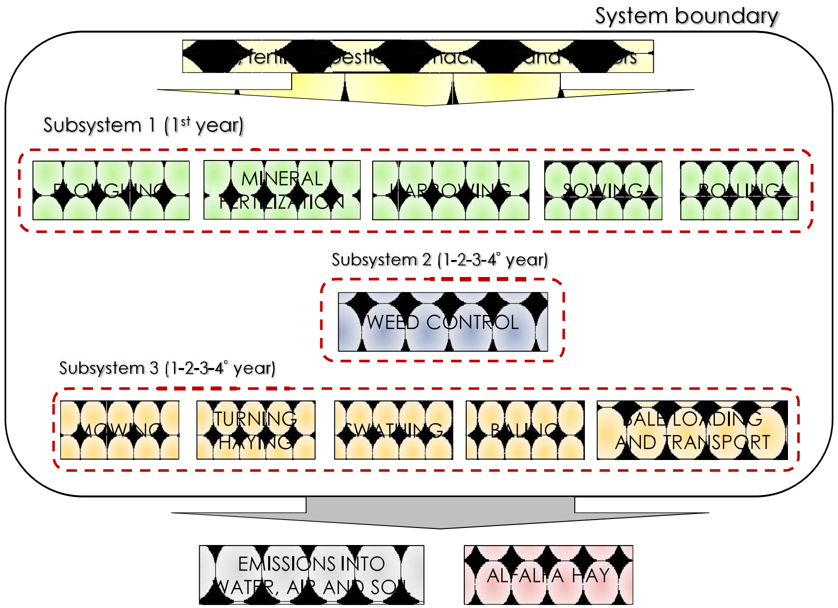
*Graphical Abstract

AIM

→ The environmental impact of alfalfa hay production in Northern Italy is evaluated
→ Two different production practices (Baseline **BS** - without irrigation and Alternative – **AS** with irrigation) were considered

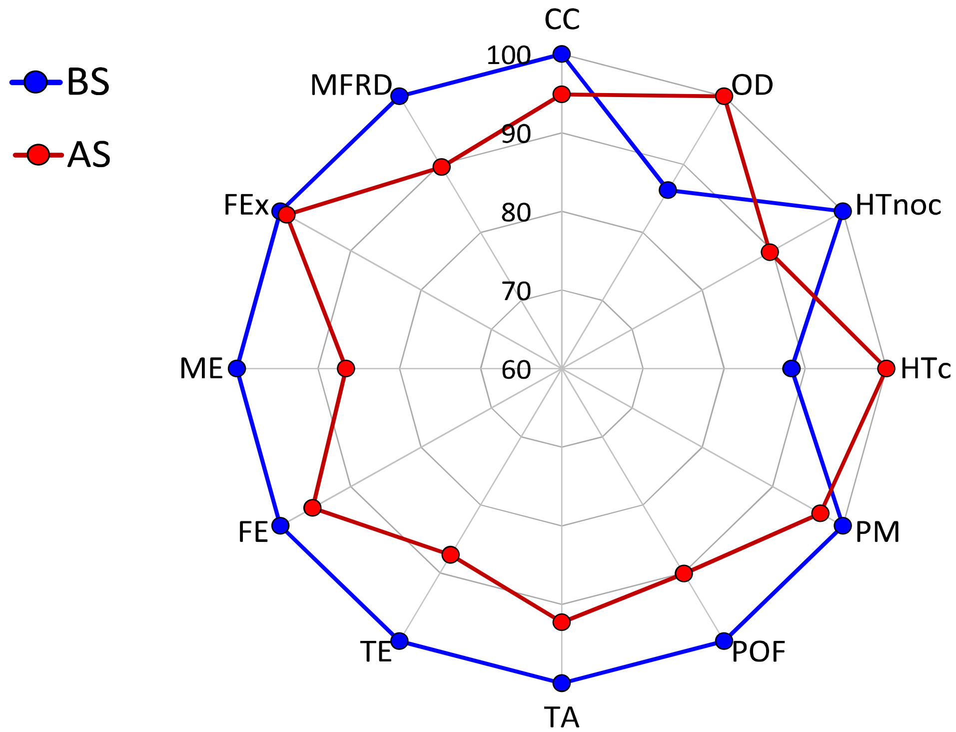
FUNCTIONAL UNIT

1 ton of alfalfa hay



RESULTS

Except for OD and HTc, hay production with irrigation shows lower impacts
For CC impact category, the impact is 84.54 and 80.21 kg CO_2/t of hay for BS and AS



Climate change (CC), Ozone depletion (OD), Particulate matter formation (PM), Human toxicity-no cancer effect (HTnoc), Human toxicity- cancer effect (HTc), Photochemical ozone formation (POF), Terrestrial acidification (TA), Terrestrial eutrophication (TE), Freshwater eutrophication (FE), Marine eutrophication (ME), Freshwater ecotoxicity (FEx), Mineral and fossil resource depletion (MFRD)

***Highlights (for review : 3 to 5 bullet points (maximum 85 characters including spaces per bullet point)**

- There are no studies evaluating the environmental impact of alfalfa hay production
- The environmental impact of alfalfa hay is evaluated using the LCA approach
- Two different production practices without and with irrigation were considered
- Climate Change is equal to 84.54 and 80.21 kg CO_2/t for the two scenarios
- Scenario with irrigation best results for 10 of the 12 evaluated impact categories

Environmental impact assessment of alfalfa (*Medicago sativa* L.) hay production

Jacopo Bacenetti[1*], Daniela Lovarelli[2], Doriana Tedesco[1], Roberto Pretolani[1], Valentina Ferrante[1]

[1]Department of Environmental and Policy Science. Università degli Studi di Milano, Via G. Celoria 2, 20133 Milan, Italy.

[2]Department of Agricultural and Environmental Science. Università degli Studi di Milano, Via G. Celoria 2, 20133 Milan, Italy.

* Corresponding author: jacopo.bacenetti@unimi.it

Abstract

On-farm production of hay and high-protein-content feed has several advantages such as diversification of on-farm cultivated crops, reduction of off-farm feed concentrates transported over long distances and a reduction in runoff during the winter season if grown crops are perennial. Among those crops cultivated for high-protein-content feed, alfalfa (*Medicago sativa* L.) is one of the most important in the Italian context. Nevertheless, up to now, only a few studies have assessed the environmental performance of alfalfa hay production. In this study, using the Life Cycle Assessment approach, the environmental impact of alfalfa hay production in Northern Italy was analyzed. More in detail, two production practices (without and with irrigation) were compared.

The results show that alfalfa hay production in irrigated fields has a better environmental performance compared to non-irrigated production, mainly because of the yield increase achieved with irrigation. In particular, for the Climate Change impact category, the impact is equal to 84.54 and 80.21 kg CO_2/t of hay for the scenario without and with irrigation, respectively. However, for two impact categories (Ozone Depletion and Human Toxicity–No Cancer Effect), the impact of irrigation completely offsets the yield increase, and the cultivation practice without irrigation shows the best environmental performance. For both scenarios, the mechanization of harvest is the main environmental hotspot, mostly due to fuel consumption and related combustion emissions.
Wide differences were highlighted by comparing the two scenarios with the Ecoinvent process of alfalfa hay production; these differences are mostly due to the cultivation practice and, in particular, to the more intensive fertilization in Swiss production.

Keywords: Fodder, Hay, Feed, Life Cycle Assessment, Irrigation

1 Introduction

The environmental impact related to agricultural activities is attracting more attention from policy makers, politicians and stakeholders. Among the different agricultural activities, livestock has by far the most impact due to emissions of pollutants such as methane, ammonia and dinitrogen monoxide released by animals and their produced slurry as well as due to feed consumption (IPCC, 2006; Baldini et al., 2018). To obtain satisfactory milk production, high attention must be paid to the feed. In particular, the consumption of protein feed is often met using soybean produced in South America, which carries considerable impact in terms of greenhouse gas emissions related to land use change and indirect land use change (IPCC, 2013). The on-farm production of high-protein-content feed is highly sought by farmers. However, it is often limited because farmers mostly aim to maximize the production of fodder and silage and buy feed concentrates. Nevertheless, the on-farm production of hay and high-protein-content feed could present several advantages, among which are the diversification of crop cultivation and crop rotations, reduced consumption of feed concentrates transported over long distances and, when perennial crops are grown, the reduction of runoff during the winter season (Bretagnolle et al., 2018).

Among the crops cultivated to produce high-protein-content feed, alfalfa (*Medicago sativa* L.) is one of the most interesting in the Italian context because it is an already commonly cultivated crop adequate to the climatic conditions (Iannucci et al., 2002), it is a legume so it improves the soil quality thanks to the fixation of atmospheric nitrogen and it has a perennial crop cycle that ranges between 3 and 4 years.

For the Northern Italy context, alfalfa plays a key role in the production of one of the most important Protected Designation of Origin (PDO) (Clal, 2018) cheeses. In particular, for the production of Parmigiano Reggiano PDO cheese, only milk produced by cows fed without silages can be used. Thus, alfalfa hay is a key feed. In the last 10 years, the agricultural area dedicated to alfalfa varied from 717,000 ha in 2008 to 672,300 ha in 2018 with a total production ranging from 22.6 to 16.8 Mt of hay (ISTAT, 2018). With regard to price, the average yearly value of alfalfa hay was 109 and 118 €/t of hay in 2016 and 2017, respectively (ISMEA, 2018).

Nevertheless, the production of alfalfa hay presents some critical aspects. For this crop, both the timing of harvest and the harvest process are critical to obtaining hay of desired quality. In fact, high quality alfalfa hay is essential to obtain a high quality feed for cows, measured in terms of its protein and fiber content. To achieve this result, essential steps are to avoid a delayed harvest or the loss of leaves (the plant portion with the higher protein content) during the hay drying process. Finally, the weather conditions during harvesting can deeply affect the quality of the produced hay (Iannucci et al., 2002). Adequate forage quality is essential for animal feed rations and weight gain, high levels of milk production, reproduction efficiency and farm profits. The maximum yield of alfalfa is achieved at the stage of full flowering, whereas quality is the highest prior to flowering. Thus, a trade-off between quality and quantity is at the basis of alfalfa hay production (Undersander et al., 1994).

To improve the quality of hay and, in particular, to reduce product and quality losses during harvesting, over the years more adept machines have been developed. In particular, the use of a mower-conditioner with full-width conditioning rollers that crush alfalfa stems speeds up the drying process (Summers et al., 1998). Thanks to the conditioning, product losses (in particular of leaves) are steeply reduced, also because conditioning allows for faster hay drying—within the same weather conditions of a traditional mower—and the correct moisture content for baling can be reached with a lower number of hay turnings.

Despite the great interest in on-farm production of protein-rich feed, up to now only a few and partial studies (Gallego et al., 2007; Little et al., 2017; Parajouli et al., 2017) have been carried out with the purpose of assessing the environmental performance of alfalfa hay production. In this context, the aim of this study is to assess the environmental impact of alfalfa hay production considering primary data collected over 4 years on a farm where alfalfa hay is produced according the guidelines for

Integrated Agriculture (Regione Lombardia, 2018). With regard to irrigation, two different production practices were considered: without and with irrigations.

2 Materials and methods

The Life Cycle Assessment (LCA) method was applied to perform the evaluation of the environmental impact. LCA is a holistic approach that uses a systematic set of procedures to convert the inputs and outputs of materials and energy that characterize a process into the associated environmental impact. Specifically, in this study, the ISO standard 14040/44 methodology (ISO, 2006) and the Product Category Rules (PCR) guidelines developed for "Arable Crops" (Environdec, 2014) were followed, and the attributional approach was used to model the alfalfa hay production process.

According to ISO 14040/44 (ISO, 2006), a LCA involves four distinct and interdependent phases:

i) goal and scope, which includes functional unit selection and system boundary definition;

ii) life cycle inventory, which involves the definition of energy and material flows between the system and the environment and through the different subsystems and operations of the evaluated system;

iii) impact assessment, during which the inventory data are converted in environmental indicators; and

iv) discussion and interpretation of the results, where the results from the inventory analysis and impact assessment are summarized, sensitivity and uncertainty analysis are carried out and recommendations are given.

2.2 Description of crop cultivation

As mentioned above, alfalfa (*Medicago sativa* L.) is one of the most widespread fodder crops in Italy; in the eastern part of the Po river valley (a plain area located in Norther

Italy), besides to meadows, it represents the main crop for hay production in dairy farms.

The cultivation practice, carried out in accordance with the principles of integrated agriculture (Regione Lombardia, 2018), takes place over 4 years and includes several operations; these operations have been broken down into three subsystems:

Subsystem A: soil tillage and sowing. Primary tillage is performed with a moldboard plow (35 cm deep), while secondary tillage involves an intervention with a rotary harrow (10 cm deep). The sowing is performed using a mechanical universal seeder (45 kg/ha of seed). After the sowing, to help seed germination, a rolling is carried out.

Subsystem B: crop management. In contrast to other fodder crops or to cereal cultivation for silage production, the cultivation practice of alfalfa involves only one application of herbicide (2 kg/ha) per year. This occurs mainly to prevent the growth of other meadow plants that may affect alfalfa protein quality. During the first year of the crop cycle, fertilization with urea (30 kg of N/ha) is also performed; during the following years, in order to enhance N-fixation from the crop, no additional fertilization is performed. Moreover, no irrigation is scheduled.

Subsystem C: harvesting and transport operations. Harvesting takes place 5 times per year from May to October and is carried out using different machines. Each harvest is conducted by 1) mowing, carried out with a mower-conditioner; 2) swathing, carried out with a rake; 3) hay turning, carried out with a rotary tedder; 4) baling, performed using a round baler; 5) transport of the hay bales at the farm using a tractor coupled with a front loader and a farm trailer. Considering an average of 3 days for on-field hay drying, for each harvest mowing and baling take place 1 time while swathing and turning take place 3 and 2 times, respectively. The mowing was carried out at a speed of 6-8 km/h to have adequate conditioning and optimize drying while minimizing shattering and leaf loss. Under-conditioning increases the risk of rain damage, while over-conditioning increases cutting, raking and baling losses.

2.1 Goal and scope definition

The goal of this study is to assess the environmental impact of alfalfa hay production in Northern Italy and, in particular, in the Lombardy region, which is the most important Italian region for dairy production (40% of Italian milk production takes place in Lombardy).

The alfalfa cultivation performed according the Guidelines for Integrated agriculture (Regione Lombardia, 2018) was evaluated by means of LCA. The farm was selected because it is one of the experimental farms where field tests on different fodder crops are carried out following the guidelines for integrated agriculture (Regione Lombardia, 2018). On this farm, alfalfa has been cultivated for several years and several cropping cycles; in 2017, 45 fields were grown with alfalfa, contributing to a global agricultural area of 30 ha (average dimension per field 0.7 ha).

The cultivation practice is also quite standardized in its traditional conformation, although mechanical improvements can still be suggested. In particular, alfalfa hay has different haying requests with respect to other meadow hays due to the need to preserve protein content and hay quality by paying attention mainly to the plant leaves. The research questions are as follows:

- How much is the environmental impact related to the production of 1 ton of alfalfa hay?
- What are the environmental hotspots for the evaluated process?
- Considering alfalfa hay, are the processes involved in the Ecoinvent Database[1] representative of the Italian context?

The outcomes of this study will be useful to LCA practitioners because they represent the first results of a full environmental impact assessment of alfalfa cultivation, in particular in a Mediterranean region where hay is produced instead of silage.

[1] The Ecoinvent Database is an international database for LCA studies. Produced by the Ecoinvent Centre, it is one of the world's leading life cycle inventory data sources and provides documented process data for thousands of products (https://www.ecoinvent.org/).

2.3 Functional unit

Among the different steps defined by the ISO standards, selection of the functional unit (FU) is crucial to allow fair comparison with previous studies. According to ISO 14040 (ISO 14040, 2006), the functional unit is defined as the quantified performance of a product system, and it is used as a reference unit in an LCA. Over the years, concerning the agricultural processes the following functional units have usually been selected:

- Mass-based FU, such as the mass of grain (Noya et al., 2015; Renzulli et al., 2015; Fusi et al., 2017), fruit (Nikkhah et al., 2017; Ingrao et al., 2014; Bernardi et al., 2018), milk (Bacenetti et al., 2016; Baldini et al., 2017; Vida et al., 2017) and meat (Meier et al., 2015; Bava et al., 2017);
- Area-based FU; usually for agricultural processes 1 ha is considered (Lovarelli et al., 2017a; Lovarelli et al., 2017b);
- Energy-based FU, such as i) the energy produced (e.g., electricity from biogas; Lijò et al., 2014; Lijò et al., 2015; Lijò et al., 2017) and ii) the energetic value of the product (Pierobon et al., 2015; Bacenetti et al., 2017).

In this study, consistently with PCR for "Arable Crops" (Environdec, 2014) as well as with other LCA analyses focused on hay and fodder production (Cederberg et al., 2000; Nemececk et al., 2011; Zucali et al., 2018), 1 ton of alfalfa hay (at moisture of 14%) was chosen as the FU.

2.4 System boundary

During system boundary definition, the processes included or excluded from the analysis are identified. In this study, a "cradle to farm gate" perspective was adopted. For the three sections, the life cycle of each agricultural process was included within the system boundary. Consequently, the following activities were included: raw materials extraction (e.g., fossil fuels, metals and minerals), manufacture of the agricultural inputs (e.g., seed, fertilizers and agricultural machines), use of the agricultural inputs (fertilizer emissions, diesel fuel emissions and tire abrasion emissions), maintenance and final disposal of tractors and operative machines. The system boundaries of the studied alfalfa hay production system are reported in **Figure 1**.

Figure 1 – Around here

In regard to the emissions related to crop cultivation, different emission sources were considered: emissions of N and P compounds related to ammonia volatilization, denitrification, nitrogen leaching and runoff as well as emissions related to fuel combustion. According to the PCR "Arable Crops" guideline (Environdec, 2014), no change in the soil organic carbon content was considered.

2.4.1 Alternative scenario

Alfalfa is usually cultivated without irrigation. Nevertheless, in recent years use of irrigation has spread in order to reduce the negative consequences of summer drought and thus increase yield.

Therefore, an alternative scenario (AS) was considered: besides the baseline (BS) described in the previous subchapter 2.2, the production of alfalfa hay in irrigated fields was considered. In the AS, irrigation (150 m^3) was carried out with a sprinkler irrigator coupled with a 90 kW tractor after each harvesting, excluding the last cut. No differences in the chemical and physical characteristics were taken into account for the hay produced in the two scenarios.

2.5 Inventory

Primary inventory data regarding crop cultivation were collected via surveys at the farm and questionnaires with the farmer. Specifically, a data sheet for the questionnaire was developed that includes the following sections:

- Section 1 – Cultivation practice includes information about timing and the number of repetitions of the different field operations;

- Section 2 – Field operation includes for each field operation information about the operative machines (size, mass, length and width, required power, age, annual average working time, life span) and tractors (power, mass, exhaust gases emissions stage, age, annual working time, life span) used;
- Section 3 – Inputs includes information about the different production factors consumed (fuel, pesticides, fertilizers, etc.). The diesel fuel consumption was directly measured with the "full-tank method" (Lovarelli et al., 2016) during surveys on the fields.

The amount of tractors and agricultural equipment depleted for each field operation was calculated considering the annual working time and the physical and economic life span. According to Lovarelli and Bacenetti (2017), physical life span (h) was considered equal to 12,000 h for tractors; 2,000 h for plow, harrow, seeder and fertilizer spreader and 3,000 h for farm trailers. Concerning the economic life span (years), 12 years were taken into account for tractors, farm trailers and spreader; 8 years for plow, harrow, fertilizer spreader and seeder (Bodria et al., 2006). **Table 1** reports the main inventory data adopted in the analysis.

Table 1 – Around here

Concerning the background data, information regarding the production of seeds, diesel fuel, urea, pesticides, tractors and agricultural machines was retrieved from the Ecoinvent Database v.3 (Weidema et al., 2013).

For the AS, diesel fuel consumption equal to 17 kg/ha per each irrigation was estimated according to Lovarelli et al. (2016). According to Jia et al. (2006), Almarshadi et al. (2011), Ismail et al. (2013), Iannucci et al., (2002) and Regione Lombardia (2018), an average increase of hay yield equal to 20% was considered.

Emissions due to fertilizer applications were evaluated considering soil type, climatic conditions and type of fertilizer. Nitrogen emissions (nitrate leaching, ammonia volatilization and nitrous oxide from denitrification) were estimated following the model proposed by Brentrup et al. (2000). Specifically, NH_3 volatilization, emissions of N_2O and NO_3 leaching were assessed considering the soil characteristics (texture, pH, CEC), climate (temperature, wind, precipitation) and the type of fertilizers. According to Zucali et al. (2018), for alfalfa hay the following characteristics were considered: neutral detergent fiber[2] 52%, crude protein[3] 15.5%, net energy for lactation 3.9 MJ/kg of dry matter and digestible protein in the small intestine when rumen-fermentable nitrogen is the limiting factor 102 g/kg of dry matter. Phosphate emissions were calculated following Prahsun (2006) and Nemecek and Kägi (2007) considering leaching to the groundwater (assessed using a factor of 0.06 kg $P \cdot ha^{1} \cdot year^{-1}$) and runoff to surface water (evaluated considering 0.175 kg $P \cdot ha^{-1} \cdot year^{-1}$ as emission factor). Phosphate emissions through erosion to surface waters were not included because erosion was considered equal to zero thanks to the crop presence that avoids bare soil.

Table 2 reports the different Ecoinvent processes considered in the analysis as well as the modifications done.

Table 2 – Around here

2.7 Life Cycle Impact Assessment (LCIA)

During LCIA, inventory data are converted into a reduced number of environmental indicators using specific characterization factors. In this study, using the ILCD (International Reference Life Cycle Data System) midpoint method (Wolf et al., 2012), the LCIA method endorsed by the European Commission, the following impact categories were evaluated:

[2] Neutral detergent fiber (NDF) is the percentage of cell walls or fiber in a feed that is digested in a specified time (usually 24, 30 or 38 hours). NDF is inversely related to animal intake and the energy that an animal can derive from a feedstuff (Undersander et al., 1994).

[3] Crude protein (CP) is a mixture of true protein and non-protein nitrogen. It is determined by measuring total nitrogen and multiplying this number by 6.25. Crude protein content indicates the capacity of the feed to meet an animal's protein needs. Generally, moderate to high CP is desirable since this reduces the need for supplemental protein. Forage cut early or with a high percentage of leaves has a high CP content (Undersander et al., 1994).

- Climate Change (CC, expressed as kg CO_2 eq.),
- Ozone Depletion (OD, expressed as kg CFC-11 eq.),
- Particulate Matter Formation (PM, expressed as kg PM2.5 eq),
- Human Toxicity–No Cancer Effect (HTnoc, expressed as CTUh),
- Human Toxicity–Cancer Effect (HTC, expressed as CTUh),
- Photochemical Ozone Formation (POF, expressed as kg NMVOC eq.),
- Terrestrial Acidification (TA, expressed as molc H+ eq.),
- Terrestrial Eutrophication (TE, expressed as molc N eq.),
- Freshwater Eutrophication (FE expressed as kg P eq.),
- Marine Eutrophication (ME, expressed as kg N eq.),
- Freshwater Ecotoxicity (FEx, expressed as CTUe),
- Mineral and Fossil Resource Depletion (MFRD, expressed as kg Sb eq.).

3 Results and Discussion

3.1 Baseline scenario

Table 3 reports the environmental impact of alfalfa hay production as well as the relative contribution of the three subsystems. Among the three subsystems, although subsystem A – soil tillage is carried out only once during the crop cycle, it is responsible for a share of the environmental impact ranging from 6.4% in HTnoc to 39.9% in FE. Subsystem C – harvesting is by far the most important subsystem, and its contribution ranges from 59.4% in FE to 92.9% in HTnoc. Finally, only a small share of the impact is related to subsystem B – crop management; in more detail, this subsystem accounts for more than 1% of the total impact only in OD and FEx, mostly because of pesticide emissions into the soil.

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Table 3 – Around here

The relative contributions to the impact of each input and output are shown in **Figure 2**.

For all of the 12 evaluated impact categories, mechanization of field operations is by far the main environmental hotspot. Consumption of production factors such as seed, urea and pesticide is always responsible for less than 10% of the impact for all the evaluated impact categories, except for PM (11%, of which about 80% is due to urea production) and ME (21%, of which about 96% is due to urea production).

Among the different mechanized field operations, the turning of hay, with an impact ranging from 21% in FE to 38% in HTnoc, is the most impacting operation, followed by swathing (from 17% in CC and ME to 25% in HTnoc and MFRD). For the different field operations,

- the production of diesel fuel is the most important hotspot for OD (from 60% to 75% of the impact);
- the emissions related to diesel fuel combustion, with a share of the total impact higher than 50%, are the main contributors for CC, HTnoc, POF, TA, TE and ME;

the manufacture, maintenance and disposal of the tractor are the main responsible (>85%) for MFRD.

Figure 2 – Around here

To test the robustness of the results and investigate the effect of key assumptions, the hay yield and distance between the fields and the farm were considered for the sensitivity analysis. For hay yield, the minimum and maximum yields recorded at the farm over a 12-years period were considered, first assuming the minimum (9.40 t/ha at commercial moisture) and then the maximum (12.79 t/ha at commercial moisture). Concerning the transport distance, an increase from 0.2 to 5 km was considered.

The results of the sensitivity analysis, reported in **Table 4**, highlight how the environmental results are affected deeply by alfalfa hay yield but only slightly by the transport distance.

The impact categories more affected by the increase in the transport distance are the human-toxicity impacts, mainly due to the emissions of pollutants related to the consumption of diesel during transport.

Table 4 – Around here

3.2 Comparison between BS and the AS

Figure 3 shows the comparison between the two scenarios, baseline and alternative, in which irrigation is carried out and a higher hay yield is achieved. Except for OD and HTc, for all other evaluated impact categories, hay production with irrigation shows a lower environmental impact. Thanks to the yield increase, the AS shows an impact reduction ranging from 1% for FEx to 13% for ME. On the contrary, due to irrigation, the AS presents a higher impact for HTc (+13.2%, mainly due to the manufacture and maintenance of the agricultural machine and, in particular, to the consumption of cast iron) and OD (+16.0%, mainly due to the diesel fuel consumed during irrigation). For OD and HTc, the increased impact related to irrigation completely offsets the environmental benefits related to the yield increase.

Figure 3 around here

An uncertainty analysis was carried out with the Monte Carlo technique (1,000 iterations and a confidence interval of 95%) to test the robustness of the achieved results in regard to the comparison between the two scenarios. **Figure 4** reports these results. The bars on the left represent the probability that the environmental impact of BS is lower than AS, while those on the right mean the opposite (the environmental impact of hay production in BS is higher than that of hay produced in an irrigated field). Except for FEx, for all the other evaluated impact categories there is a reduced uncertainty level. In particular, for almost all impact categories, BS has a higher impact than AS with a level of statistical significance higher than 85%; similarly, the level of statistical significance related to the case that BS has a lower impact than AS is almost 100% for OD and HTc. Thus, these results show that the uncertainty due to selection of the data source, model imprecision and variability of data does not significantly affect the results.

Figure 4 – Around here

Considering the environmental impact quantified for the AS, its process hotspots are reported in **Figure 5**. The impact of irrigation is lower than 15% for all the evaluated impact categories except for OD (29%), HTc (27%) and FEx (16%). Although the impact is completely offset by the yield increase, irrigation involves a non-negligible impact, and attention must be paid to guaranteeing the overall environmental sustainability of alfalfa hay production.

Figure 5 – Around here

3.3 Comparison with the database process

Figure 6 shows the comparison between the two alternative scenarios and the Ecoinvent process for alfalfa hay production. The Ecoinvent process for alfalfa production in Switzerland refers to integrated production without irrigation and is characterized by a yield of 11.75 t/ha (moisture content 85%) for an average production period of 3 years.

For some impact categories such as CC, HTnoc, FEx and MFRD, the differences among the three processes for hay production are reduced (about 10%), whereas for the other evaluated impact categories the differences are wider. For TA, TE and FE, the hay production in Italy achieves a considerable impact reduction (58-80%) compared to the Ecoinvent process. On the contrary, for OD and POF, which are impact categories affected by the consumption of diesel fuel, the impact of BS and AS is higher compared to the Ecoinvent process. In particular, for the Climate Change impact category, the impact is 84.54 and 80.21 kg CO_2/t of hay for the scenario without and with irrigation, respectively, and 84.85 kg CO_2/t for the integrated production in Switzerland.

Figure 6 – Around here

The main impact differences between the alfalfa production in Switzerland from integrated agriculture and the production in Italy are related to the different aspects of crop cultivation. For the impact categories (TA, TE, FE and ME) affected by the emissions of N and P compounds into the atmosphere, the two Italian scenarios show considerably better performances due to reduced fertilizations during the crop cultivation (50 kg/ha of urea in Italy compared to 50 kg/ha of P2O5 from mineral fertilisers, 15.7 t/ha of animal slurry and 7.8 t/ha of manure in Switzerland). For OD and POF, the Ecoinvent process shows a lower impact respect to AS (-55% for OD and - 45% for POF) mainly due to lower fuel consumption during harvesting performed with only one intervention using a mower followed by a self-loading trailer.

4 Conclusions

The alternative scenario shows better environmental performance compared to the baseline, mainly because of the yield increase achieved thanks to irrigation, even if irrigation and its related impact must be accounted for. Therefore, when water is available for irrigation, the production of alfalfa hay in irrigated fields should be preferred to production without irrigation.

With respect to the process involved in the Ecoinvent Database (integrated production in Switzerland), wide differences were highlighted. These differences were partially due to the different yields but mainly to the different cultivation practices, in particular with regard to fertilization and the related emissions.

Finally, alfalfa being a legume, future research activities should consider that alfalfa cultivation could involve interesting benefits for its nitrogen-fixing capability and the improvement of soil quality. Although these last suggestions are difficult to measure with the impact categories currently available, their role should not be omitted from evaluations. Moreover, for a whole evaluation of the environmental consequences related to alfalfa hay production, the following aspects should be evaluated: additional irrigation systems and benefits related to the improvement of soil quality (e.g., by considering the possible increase in soil organic carbon content). Concerning the LCA methodological choices, functional units more strictly related to the chemical and physical characteristics of hay (e.g., crude protein) should be considered besides the mass-based FU.

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TABLE

Table 1 – Inventory data

FIELD OPERATION	**YEAR**	**REP.**	**TRACTORS** (power & mass)	**OPERATIVE MACHINE**	**TIME** ($h \cdot ha^{-1}$)	**PRODUCTION FACTORS**
Ploughing	1	1	75 kW 4450 kg	3-furrows plough, 35 cm deep	1.5	22 kg $\cdot ha^{-1}$ of diesel
Harrowing	1	1	75 kW 4450 kg	Rotary harrow, 3 m wide, 10 cm deep	1.0	18 kg $\cdot ha^{-1}$ of diesel
Sowing	1	1	40 kW 2200 kg	Mechanical seeder 3 m wide	0.8	3.2 kg $\cdot ha^{-1}$ of diesel 45 kg $\cdot ha^{-1}$ of seed
Rolling	1	1	40 kW 2200 kg	Roll, 3 m wide	0.5	3.2 kg $\cdot ha^{-1}$ of diesel
Weed management	1,2,3	1	40 kW 2200 kg	Sprayer, 600 dm^3, 15 m wide	0.5	2.2 kg $\cdot ha^{-1}$ of diesel 2 kg kg $\cdot ha^{-1}$ of erbicide (3.7% imazamox)
Mowing	1,2,3	5	62.5 kW 3800 kg	Mower-conditioner, 3 m wide	0.65	5.5 kg $\cdot ha^{-1}$ of diesel
Turning	1,2,3	15	40 kW 2200 kg	Rake, 5.5 m wide	0.35	2.3 kg $\cdot ha^{-1}$ of diesel
Swathing	1,2,3	10	40 kW 2200 kg	Windrower	0.35	2.1 kg $\cdot ha^{-1}$ of diesel
Bailing	1,2,3	5	75 kW 4450 kg	Round baler	0.55	0.2 kg $\cdot bale^{-1}$ of diesel
Transport	1,2,3	5	62.5 kW 3800 kg	Farm Trailer	0.5 h	0.2 km of distance

Table 2 – Ecoinvent processes used for the environmental modeling

PROCESS	USED FOR	CHANGES
Tillage, ploughing {CH}| processing | Alloc Def, U	Ploughing	Modified considering the different fuel consumption and working times
Tillage, harrowing, by rotary harrow {CH}| processing | Alloc Def, U	Harrowing	
Sowing {CH}| processing | Alloc Def, U	Sowing	
Tillage, rolling {CH}| processing | Alloc Def, U	Rolling	
Application of plant protection product, by field sprayer {CH}| processing | Alloc Def, U	Weed management	
Fertilising, by broadcaster {CH}| processing | Alloc Def, U	Mineral fertilization	
Mowing, by rotary mower {CH}| processing | Alloc Def, U	Mowing	
Haying, by rotary tedder {CH}| Alloc Def, U Turning	Turning	
Swath, by rotary windrower {CH}| processing | Alloc Def, U	Swathing	
Bale loading {CH}| processing | Alloc Def, U	Bale loading on the trailer	
Baling {CH}| processing | Alloc Def, U	Bailing	Modified considering the different fuel consumption and working times, consumption of plastic film excluded
Transport, tractor and trailer, agricultural {CH}| processing | Alloc Def, U	Transport from field to the farm	n/a
Clover seed, Swiss integrated production, at farm {CH}| production | Alloc Def, U	Alfalfa seed	Modified considering the average seed yield of alfalfa
[sulfonyl]urea-compound {GLO}| market for | Alloc Def, U	Herbicide (3.7% imazamox)	n/a
Urea, as N {GLO}| market for | Alloc Def, U	Mineral fertilization	n/a
Irrigation {CH}| processing | Alloc Def, U	Irrigation in AS	Modified considering the different fuel consumption and 150 m^3/ha of water for each irrigation

Table 3 – Absolute results for the FU and relative contribution of the three subsystems

Impact category	Score	Contribution to the different subsystems (%)		
		S1	S2	S3
CC	84.54 kg CO_2 eq	16.35	0.64	83.02
OD	11.20 mg CFC^{-11} eq	15.24	1.27	83.49
HTnoc	$1.17 \cdot 10^{-4}$ CTUh	6.42	0.69	92.89
HTc	$5.36 \cdot 10^{-6}$ CTUh	15.93	0.76	83.31
PM	67.85 g PM2.5 eq	18.81	0.70	80.49
POF	0.795 kg NMVOC eq	10.08	0.54	89.38
TA	0.794 molc H+ eq	19.56	0.64	79.80
TE	3.10 molc N eq	18.99	0.47	80.54
FE	26.52 g P eq	39.90	0.68	59.43
ME	352.72 g N eq	34.53	0.43	65.04
FEx	516.79 CTUe	12.01	2.30	85.69
MFRD	16.08 g Sb eq	8.32	0.76	90.92

Table 4 – Results of the sensitivity analysis for hay yield and transport distance

IMPACT CATEGORY	Yield		Transport 5 km
	MIN	MAX	
CC	7.7%	-14.6%	2.2%
OD	8.3%	-15.7%	1.8%
HTnoc	8.6%	-16.2%	4.3%
HTc	8.1%	-15.3%	3.7%
PM	7.9%	-15.0%	2.6%
POF	8.1%	-15.2%	1.7%
TA	8.2%	-15.5%	1.9%
TE	8.4%	-15.8%	1.6%
FE	8.8%	-16.5%	2.0%
ME	8.7%	-16.4%	1.3%
FEx	8.3%	-15.7%	3.0%
MFRD	8.4%	-15.8%	1.6%

FIGURE CAPTIONS

Figure 1 – System boundary for alfalfa hay production

Figure 2 - Hotspot identification for BS (no irrigation)

Figure 3 – Relative comparison between BS and AS

Figure 4 – Results of the uncertainty analysis

Figure 5 – Environmental hotspot identification of the AS (with irrigation)

Figure 6 – Comparison among the two evaluated scenarios for alfalfa hay production in Italy and the Ecoinvent process for alfalfa production in Switzerland from integrated agriculture.

Figure 1

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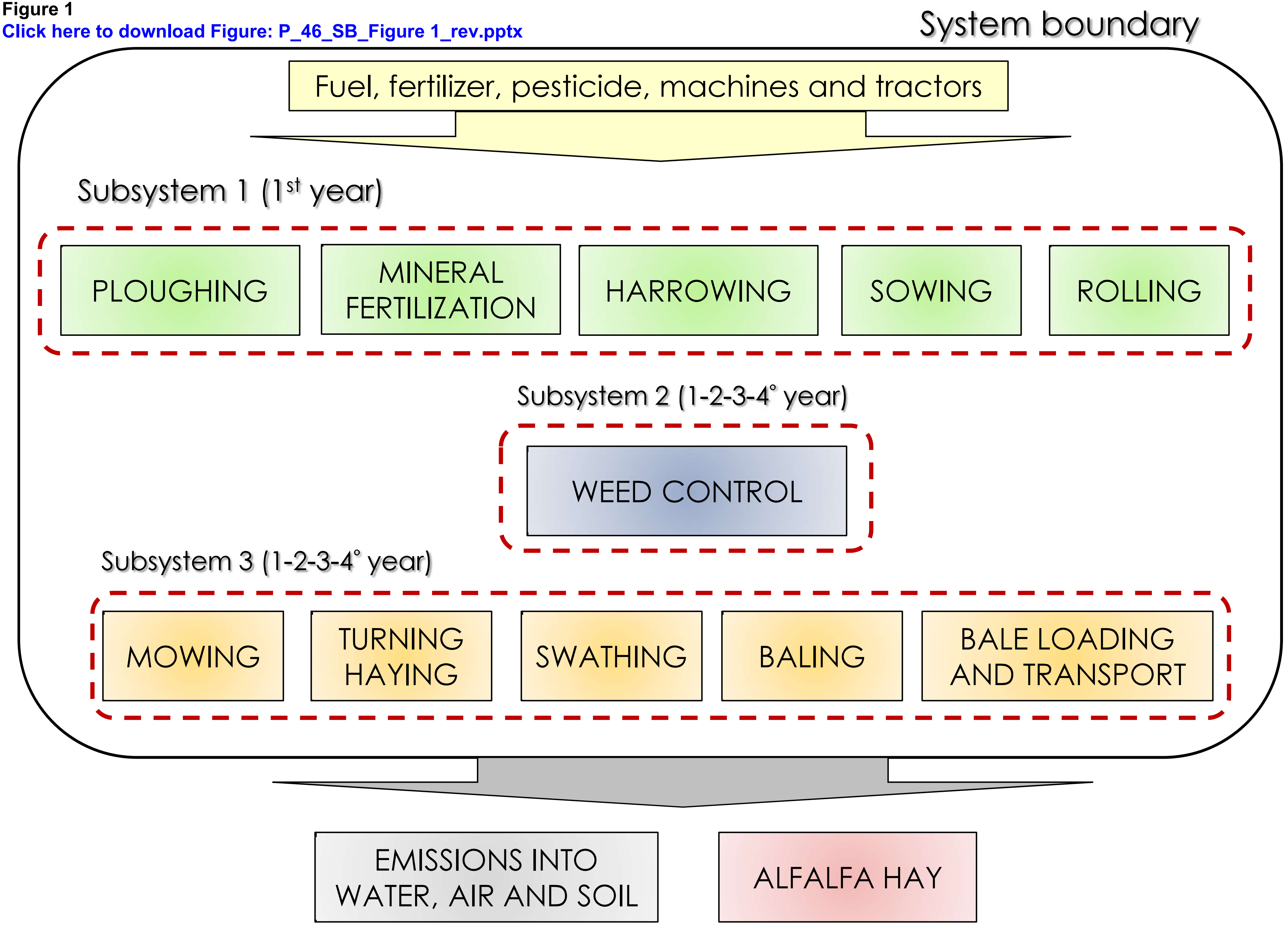

Figure 2

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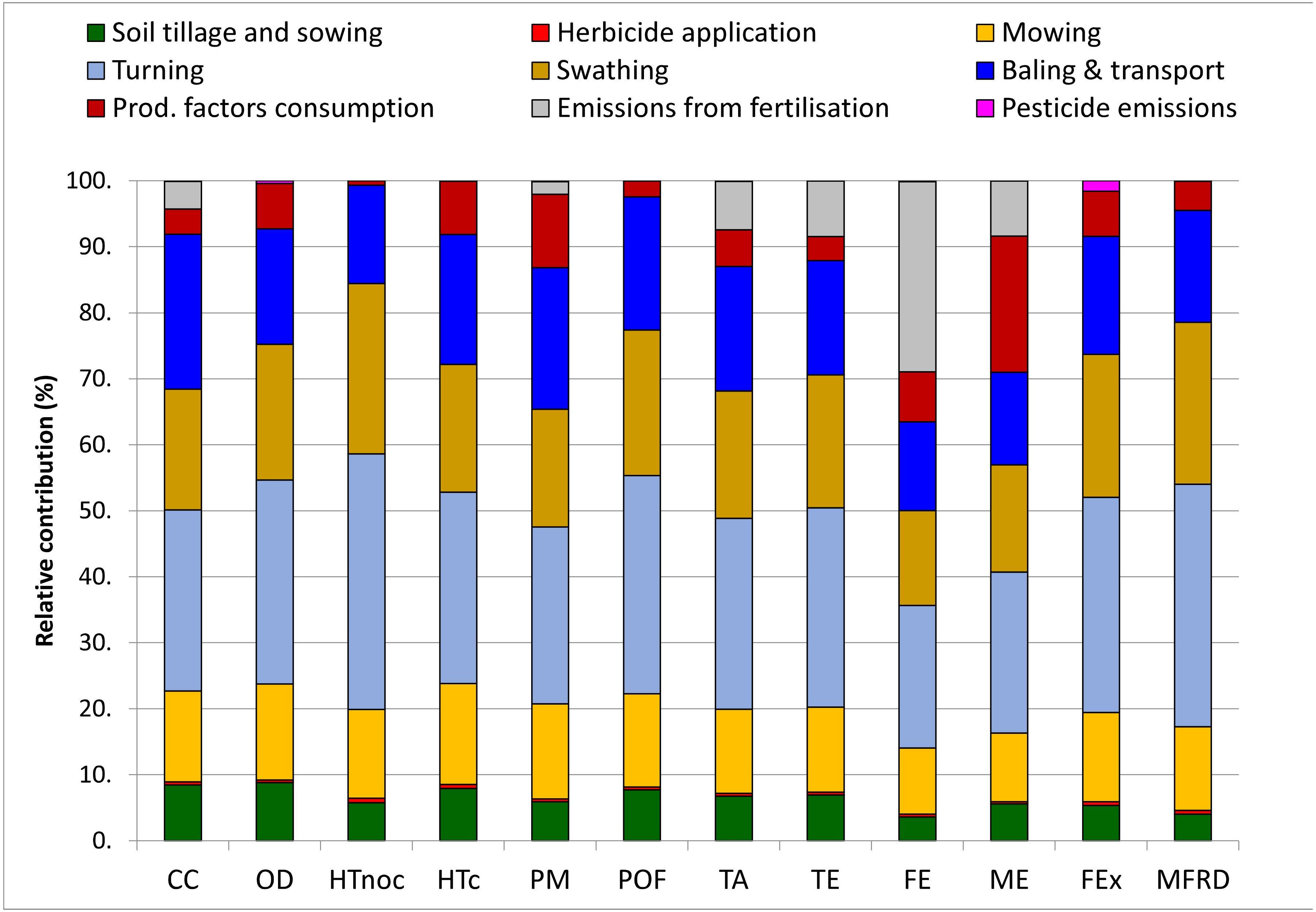

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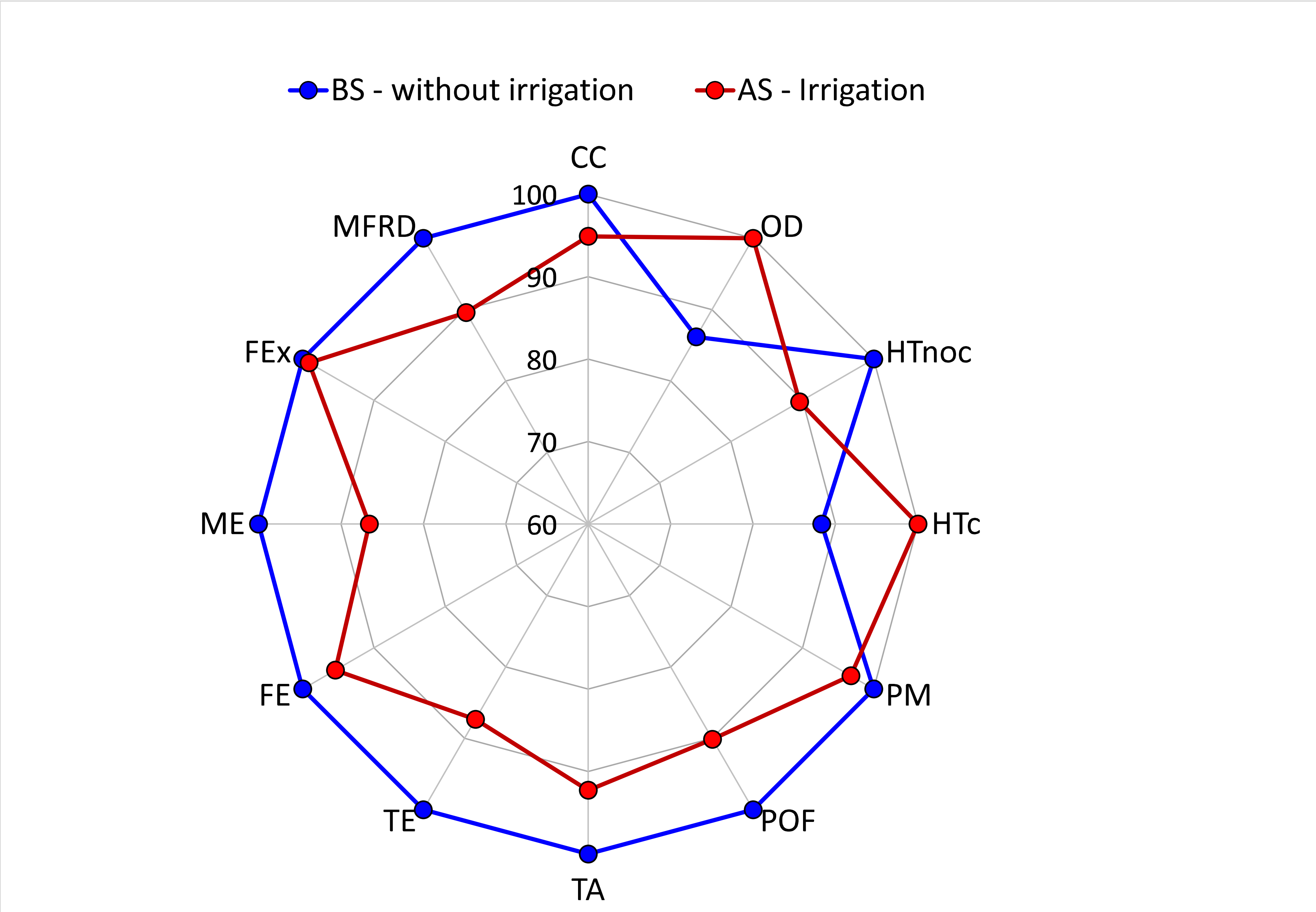

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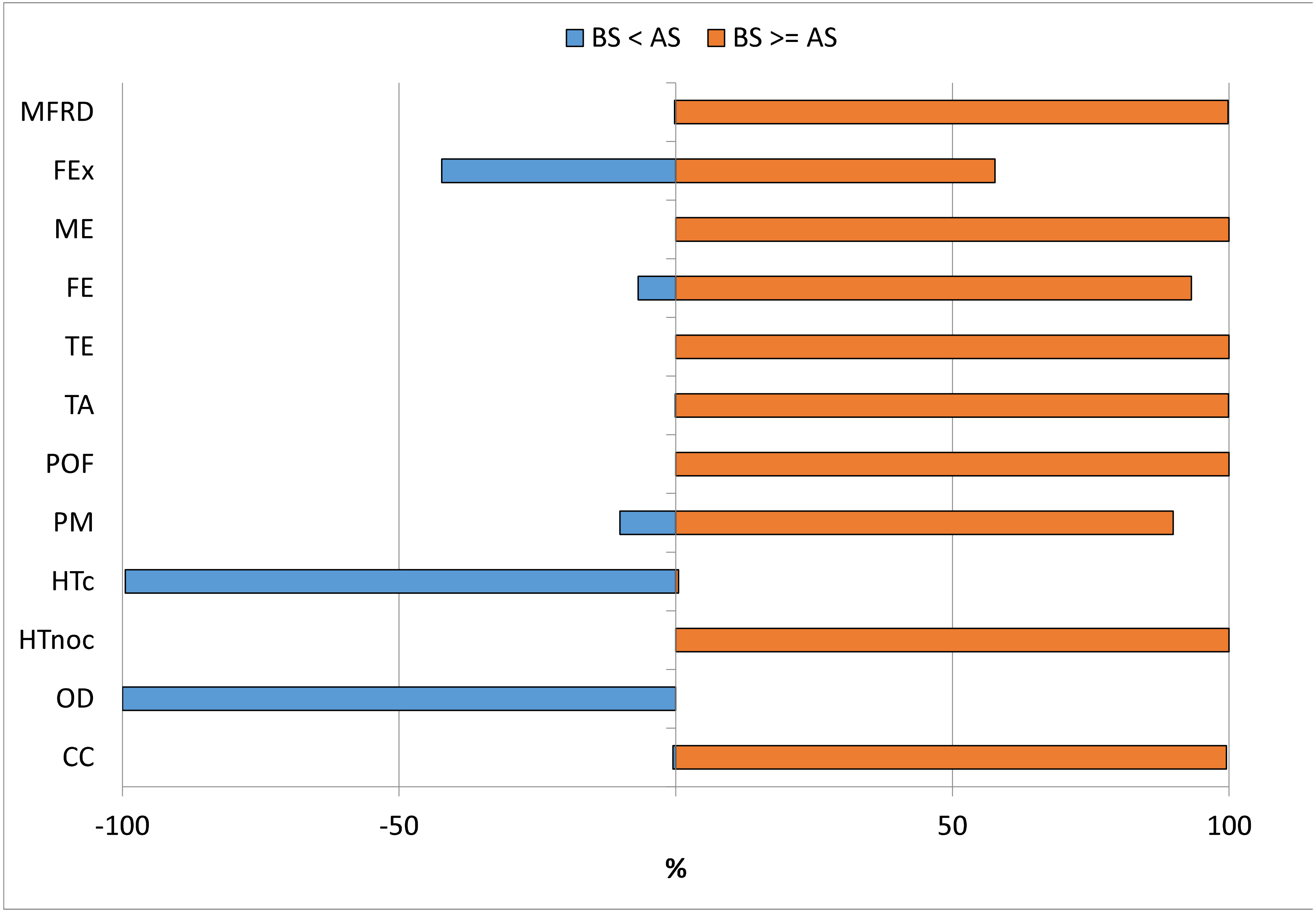

Figure 5

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