ISO), 2006b. Environmental Management – Life Cycle Assessment – Requirements and Guidelines. EN ISO 14044.

Landert, J., Pfeifer, C., Carolus, J., Schwarz, G., Albanito, F., Muller, A., Smith, P., Sanders, J., Schader, C., Vanni, F. and Prazan, J., 2020. Assessing agro-ecological practices using a combination of three sustainability assessment tools. Landbauforschung, 70(2), pp.129-144.

Meier, M., Hörtenhuber, S., Schader, C., Stolze, M., 2017. Biolandbau und Nachhaltigkeit: Ökobilanzierung biologischer Lebensmittel. FiBL Faktenblatt. Forschungsinstitut für biologischen Landbau, Frick, Wien.

Perrin, A., Basset-Mens, C. and Gabrielle, B., 2014. Life cycle assessment of vegetable products: a review focusing on cropping systems diversity and the estimation of field emissions. The International Journal of Life Cycle Assessment, 19(6), pp.1247-1263.

Pineda, I.T., Lee, Y.D., Kim, Y.S., Lee, S.M. and Park, K.S., 2020. Review of inventory data in life cycle assessment applied in production of fresh tomato in greenhouse. Journal of Cleaner Production, p.124395.

Quirós, R., Villalba, G., Gabarrell, X. and Munoz, P., 2015. Life cycle assessment of organic and mineral fertilizers in a crop sequence of cauliflower and tomato. International journal of environmental science and technology, 12(10), pp.3299-3316.

Riley, H., Løes, A.K., Hansen, S. and Dragland, S., 2003. Yield responses and nutrient utilization with the use of chopped grass and clover material as surface mulches in an organic vegetable growing system. Biological agriculture & horticulture, 21(1), pp.63-90.

van der Werf, H.M., Knudsen, M.T. and Cederberg, C., 2020. Towards better representation of organic agriculture in life cycle assessment. Nature Sustainability, 3(6), pp.419-425.

van Zelm, R., Huijbregts, M.A., den Hollander, H.A., Van Jaarsveld, H.A., Sauter, F.J., Struijs, J., van Wijnen, H.J. and van de Meent, D., 2008. European characterization factors for human health damage of PM10 and ozone in life cycle impact assessment. Atmospheric Environment, 42(3), pp.441-453.

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., and Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. The International Journal of Life Cycle Assessment, [online] 21(9), pp.1218–1230.

Appendix A

All environmental impact category descriptions are provided below and according to their implementation in the IMPACT World+ LCIA methodology set (Bulle et al., 2019).

The **energy demand** (also referred to in the text as “energy use”) method identifies fossil-based energy use, and as such, serves as an indicator for resource depletion. Values are given in MJ-deprived equivalents.

Global warming potential is computed for a 100-year time horizon according to the 2013 IPCC method. Carbon dioxide equivalent factors of 265 for nitrous oxide and 28 for methane are used to arrive at an end value, given in kg CO_2 equivalents.

Photochemical oxidant formation (referred to in the text as “ozone formation”) is a result of nitrogen oxides (NO_X) and non-methane volatile organic compounds (NMVOC) emitted to the air and subsequently transformed into tropospheric ozone; at this low atmospheric level, ozone poses a threat to both living organisms and human-made materials (van Zelm et al. 2008). Computed values for this indicator are given in kg of emitted NMVOC equivalents.

Ozone (layer) depletion, on the other hand, is an indicator concerned with ozone in the stratosphere, where its presence shields the earth from damaging UV-radiation. Depletion is indicated by kg of chlorofluorocarbons (CFCs) equivalents released to the air.

Two separate indicators are used to address aquatic eutrophication so as to distinguish between N- and P-related emissions, which have different behaviors once emitted to the environment—the former being much more mobile. For **eutrophication-N**, nitrogen is identified as the limiting factor, whereas phosphorus is the limiting factor in **eutrophication-P**. Impacts are described in kg of N and P equivalents, respectively.

Aquatic acidification is mostly influenced by excess sulfur oxides, ammonia, and nitrogen dioxide in the air. Impacts are provided in kg SO_2 equivalents.

Aquatic ecotoxicity relies on the USEtox model and is given in comparative toxic units per kg of an emitted chemical.

Water scarcity makes use of the AWARE consensus model and is expressed in cubic meters of water used. As with energy use, this impact category can also be used as an indication or resource use.

Appendix B

Table B 1. Potential environmental impacts per kg FM marketable yield of observed Belgium crop products, organized by season, cultivar, and system.

		Winter 2018				Summer 2019				Summer 2020	
		Purslane		Mizuna	Swiss Chard	Radish		Tomato		Cherry Tomato	
		BAU	INN	INN	INN	BAU	INN	BAU	INN	BAU	INN
Global warming potential	kg CO2 eq	0.0174	0.0065	0.0061	0.0099	0.0092	0.0201	0.0094	0.0081	0.0053	0.0067
Energy use	MJ deprived	0.272	0.102	0.095	0.155	0.123	0.296	0.147	0.088	0.075	0.097
Ozone formation	kg NMVOC eq	1.3E-04	4.8E-05	4.5E-05	7.3E-05	9.2E-05	1.7E-04	6.4E-05	5.5E-05	3.2E-05	4.2E-05
Ozone depletion	kg CFC-11 e	3.8E-09	1.4E-09	1.3E-09	2.2E-09	1.5E-09	3.9E-09	1.9E-09	1.1E-09	7.5E-10	1.0E-09
Aquatic eutrophication-P	kg PO4 P-lim	5.9E-07	2.2E-07	2.0E-07	3.3E-07	2.2E-07	6.0E-07	2.9E-07	1.3E-06	1.1E-07	1.5E-07
Aquatic eutrophication-N	kg N N-lim e	2.4E-06	8.8E-07	8.2E-07	1.3E-06	1.6E-06	3.1E-06	1.2E-06	4.1E-06	6.2E-07	8.1E-07
Aquatic acidification	kg SO2 eq	1.9E-10	7.3E-11	6.8E-11	1.1E-10	1.3E-10	2.5E-10	1.0E-10	1.9E-10	6.0E-11	7.7E-11
Aquatic ecotoxicity	CTUe	42.98	16.14	15.02	24.43	37.63	63.38	29.86	24.67	29.21	33.79
Water scarcity	m3 world-eq	0.00189	0.00071	0.00066	0.00107	0.00074	0.00194	0.00245	0.00230	0.00193	0.00214

Table B 2. Potential environmental impacts per kg FM yield of observed Denmark crop products, organized by season, cultivar, and system.

		Summer 2019		Summer 2020	
		Tomato			
		BAU	INN	BAU	INN
Global warming potential	kg CO2 eq	0.030	0.016	0.071	0.020
Energy use	MJ deprived	0.42	0.19	0.98	0.25
Ozone formation	kg NMVOC eq	6.2E-05	5.0E-05	1.5E-04	6.6E-05
Ozone depletion	kg CFC-11 e	1.1E-09	7.4E-10	2.7E-09	9.7E-10
Aquatic eutrophication-P	kg PO4 P-lim	7.5E-08	7.7E-08	1.9E-07	1.0E-07
Aquatic eutrophication-N	kg N N-lim e	2.5E-06	1.3E-06	5.9E-06	1.7E-06
Aquatic acidification	kg SO2 eq	2.5E-10	1.6E-10	5.9E-10	2.1E-10
Aquatic ecotoxicity	CTUe	242	146	566	188
Water scarcity	m3 world-eq	0.0044	0.0019	0.0102	0.0024

Table B 3. Potential environmental impacts per kg FM marketable yield of observed France crop products, organized by season, cultivar, and system.

		Winter									Summer							
		2018		2019		2018	2019	2018	2019	2018	2018		2020	2019		2020		2018
		Lettuce				Lamb's Lettuce		Spinach		Kohlrabi	Tomato			Eggplant		Cucumber		
		BAU	INN	BAU	INN	INN	INN	INN	INN	INN	BAU	INN	INN	BAU	INN	BAU	INN	INN
Global warming potential	kg CO2 eq	0.024	0.066	0.025	0.039	0.255	0.144	0.097	0.063	0.049	0.013	0.039	0.052	0.022	0.048	0.038	0.035	0.081
Energy use	MJ deprived	0.45	0.85	0.44	0.54	3.24	1.91	1.25	0.84	0.63	0.23	0.46	0.63	0.58	0.66	0.60	0.43	0.95
Ozone formation	kg NMVOC eq	1.7E-04	3.1E-04	1.8E-04	1.9E-04	1.2E-03	7.1E-04	4.5E-04	3.1E-04	2.3E-04	7.9E-05	1.8E-04	2.6E-04	1.4E-04	2.2E-04	2.2E-04	1.8E-04	3.7E-04
Ozone depletion	kg CFC-11 e	3.2E-09	5.3E-09	3.3E-09	3.4E-09	2.1E-08	1.3E-08	7.9E-09	5.5E-09	4.0E-09	1.9E-09	3.4E-09	4.8E-09	2.9E-09	3.9E-09	4.8E-09	3.3E-09	7.0E-09
Aquatic eutrophication-P	kg PO4 P-lim	6.8E-06	9.4E-06	7.8E-06	4.8E-06	3.7E-05	1.8E-05	1.4E-05	8.1E-06	6.9E-06	3.8E-07	5.7E-06	5.7E-06	2.5E-07	7.1E-06	1.0E-06	3.9E-06	1.2E-05
Aquatic eutrophication-N	kg N N-lim e	4.1E-06	5.2E-05	4.4E-06	2.7E-05	2.0E-04	1.0E-04	7.7E-05	4.5E-05	3.8E-05	1.9E-06	3.1E-05	3.3E-05	2.1E-06	3.9E-05	6.8E-06	2.2E-05	6.5E-05
Aquatic acidification	kg SO2 eq	3.1E-10	2.2E-09	3.3E-10	1.2E-09	8.8E-09	4.5E-09	3.3E-09	2.0E-09	1.6E-09	2.8E-10	1.4E-09	1.8E-09	2.5E-10	1.7E-09	9.6E-10	1.2E-09	3.0E-09
Aquatic ecotoxicity	CTUe	118	473	115	274	1836	1006	697	442	350	119	305	674	160	351	631	459	634
Water scarcity	m3 world-eq	0.313	0.358	0.271	0.249	1.286	0.778	0.528	0.343	0.280	0.008	0.009	0.019	0.622	0.377	0.025	0.013	0.019

Table B 4. Potential environmental impacts per kg FM marketable yield of observed Italy crop products, organized by season, cultivar, and system.

		Winter 2018			Summer 2019			Winter 2019						Summer 2020		
		Rocket			Tomato			Lettuce			Kohlrabi			Butternut Squash		
		BAU	INN-bd	INN-ae	BAU	INN-bd	INN-ae	BAU	INN-bd	INN-ae	BAU	INN-bd	INN-ae	BAU	INN-bd	INN-ae
Global warming potential	kg CO2 eq	0.0432	0.0091	0.0102	0.0384	0.0160	0.0186	0.0362	0.0106	0.0123	0.0194	0.0093	0.0087	0.0320	0.0147	0.0109
Energy use	MJ deprived	0.55	0.13	0.14	0.48	0.22	0.25	0.47	0.15	0.18	0.24	0.13	0.12	0.40	0.21	0.16
Ozone formation	kg NMVOC eq	2.1E-04	8.4E-05	1.1E-04	2.6E-04	1.6E-04	1.8E-04	2.0E-04	1.1E-04	1.2E-04	1.2E-04	9.6E-05	9.0E-05	1.9E-04	1.5E-04	1.1E-04
Ozone depletion	kg CFC-11 e	3.1E-09	1.4E-09	1.5E-09	3.8E-09	2.8E-09	3.3E-09	3.3E-09	1.9E-09	2.3E-09	2.0E-09	1.7E-09	1.6E-09	3.0E-09	2.7E-09	2.0E-09
Aquatic eutrophication-P	kg PO4 P-lim	3.9E-07	2.1E-07	2.3E-07	5.4E-07	4.2E-07	5.0E-07	4.4E-07	2.9E-07	3.5E-07	2.7E-07	2.6E-07	2.4E-07	4.1E-07	4.1E-07	3.0E-07
Aquatic eutrophication-N	kg N N-lim e	5.2E-06	1.5E-06	2.7E-06	5.6E-06	2.9E-06	3.3E-06	4.3E-06	2.0E-06	2.2E-06	2.4E-06	1.7E-06	1.6E-06	3.8E-06	2.7E-06	2.0E-06
Aquatic acidification	kg SO2 eq	7.4E-10	1.2E-10	4.0E-10	6.7E-10	2.2E-10	2.6E-10	5.2E-10	1.5E-10	1.7E-10	2.5E-10	1.3E-10	1.3E-10	4.0E-10	2.1E-10	1.6E-10
Aquatic ecotoxicity	CTUe	773.47	38.28	489.76	591.46	56.23	64.38	417.96	35.21	40.34	145.94	31.28	29.14	255.87	49.54	36.73
Water scarcity	m3 world-eq	0.01758	0.00135	0.00188	0.00426	0.00139	0.00163	0.01472	0.00115	0.00134	0.00208	0.00101	0.00094	0.00345	0.00160	0.00119

Table B 5. Potential environmental impacts per kg FM yield of observed Switzerland crop products, organized by season, cultivar, and system.

		Winter 2018							Winter 2019		Winter 2020			
		Purslane	Radis	Kohlrabi	Lettuce		Lambs Lettuce							
		INN-m	INN-m	INN-am	BAU-h	BAU-ff	BAU-h	BAU-ff	BAU-h	BAU-ff	BAU-h	BAU-ff	INN-m	INN-am
Global warming potential	kg CO2 eq	0.098	0.098	0.951	3.597	0.298	0.042	0.020	8.633	0.071	0.115	0.249	0.349	0.470
Energy use	MJ deprived	1.76	1.95	16.36	62.87	5.32	0.81	0.41	153.81	3.35	4.55	14.55	14.92	18.69
Ozone formation	kg NMVOC eq	1.5E-04	2.3E-04	2.0E-03	3.1E-03	4.6E-04	1.5E-04	1.0E-04	7.4E-03	2.3E-04	3.4E-04	5.8E-04	1.0E-03	1.4E-03
Ozone depletion	kg CFC-11 e	5.6E-08	1.6E-08	6.0E-07	6.1E-07	1.7E-07	5.5E-09	2.2E-09	1.5E-06	1.6E-08	2.4E-08	6.7E-08	7.1E-08	9.1E-08
Aquatic eutrophication-P	kg PO4 P-lim	1.2E-07	3.6E-07	2.1E-05	1.4E-06	3.8E-07	2.9E-07	2.1E-07	3.4E-06	4.4E-07	6.4E-07	9.4E-07	2.4E-05	3.5E-05
Aquatic eutrophication-N	kg N N-lim e	2.8E-06	4.7E-06	1.4E-04	4.4E-05	8.5E-06	3.1E-06	2.2E-06	1.2E-04	1.5E-05	1.9E-05	6.1E-05	1.9E-04	2.6E-04
Aquatic acidification	kg SO2 eq	3.5E-10	4.3E-10	8.1E-09	5.6E-09	1.1E-09	3.3E-10	2.3E-10	1.4E-08	9.6E-10	1.3E-09	3.5E-09	8.4E-09	1.2E-08
Aquatic ecotoxicity	CTUe	103.24	198.18	1799.22	1315.25	333.96	201.18	147.83	3831.55	826.59	1030.10	3379.07	4053.19	5187.37
Water scarcity	m3 world-eq	2.1E-02	7.7E-02	2.2E-01	7.0E-02	5.6E-02	5.4E-02	4.1E-02	1.6E-01	8.0E-02	1.1E-01	2.1E-01	2.1E-01	2.7E-01

Table B 6. Potential environmental impacts per kg FM yield of observed Switzerland crop products, organized by season, cultivar, and system.

		Winter 2019					Summer 2019				Summer 2020			
		Lettuce Leaf of Oak		Plantago	Spinach		Melon		Tomato					
		BAU-h	BAU-ff	INN-m	INN-m	INN-am	INN-m	INN-am	BAU-h	BAU-ff	BAU-h	BAU-ff	INN-m	INN-am
Global warming potential	kg CO2 eq	6.994	0.801	0.782	0.166	1.141	0.155	0.170	0.026	0.024	0.421	0.088	0.118	0.132
Energy use	MJ deprived	127.45	20.42	18.84	4.40	25.73	4.21	4.37	1.31	1.22	8.48	5.28	5.35	5.78
Ozone formation	kg NMVOC eq	6.7E-03	1.5E-03	1.5E-03	6.1E-04	2.2E-03	5.3E-04	5.4E-04	6.7E-05	6.0E-05	4.1E-04	1.8E-04	3.1E-04	3.5E-04
Ozone depletion	kg CFC-11 e	1.5E-06	3.9E-07	3.3E-07	2.3E-08	4.8E-07	8.7E-08	8.5E-08	6.4E-09	6.0E-09	7.4E-08	2.4E-08	2.5E-08	2.7E-08
Aquatic eutrophication-P	kg PO4 P-lim	4.9E-06	2.9E-06	2.5E-05	2.0E-05	3.7E-05	1.6E-05	1.6E-05	1.1E-06	3.9E-07	1.2E-06	1.2E-06	7.4E-06	8.6E-06
Aquatic eutrophication-N	kg N N-lim e	1.3E-04	5.8E-05	1.8E-04	1.2E-04	2.6E-04	1.0E-04	1.0E-04	5.5E-06	5.2E-06	1.2E-05	2.2E-05	6.0E-05	6.8E-05
Aquatic acidification	kg SO2 eq	1.4E-08	4.5E-09	9.0E-09	5.2E-09	1.3E-08	4.6E-09	4.5E-09	3.8E-10	3.3E-10	1.1E-09	1.3E-09	2.7E-09	3.1E-09
Aquatic ecotoxicity	CTUe	4289.43	2634.97	3261.55	1554.42	4275.52	1392.17	1353.58	322.87	299.59	554.15	1226.29	1423.91	1550.59
Water scarcity	m3 world-eq	1.7E-01	1.5E-01	1.5E-01	8.7E-02	2.2E-01	6.2E-02	6.6E-02	2.3E-02	2.1E-02	3.0E-02	6.9E-02	6.8E-02	7.5E-02