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PAPER



Partial replacement of soybean meal with soybean silage and responsible soybean meal in lactating cows diet: part 2, environmental impact of milk production

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ABSTRACT

Soybean meal, the main protein source for livestock in Italy, is associated with high environmental impact in terms of land use change. Thus alternative protein sources are advisable. The study aimed to evaluate through a Life Cycle Assessment (LCA) approach the environmental impact of milk production systems characterised by different diets of lactating cows including different sources of soybean. Four scenarios were identified: (1) conventional soybean meal (CON), (2) conventional soybean meal and soybean silage (SBS), (3) responsible soybean meal defined by the FEFAC guidelines (CON + RSM), (4) soybean silage and responsible soybean meal (SBS + RSM). Inventory data were derived from a previous *in vivo* trial on lactating cows and farmer interviews. Secondary data were obtained from the Ecoinvent® and the Agri-footprint databases. The LCA was performed using the SimaPro V 8.3. Soybean silage showed higher global warming potential (GWP), marine eutrophication and human toxicity compared with lucerne hay, the most utilised self-produced protein feed, due to the high contribution of mechanical operations in the field. The GWP of milk (kg CO₂eq/kg FPCM) decreased from 1.38 of the CON scenario to 1.17 of SBS and 1.13 of CON + RSM; the best result was obtained by combining soybean silage with responsible soybean meal: 1.01. Furthermore, the scenarios using RSM reduced agricultural land occupation and natural land transformation. The inclusion of SBS and RSM is an interesting option to reduce environmental impact of milk production, maximising yields of DM and CP per hectare and representing an alternative protein source.

HIGHLIGHTS

- The ration of dairy cows represents one of the main causes of the environmental impact of the livestock sector due to the impact for feed production (forage and concentrate)
- Feeding soybean meal as protein source has high environmental impact since it is linked with deforestation in South America
- Alternative protein sources like soybean silage and soybean meal produced sustainably could reduce the environmental impact of the sector

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Introduction

According to the international bibliography (e.g. Lovarelli et al. 2019; Laca et al. 2020), the main cause of greenhouse gas (GHG) emissions at the dairy farm level is enteric fermentation, followed by feed production and manure management. Feed emission is, precisely, the second largest category of emissions, contributing about 36% to milk emissions (Gerber et al. 2013). Regarding feed production, the trend in Northern Italy is to satisfy the energy requirement of the herd through the self-production of whole-plant maize silage (Gislón et al. 2020a) while purchasing

protein sources from the market (Borreani et al. 2013), in particular, soybean meal. The use of soybean meal is positively correlated to the environmental impact of the ration (Gislón et al. 2020a), mainly for its geographical origin. According to ASSALZOO (2019) data, 50% of soybean meal used in Italy is imported, and 33.8% is produced locally from imported seeds, mainly from Argentina, the USA, and Brazil. The other 16.2% is produced from Italian soybean (Eurostat 2020).

Soybean is grown in South America on former virgin lands. In Argentina and Brazil it was estimated that 9% and 15.6% of the new soybean area was

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associated with deforestation, respectively (Malins 2020), clearing forests and savannahs in Argentina, and the Amazon forest and Cerrado in Brazil, with loss of biodiversity and C stock in the soil (Bickel and Dros 2003). Decreasing the use of soybean meals, thus, may be considered as an effective strategy to enhance the sustainability of the dairy cow livestock system (Gislon et al. 2020a) and, in this regard, the use of self-produced high protein forages could reduce the reliance of farms on imported soybean meal (Tabacco et al. 2018). Furthermore, on-farm legumes cultivation, in rotation with grain crops, has other environmental benefits, in particular, the potential to reduce N fertilisation due to N fixation capacity of these species (Nemecek et al. 2008), to break the life cycle of crop-specific pathogens, pest, and weeds compared to monoculture and to increase soil organic carbon (Kirkegaard et al. 2008; Stagnari et al. 2017). In the study of Zucali et al. (2018), the scenario with protein-rich forage in the cropping system (i.e. lucerne preserved as hay and soybean preserved as silage) was judged the best one for the lowest environmental impact per unit of product (fat and protein corrected milk, FPCM), in terms of acidification, eutrophication, and non-renewable fossil energy use, besides showing the highest feed self-sufficiency and reduction of chemical N fertilisation. The inclusion of soybean silage in lactating cows total mixed ration (TMR) was investigated in the companion paper (Rota Graziosi et al. submitted), and the authors found promising results, as no differences in DMI and milk production were found between a control diet (based on soybean meal) and a diet with the inclusion of soybean silage in partial substitution of soybean meal. On the opposite, in Comino et al. (2018), cows fed a diet with soybean silage in complete substitution of soybean meal and cotton seed had lower milk yield, but higher milk fat and protein concentrations.

Another opportunity, emerging over the last years, to enhance the sustainability of the dairy cows sector is the possibility of using a 'responsible soy' for livestock feeding. The European Feed Manufacturers' Federation (FEFAC) (FEFAC and ITC 2021), indeed, suggests using responsible soy, defined as soy imported in Europe from production sites that follow sustainability guidelines. To be considered responsible, a soybean crop has to satisfy several sustainability criteria: legal compliance, working conditions, respect and protection of the environment, implementation of good agricultural practices, legal use of lands, and the protection of community relations, respecting the reserve or conservation areas. Thus, in terms of environmental

impact, the main difference between responsible and conventional soy is that the production of the second one is not associated with Land Use Change (LUC). The importance and urgency of these measures are stressed, considering that LUC accounts for more than 50% of the carbon footprint of soybean imported in Europe from Brazil (Escobar et al. 2020). The EU and other international buyers of Brazilian commodities are aware of this environmental threat. Indeed, 38% of the soybean meal consumed in the EU in 2018 was in compliance with FEFAC soy sourcing guidelines, and 19% of it was defined as 'deforestation-free' (Eurostat 2020). The certified volume of responsible soy increased 4.5 times from 2013 to 2020 (4.7 million tons in 2020) (<https://responsiblesoy.org/>).

Our hypothesis was that the substitution of conventional soybean meal with alternative protein sources, like soybean silage and responsible soybean meal, could reduce the environmental impact of dairy cows diet. To the best of our knowledge, a combination of these two protein sources was not investigated before. Thus, the aim of this study was to evaluate, through a Life Cycle Assessment (LCA) approach and also based on *in vivo* results reported in companion paper (Rota Graziosi et al. submitted), the environmental impact of four lactating cow rations. These diets were characterised by different sources of soybean: conventional soybean meal, soybean silage and responsible soybean meal.

Material and methods

The experimental diets

The yield at field of soybean silage was compared with that of other forage sources included in lactating cow diet (Table 1), both in terms of dry matter (DM) and crude protein (CP). The forages were included into two lactating cows TMR (CON and SBS, Table 2) characterised by different sources of soybean, i.e. conventional soybean meal and soybean silage. In addition, two different TMR were fed replacing soybean meal with responsible soybean meal. So, four scenarios were identified: (1) conventional soybean meal (CON, control diet), (2) conventional soybean meal and soybean silage (SBS, soybean silage), (3) responsible soybean meal as defined by the FEFAC guidelines (CON + RSM, control diet plus responsible soybean meal), or (4) soybean silage and responsible soybean meal (SBS + RSM, soybean silage plus responsible soybean meal). Soybean oil was also either from conventional soybean (for CON and SBS diets) or from responsible soybean (for CON + RSM and SBS + RSM

Table 1. Characteristics of soybean silage compared to other forage sources.

Crop Period	Crop	Feed	UAA ¹	ton AF ² /ha	ton AF	ton DM ³ /ha	% DM	ton CP ⁴ /ha	CP %DM
Spring-Summer	Soybean	Soybean silage	16	33.0	528	9.2	28.0	1.8	19.5
Spring-Summer	Maize	High moisture ear maize	10	19.5	195	12.9	66.0	1.1	8.4
Spring-Summer	Maize	Maize silage	10	55.0	550	19.3	35.0	1.5	8.0
Plurennial	Lucerne	Lucerne hay	11.5	12.0	138	10.3	86.0	2.0	19.0
Autumn-Winter	Barley	Barley silage	16	35.3	565	11.3	32.0	1.2	11.0
Autumn-Winter	Italian Ryegrass	Italian ryegrass hay	11	12.0	132	10.3	86.0	0.8	8.0

¹UAA = utilised agricultural area²AF = as fed³DM = dry matter⁴CP = crude protein.**Table 2.** Ingredients and chemical composition of the four lactating cows rations.

Item (% of DM)	CON ¹	SBS ²	CON + RSM ³	SBS + RSM ⁴
High moisture ear maize	–	15.6	–	15.6
Soybean silage	–	12.4	–	12.4
Barley silage	10.3	10.2	10.3	10.23
Lucerne hay	9.52	9.43	9.52	9.43
Maize silage	25.5	9.22	25.5	9.22
Maize meal	16.4	8.72	16.4	8.72
Flaked maize grain	7.31	7.27	7.31	7.27
Soybean meal	10.7	6.91	–	–
Responsible soybean meal	–	–	10.7	6.91
Molasses cane	4.83	4.81	4.83	4.81
Wheat straw	1.95	1.95	1.95	1.95
Sunflower meal	5.00	4.94	5.00	4.94
Barley grain	2.80	2.79	2.80	2.79
Maize gluten feed	1.50	1.51	1.50	1.51
Wheat shorts	2.30	2.25	2.30	2.25
Soybean oil	0.60	0.62	–	–
Responsible soybean oil	–	–	0.60	0.62
MinVit ⁵	1.30	1.32	1.30	1.32
Chemical composition (as % of DM unless differently stated)				
DM (% of AF)	49.6	48.9	49.6	48.9
Ash	5.90	6.38	5.90	6.38
OM	94.1	93.6	94.1	93.6
CP	14.7	15.2	14.7	15.2
Sol CP (% of CP)	21.6	29.8	21.6	29.8
EE	2.72	3.33	2.72	3.33
NDF	30.6	30.4	30.6	30.4
ADF	18.8	18.9	18.8	18.9
ADL	3.81	3.89	3.81	3.89
NDIP	1.32	1.34	1.32	1.34
ADIP	1.03	0.96	1.03	0.96
NFC	46.0	44.8	46.0	44.8
N-NH ₃ (% of total N)	15.1	13.9	15.1	13.9

¹CON = conventional soybean meal²SBS = conventional soybean meal and soybean silage³CON + RSM = responsible soybean meal⁴SBS + RSM = soybean silage and responsible soybean meal⁵Each kg contained: 31 g Fe, 70.5 g Zn, 30.4 g Mn, 100 mg Se, 2 g I, 60 mg Mo, 6.9 g Cu, 500 mg beta carotene, 4,000,000 IU Vitamin A, 800,000 IU Vitamin D3, 20,500 IU Vitamin E, 2450 IU Vitamin B1, 343 IU Vitamin B6, 20 IU Vitamin B12, and 52,000 IU Vitamin PP

diets). The environmental impact of milk production systems in the four scenarios were investigated based on the results reported in companion paper (Rota Graziosi et al. submitted). In this latter study, a total of 36 Holstein cows were involved in the study, and data regarding diet composition, intake, milk production and quality, digestibility, and N balance were collected and used in the present paper.

Life cycle assessment

The environmental sustainability was performed through LCA method, structured following ISO 14040-compliant and ISO 14044-compliant LCA methodology (ISO 2006a, 2006b).

Goal and scope definition

The goals of this LCA study were to quantify the environmental sustainability of different forage sources, individual daily administered TMR, and milk production to evaluate the possible effects of the use of different soybean sources in lactating cow diets.

Functional units, allocation and system boundaries

In order to compare the sustainability of soybean silage with that of other forage sources, 1 ton of DM and 1 ton of CP were considered as functional units (FU). In addition, the individual daily supplied diet was considered as FU. For the analysis of different milk production scenarios, the considered FU was 1 kg of fat and protein corrected milk (FPCM; 4.0% fat and 3.3% protein), calculated as suggested by the International Dairy Federation (IDF (International Dairy Federation) 2015). Therefore, the allocation between FPCM and meat was calculated using a physical method (IDF (International Dairy Federation) 2015).

An attributional approach, which considered from cradle to farm gate system boundaries, was adopted. All the inputs (e.g. off-farm feeds and bedding, machinery, fuel, lubricants, electricity, organic and mineral fertilisers, pesticides, plastics, and water), and outputs (i.e. emissions to the air, soil and water, milk, and meat) involved in the production process were considered within the system boundaries (Figure 1).

Life cycle inventory (LCI)

Primary data of the foreground system were derived from the in vivo trial (Rota Graziosi et al. submitted) concerning feed rations (ingredients and nutritive values) and animal performances (e.g. milk production, nitrogen balance). In particular, the daily milk production was pared to 32.7 kg/cow for CON diet and

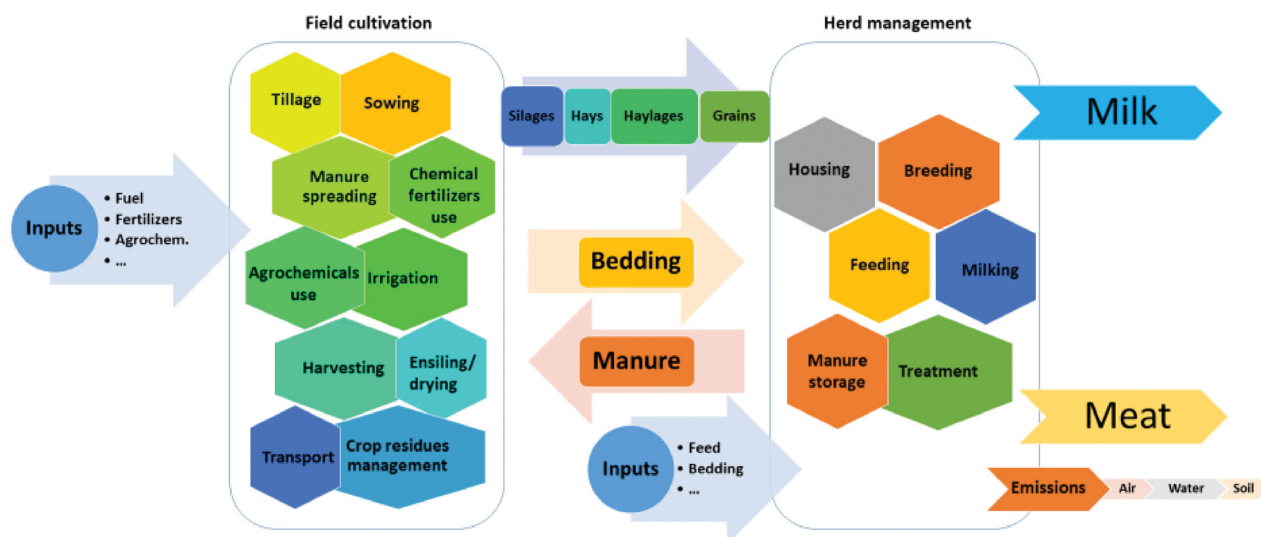


Figure 1. System boundaries.

33.2 kg/cow for SBS diet, the same productions were considered for the two scenarios (CON + RSM and SBS + RSM diets). Primary data were also collected by directly interviewing the farmer. Information about the cropping system (feed crops and their DM yields, tillage, methods adopted for feed conservation, fuel, purchased seeds, pesticides, and fertilisers), the purchased forages and concentrates (type and origin), the herd composition, and the manure management were collected, using a questionnaire.

Secondary data related to the background system (production of seeds, raw materials, fuels, fertilisers, pesticides, tractors and agricultural machines, transport) were obtained from the ECOINVENT[®] and the Agri-footprint databases.

Emission estimation

Feed emissions calculation. The environmental impact of feed raw materials was obtained from the Ecoinvent (2013), Eco-Alim (2015), and Agri-Footprint (2014) databases. The environmental impact of forages was calculated considering inputs needed at the field level (e.g. fossil fuel, seeds, fertilisers, pesticides, agricultural machines), feed processing (e.g. drying, ensiling), and transport.

The effects on direct and indirect N₂O emissions derived by the application on the field of organic (solid and slurry) and inorganic fertilisers, as well as crop residues, were accounted for, using Intergovernmental Panel on Climate Change guidelines (IPCC 2019b). Also, NO₃ emissions from organic and inorganic fertilisers application were considered (IPCC 2019b). NH₃ from manure and chemical fertilisers spreading was accounted for, using the European

Environment Agency method (EEA (European Environment Agency) 2019a, 2019b), as well as NO₂ from chemical fertilisers spread in the field (EEA (European Environment Agency) 2019a). PO₄ transport to water resulting from chemical fertilisers spreading were computed as proposed by Nemecek and Kägi (2007).

For conventional soybean meal and oil, direct LUC was included in the assessment. Different LUC methods result in significantly different outputs; in this study, we used values reported by the Agri-Footprint database (Soybean meal, from crushing (solvent), at plant/BR Economic and Crude soybean oil, from crushing (solvent), at plant/BR Economic, Agri-Footprint, 2014). Therefore, 4.05 kg of CO₂eq/kg soybean meal and 11.2 kg of CO₂eq/kg soybean oil, for soybean from South America were considered. For all purchased conventional soybean meal and oil, an amount of 20% from Italy and 80% from South America was considered (ASSALZOO (Associazione Nazionale tra i Produttori di Alimenti Zootecnici) 2018). Responsible soybean meal and oil environmental impacts were evaluated based on data reported by Agri-Footprint database (Agri-Footprint 2020). The process of responsible soybean, at farm, describes the cultivation process of Soybeans in Brazil, from 14 participating farms in the ProAgros project (part of the Sustainable Farming Assurance Programme, SFAP). No LUC contributes to the environmental impact of the responsible soybean process. An economical allocation was performed for responsible soybeans at the farm (from SFAP farms), responsible soybean meal (solvent), responsible soybean hull (solvent) and responsible crude soybean oil (solvent). For all purchased

Table 3. Equations used for the estimation of the GHG emissions on farm.

Pollutant	Source	Equation	Reference
CH ₄	Enteric	Lactating cows: CH ₄ (kg head ⁻¹ yr ⁻¹) = ((124 + 13.3 · DMI)) · 365/1000	Equation 2 in Niu et al. (2018)
		Others: CH ₄ (kg head ⁻¹ yr ⁻¹) = (GE ¹ · (Ym/100))/55.65	Equation 10.21 in IPCC (2019a)
		GE (kJ) = 17,350 + (234.46 · EE% ²) + (62.8 · CP%) – (184.22 · Ash %)	Ewan (1989)
	Manure storage	Ym = 6.3	Table 10.12 in IPCC (2019a)
		CH ₄ (kg head ⁻¹ yr ⁻¹) = (VS ³ · 365) × [B0 ⁴ · 0.67 · MCF ⁵ /100 · AWMS ⁶]	Equation 10.23 in IPCC (2019a)
		VS (kg day ⁻¹) = [GE · (1 – DE ⁷ /100) + (UE · GE ⁸)] · [(1 – Ash)/18.45]	Equation 10.24 in IPCC (2019a)
		DE: feed digestibility	INRA (Institut national de la recherche agronomique) (2007)
		B0 dairy cattle: 0.24	Table 10.16 in IPCC (2019a)
		B0 non dairy cattle: 0.18	Table 10.16 in IPCC (2019a)
		MCF liquid slurry and pit storage: 37%	Table 10.17 in IPCC (2019a)
		MCF solid storage: 4%	Table 10.17 in IPCC (2019a)
N ₂ O direct	Manure storage	N ₂ O (kg yr ⁻¹) = [Σ([Σ((N · Nex ⁹) · AWMS) + N] · EF ¹⁰)] · 44/28	Equation 10.25 in IPCC (2019a)
		N: annual nitrogen input via co-digestate in the country	
		EF solid storage: 0.01	Table 10.21 in IPCC (2019a)
		EF liquid slurry: 0.005	Table 10.21 in IPCC (2019a)
		EF pit storage: 0.002	Table 10.21 in IPCC (2019a)
	Field	N ₂ O = (Fsn ¹¹ + Fon ¹²) · EF + (Fcr ¹³ + Fsom ¹⁴) · EF · 44/28	Equation 11.2 in IPCC (2019b)
		Fon: annual amount of N from managed animal manure applied to soil (Nex – Frac_Loss ¹⁵ + N bedding ¹⁶)	Equation 10.34 in IPCC (2019a)
		Frac Loss = Frac Gas + Frac Leachs + Frac N ₂ MS + EF	Equation 10.34A in IPCC (2019a)
		EF solid storage: 0.01	Table 10.21 in IPCC (2019a)
		EF liquid slurry: 0.005	Table 10.21 in IPCC (2019a)
N ₂ O indirect	Manure storage	EF pit storage: 0.002	Table 10.21 in IPCC (2019a)
		N ₂ O = N volatilization ¹⁷ · EF · 44/28	Equation 10.28 in IPCC (2019a)
		N volatilisation = ((Nex · AWMS) + Ncdg) · Frac Gas _MS ¹⁸ /100	Equation 10.26 in IPCC (2019a)
		Frac Gas _MS solid storage: 0.30	Table 10.22 in IPCC (2019a)
		Frac Gas _MS liquid slurry: 0.30	Table 10.22 in IPCC (2019a)
	Field	Frac Gas _MS pit storage: 0.28	Table 10.22 in IPCC (2019a)
		EF: 0.01	Table 11.3 in IPCC (2019b)
		N ₂ O(ATDN) = [(Fsn · Frac_GasF ¹⁹) + (Fon · Frac_GasM ²⁰)] · EF · 44/28	Equation 11.9 in IPCC (2019b)
		Frac_GasF: 0.11	Table 11.3 in IPCC (2019b)
		Frac_GasM: 0.21	Table 11.3 in IPCC (2019b)
		EF: 0.01	Table 11.3 in IPCC (2019b)
		N ₂ O(L) = (Fsn + Fon + Fprp + Fcr + Fsom) · Frac_Leachs ²¹ · EF · 44/28	Equation 11.10 in IPCC (2019b)
		Frac_Leach: 0.24	Table 11.3 in IPCC (2019b)
		EF: 0.011	Table 11.3 in IPCC (2019b)

¹GE = gross energy intake (MJ/d); ²EE% = ether extract of feed (% DM); ³VS = daily volatile solid excreted (kg of DM/animal); ⁴B0 = maximum methane-producing capacity for manure (m³); ⁵MCF = methane conversion factors for each given manure management system (%); ⁶AWMS = fraction of livestock manure handled using each given manure management system (dimensionless); ⁷DE% = energy digestibility of feed (%); ⁸(UE · GE) = urinary energy expressed as fraction of GE (dimensionless); ⁹Nex = annual N excretion (kg of N/animal); ¹⁰EF = emission factor for direct N₂O emissions from a given manure management system (kg of N₂O-N/kg of N in manure management system); ¹¹Fsn = annual amount of synthetic fertiliser N applied to soils (kg of N); ¹²Fon = annual amount of animal manure, compost, sewage sludge and other organic N additions applied to soils (kg of N); ¹³Fcr = annual amount of N in crop residues (above and below ground), including N-fixing crops, and from forage/pasture renewal, returned to soils (kg of N); ¹⁴Fsom = amount of N mineralised from loss in soil organic C in mineral soils through land-use change or management practices; ¹⁵Frac_loss = fraction of managed manure N that is lost in a given manure management system (%); ¹⁶N_bedding = annual amount of N from bedding (kg of N/animal); ¹⁷N volatilisation = annual amount of manure N that is lost due to volatilisation of NH₃ and nitric oxide compounds (NO_x; kg of N); ¹⁸Frac_GasMS = fraction of managed manure N that volatilises as NH₃ and NO_x in a given manure management system (%); ¹⁹Frac_GasF = fraction of synthetic fertiliser N that volatilises as NH₃ and NO_x (%); ²⁰Frac_GasM = fraction of applied organic N fertiliser materials and of urine and dung N deposited by grazing animals that volatilises as NH₃ and NO_x (%); ²¹Frac_Leach = N fraction lost through leaching and runoff (%).

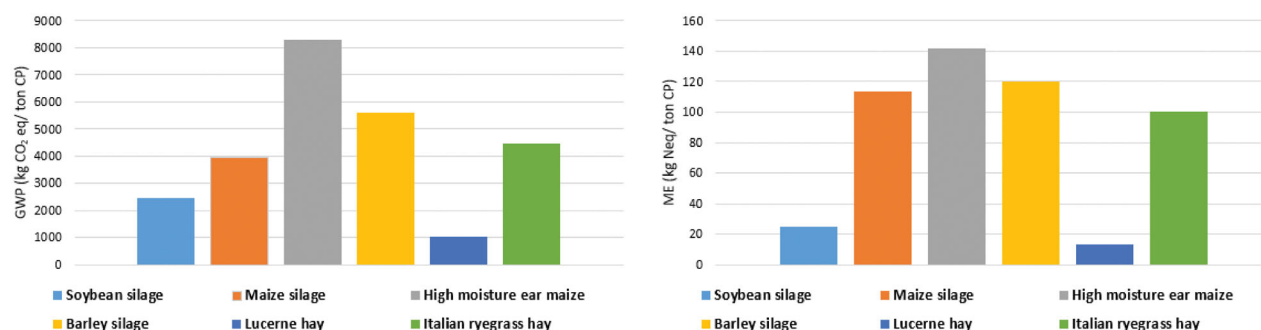
Table 4. Equations for the estimation of non-GHG emissions on farm.

Pollutant	Source	Equation	Reference
NH ₃	Housing	$TAN^1 = Nex^2 \cdot EF_TAN^3$	Equation 10 in EEA (European Environment Agency) (2019a)
		EF_TAN: 0.6	Table 3.9 in EEA (European Environment Agency) (2019a)
		$NH_3\text{hous_slurry} = TAN\text{ hous_slurry} \cdot EF\text{ hous_slurry} \cdot 17/14$	Equation 15 in EEA (European Environment Agency) (2019a)
		EF hous_slurry ⁴ : 0.24	Table 3.9 in EEA (European Environment Agency) (2019a)
		$NH_3\text{hous_solid} = TAN\text{ hous_solid} \cdot EF\text{ hous_solid} \cdot 17/14$	Equation 16 in EEA (European Environment Agency) (2019a)
		EF hous_solid ⁵ : 0.08	Table 3.9 in EEA (European Environment Agency) (2019a)
	Manure storage	$NH_3\text{storage_solid} = TAN\text{ storage_slurry} \cdot EF\text{ storage_slurry} \cdot 17/14$	Equation 33 in EEA (European Environment Agency) (2019a)
		EF storage_slurry ⁶ : 0.25	Table 3.9 in EEA (European Environment Agency) (2019a)
		$NH_3\text{storage_solid} = TAN\text{ storage_solid} \cdot EF\text{ storage_solid} \cdot 17/14$	Equation 34 in EEA (European Environment Agency) (2019a)
		EF storage_solid ⁷ : 0.32	Table 3.9 in EEA (European Environment Agency) (2019a)
	Field	$NH_3\text{applic_slurry} = TAN\text{ slurry_applic} \cdot EF\text{applic_slurry} \cdot 17/14$	Equation 39 in EEA (European Environment Agency) (2019a)
		EF applic_slurry ⁸ : 0.55	Table 3.9 in EEA (European Environment Agency) (2019a)
		$NH_3\text{applic_solid} = TAN\text{ solid_applic} \cdot EF\text{ applic_solid} \cdot 17/14$	Equation 40 in EEA (European Environment Agency) (2019a)
		EF applic_solid ⁹ : 0.68	Table 3.9 in EEA (European Environment Agency) (2019a)
		$NH_3\text{applic_fert}^{10} = N\text{ fert_applic}^{11} \cdot EF\text{ fert_type}^{12}$	Equation 4 in EEA (European Environment Agency) (2019b)
		EF urea: 159	Table 3.2 in EEA (European Environment Agency) (2019b)
		EF amm.nitr ¹³ : 0.016	Table 3.2 in EEA (European Environment Agency) (2019b)
		EF NPK ¹⁴ : 0.067	Table 3.2 in EEA (European Environment Agency) (2019b)
		EF other straight N compounds: 0.014	Table 3.2 in EEA (European Environment Agency) (2019b)
NO ₂	Manure storage	$EMMS_NO_2^{15} = (Estorage_NO_slurry + Estorage_NO_solid) \cdot 46/14$	Equation 47 in EEA (European Environment Agency) (2019a)
	Field	$NO_2\text{applic_tot} = (N\text{slurry_applic} + N\text{solid_applic} + N\text{fert_applic}) \cdot EF\text{applic}$ EFapplic: 0.04	Table 3.1 in EEA (European Environment Agency) (2019b)
NO ₃	Field	$NO_3 = N_leached \cdot 4.426$ $N_leached = (Fsn + Fon + Fprp + Fcr + Fsom) \cdot Frac_Leach$ Frac_Leach: 0.24	Equation 11.10 in IPCC (2019b)
PO ₄ ³⁻	Field	$Pgw\text{ (leached to ground water)}^{16} = Pgw^{17} \cdot Fgw^{18}$ Pgw arable land: 0.07 Pgw permanent pasture and meadow: 0.06 Fgw: $1 + 0.2/80 \cdot P_2O_5\text{slurry}$ $Pro^{19} (P\text{ lost through run-off to rivers}) = Prol^{20} \cdot Fro^{21}$ Prol open arable land: 0.175 Prol extensive meadow: 0.25 Fro fert: $0.2/80 \cdot P_2O_5\text{fert}$ Fro slurry: $0.7/80 \cdot P_2O_5\text{slurry}$ Fro manure: $0.4/80 \cdot P_2O_5\text{manure}$	Table 11.3 in IPCC (2019b) Paragraph 4.4.3 in Nemecek and Kägi (2007)

¹TAN = total ammoniacal-N; ²Nex = annual average N excretion per head (kg of N/animal); ³EF_TAN = emission factor of TAN; ⁴hous_slurry = liquid slurry in the livestock buildings; ⁵hous_solid = solid manure in the livestock buildings; ⁶storage_slurry = liquid slurry in storages; ⁷storage_solid = solid manure in storages; ⁸applic_slurry = application of liquid slurry to the field; ⁹applic_solid = application of solid manure to the field; ¹⁰NH₃ applic_fert = emission from fertiliser application to the field; ¹¹N fert_applic = total N from fertiliser application; ¹²EF fert_type = emission factor for fertiliser type; ¹³Amm nitr = ammonium nitrate; ¹⁴NPK = nitrogen-phosphorus-potassium fertiliser; ¹⁵NO₂ = nitrogen dioxide; ¹⁶Pgw = quantity of phosphorus leached to ground water (kg/ha); ¹⁷Pgw = average quantity of phosphorus leached to ground water for each land use category (kg/ha); ¹⁸Fgw = correction factor for fertilisation by slurry; ¹⁹Pro = quantity of phosphorus lost through runoff to rivers (kg/ha); ²⁰Prol = average quantity of phosphorus lost through runoff to rivers for each land use category (kg/ha); ²¹Fro = correction factor for fertilisation with each source of phosphorus.

Table 5. Environmental impact of soybean silage compared with that of other forage sources (ton dry matter).

Impact category	Unit	Soybean silage	Maize silage	High moisture ear maize	Barley silage	Lucerne hay	Italian ryegrass hay
Global warming potential (GWP)	kg CO ₂ eq	477	308	707	597	201	346
Terrestrial acidification (TA)	kg SO ₂ eq	0.39	15.6	23.2	23.9	0.57	13.3
Marine eutrophication (ME)	kg Neq	4.87	8.84	12.1	12.8	2.55	7.80
Agricultural land occupation (ALO)	m ² a	1105	533	787	902	986	996
Natural land transformation (NLT)	m ²	0.036	0.021	0.034	0.023	0.013	0.017
Human toxicity (HT)	kg 1,4-DBeq	10.97	13.69	17.50	13.29	9.30	9.93

**Figure 2.** Environmental impact in terms of global warming potential (GWP) and marine eutrophication (ME) of soybean silage compared with that of other forage sources (ton CP).

responsible soybean meal and oil, we considered an amount of 20% from Italy and 80% from Brazil (i.e. responsible soy).

GHG emissions on farm. Table 3 shows the models used for on-farm GHG estimation. CH₄ emissions from livestock enteric fermentation were estimated using different equations: the equation from Niu et al. (2018) for lactating cows, while, for the other livestock categories, the equation of IPCC (2019a) was used. For lactating cows, DMI was derived by the in vivo trial of the companion paper (Rota Graziosi et al. submitted). CH₄ emissions from manure storage were estimated using the method suggested by the IPCC (2019a). Volatile solid excretion was estimated considering the gross energy of the diets (kJ/kg of DM) evaluated using the equation of Ewan (1989). Digestibility of the feed was estimated using a calculation model developed for each type of forage and concentrate feed on the basis of the equations proposed by INRA (Institut national de la recherche agronomique) (2007). In vivo data about the chemical composition of feed and diets and digestibility, collected during the trial reported in the companion paper (Rota Graziosi et al. submitted), were used for lactating cow rations. N₂O emissions from manure storages occurred in direct and indirect forms and they were estimated using the method from IPCC (2019a). In the current study, animal nitrogen excretion of lactating cows was measured in vivo during the trial reported in the companion paper (Rota Graziosi et al. submitted). CO₂

emissions occurring during field operations (i.e. ploughing, harrowing, sowing, harvesting, and so on) were estimated using the processes of the Ecoinvent (2007) database. Emissions from livestock respiration and the variation in soil carbon stocks were not accounted for.

Other emissions on farm. Table 4 reports the models used for the estimation of acidifying and eutrophic substances emitted on farm. NH₃ and NO₂ emissions that occur during animal housing, manure storage, and spreading were estimated following the method proposed by EEA (European Environment Agency) (2019a) and EEA (European Environment Agency) (2019b), on the basis of the total amount of nitrogen excreted by the animals. Nitrogen excretion of lactating cows was measured in vivo (Rota Graziosi et al. submitted).

The NH₃-N and NO₂-N emission factors, as a proportion of total ammonia nitrogen, were specific for each manure type (slurry or solid) and each step in manure handling (EEA (European Environment Agency) 2019b). The NH₃ and NO₂ emitted during manure spreading and application of synthetic fertilisers were estimated following EEA (European Environment Agency) (2019a). The amount of N leached as NO₃ was estimated on the basis of N leached, following the IPCC (2019b) model. The amount of P lost in dissolved form to surface water (run-off) and leached was considered to estimate the transport to water of PO₄ as proposed by Nemecek and Kägi (2007).

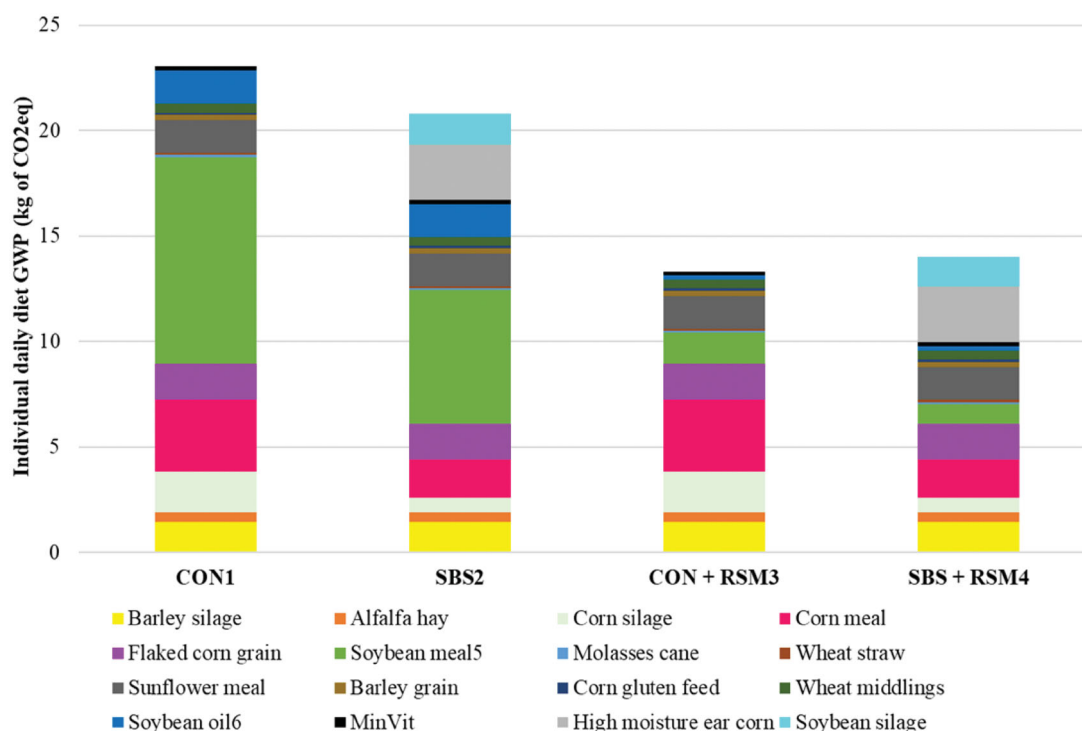


Figure 3. Global warming potential (GWP) of individual daily lactating cows TMR, characterised by different soybean sources. ¹CON = conventional soybean meal. ²SBS = conventional soybean meal and soybean silage. ³CON + RSM = responsible soybean meal. ⁴SBS + RSM = soybean silage and responsible soybean meal. ⁵Soybean meal either conventional for CON and SBS or responsible for CON + RSM and SBS + RSM. ⁶Soybean oil either conventional for CON and SBS or responsible for CON + RSM and SBS + RSM.

Off farm processes emission. The emissions related to off farm activities were calculated using LCA software, Simapro PhD 7.3.3 (PRé Consultants 2012). The processes considered included the production chain of commercial feed (from crop growing to feed factory processing), production of purchased forages and bedding material, production of chemical fertilisers, pesticides, diesel, and electricity used in the farms. Transportation was accounted for feed and bedding materials.

Life cycle impact assessment (LCIA)

After classification, environmental impact was calculated using the characterisation factors of ReCiPe Midpoint (H) V1.10/Europe Recipe H. Normalisation was also performed for milk production of the different scenarios through ReCiPe Midpoint (H) V1.10/Europe Recipe H. The LCIA was performed using the SimaPro V 8.3 software tool.

Results and discussion

Environmental impact of soybean silage compared with other forage sources

Results obtained in the present study highlight differences, in terms of environmental impact, between

soybean silage and the main farm-produced forages included in lactating cow diets (Table 5). For all the forages, the main contribution to global warming potential (GWP) was cultivation phases (especially GHG emissions into the air), followed by processing and transport, according to Mogensen et al. (2014). Soybean silage was more sustainable for GWP than barley silage and high moisture ear maize; the latter showed the highest value of GWP and HT (Table 5). The high water and N requirements of high moisture ear maize contributed significantly to GWP; this is consistent with Ma et al. (2012) in field experimental study on maize. Unlike maize, soybean silage is a low input crop regarding water and N fertilisation (both organic and inorganic), which should be favourable in terms of GWP. Ma et al. (2012) reported that low N application decreases both total GHG emissions and the GWP across all the rotation systems; hence, a forage crop with low fertilisation requirements is advisable to enhance the sustainability of the farming system. Barley Silage has a higher GWP than soybean silage (Table 5). The GWP value of barley was higher than the results of Mogensen et al. (2014), 285 kg CO₂eq/ton DM. In this latter work, differently than the present study, the authors did not take into account manure to the field but considered all fodder crops

Table 6. Environmental impact related to the milk production of different scenarios.

Impact category	Unit	CON ¹	SBS ²	CON + RSM ³	SBS + RSM ⁴
Global warming potential (GWP)	kg CO ₂ eq	1.38	1.17	1.13	1.01
Terrestrial acidification (TA)	kg SO ₂ eq	0.023	0.022	0.022	0.021
Marine eutrophication (ME)	kg Neq	0.008	0.007	0.007	0.007
Agricultural land occupation (ALO)	m ² a	0.94	0.91	0.77	0.84
Natural land transformation (NLT)	m ²	0.00371	0.00252	0.00005	0.00004
Human toxicity (HT)	kg 1,4-DBeq	0.037	0.028	0.033	0.027

¹CON = conventional soybean meal²SBS = conventional soybean meal and soybean silage³CON + RSM = responsible soybean meal⁴SBS + RSM = soybean silage and responsible soybean meal

fertilised only by inorganic N. In González-García et al. (2016), in a study conducted in Spain, barley silage gave a value of GWP closer to the one of Mogensen et al. (2014) (i.e. 321 kg CO₂eq/ton DM), but the authors concluded that this value is highly dependent on agricultural practices and system boundaries. Hence a certain variation has to be expected across studies. Soybean silage showed a higher GWP value than maize silage, Italian ryegrass hay, and lucerne hay (Table 5). The latter is similar to soybean silage for DM yield and CP content, but showed a lower GWP, mainly due to the low contribution from field operation, in particular tillage. However, the large seeding window of soybean allows it to grow in succession to different winter crops, maximising yields of DM and CP per hectare. For example, cultivating soybean for silage after a mixture of winter cereal and legume forages makes it possible to harvest more than 15 t DM/ha per year (Tabacco and Comino 2019). GWP obtained for lucerne hay was similar to the one reported by Adom et al. (2012), 170 kg CO₂eq/ton DM, but lower than the one reported by Fathollahi et al. (2018). This previous study found a value for the GWP of maize silage (329 CO₂eq/ton DM) similar to the present study. On the opposite, GWP of maize silage was slightly higher compared to the result obtained by Xu et al. (2018), 680 kg CO₂eq/ton AF, as well as to the data of Adom et al. (2012) and Mogensen et al. (2014), 200 and 224 kg CO₂eq/ton DM, respectively. Compared to the studies mentioned above, the difference can be explained by the organic fertilisation of the maize silage of the present study and subsequent emissions into the air.

High human toxicity (HT) characterised high moisture ear maize, similarly to soybean silage and maize and barley silage (Table 5). This was mainly due to mechanical operations in the field (e.g. ensiling), besides the use of inorganic and organic fertilisers.

High values of TA and MA also characterised barley silage and high moisture ear maize, and this is correlated to the transport of nutrients to groundwater which is linked to the consistent use of manure

adopted by the present farm. Compared to the barley of González-García et al. (2016), and to the corn silage and alfalfa hay of Fathollahi et al. (2018), TA was higher in the present study for barley (23.9 vs. 14.1 kg SO₂eq/ton DM), corn (15.6 vs. 7.1), but lower for alfalfa (0.57 vs. 5.81). This was probably due to higher manure application. In the present study, most solid manure produced by cows was spread on annual crops for ensiling, excluding soybean, to reduce the growing period and favour high yield at harvest. Soybean silage and alfalfa hay had rather low results of TA and ME because organic and inorganic fertilisers were not used.

The highest agricultural land occupation (ALO) was observed for soybean silage (Table 5). This impact category follows the phase of land transformation from natural to human utilisation; the occupation affects the original habitat and the original species composition (Huijbregts et al. 2016). The high value of ALO reported for soybean silage was probably due to the wide use of herbicides and insecticides, especially compared with the other forages. For example, barley silage, lucerne hay, and Italian ryegrass hay, which did not require the use of pesticides, had similar values for ALO. Soybean silage also showed the highest result for natural land transformation (NLT), similar to maize crops and barley silage (Table 5). NLT in Fathollahi et al. (2018) was 0.07 and 0.08 m² for corn silage and alfalfa hay, respectively, lower than the present study.

Since soybean silage is an important contributor to the protein requirement of lactating cows, its sustainability for GWP and ME was compared with that of other forage sources in terms of CP yield (Figure 2). Soybean silage protein yield (t/ha) was similar to lucerne hay (Table 1), even though the GWP per unit of CP of soybean silage was twice that of lucerne hay (2439 and 1034 kg CO₂eq/ton CP, respectively). However, being an annual crop, soybean has some agronomic and management advantages compared to lucerne, as it is easier to insert in crop rotation with maize and it gives farmers more opportunities to apply manure; in addition, the same machinery

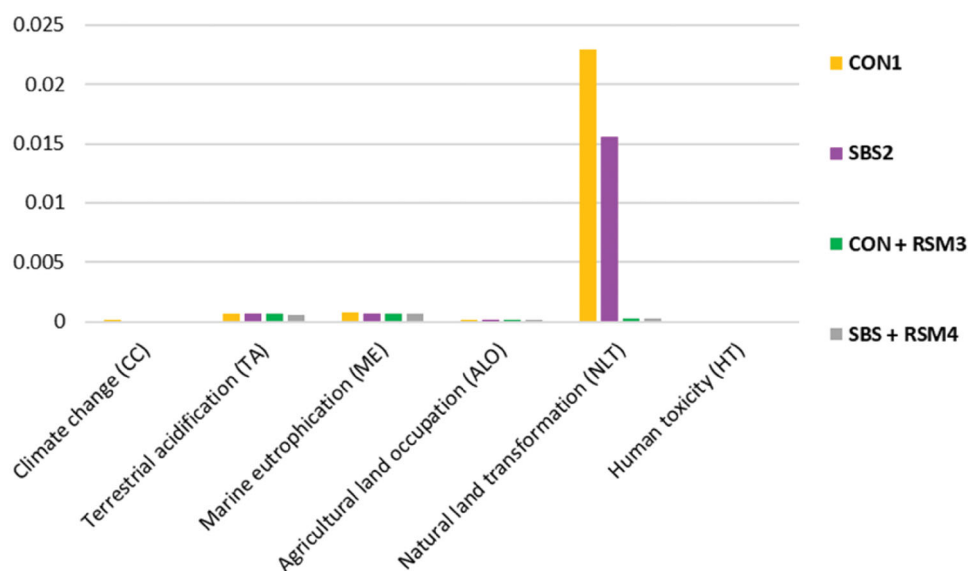


Figure 4. Normalisation data for each impact category considered in the present study. ¹CON = conventional soybean meal. ²SBS = conventional soybean meal and soybean silage. ³CON + RSM = responsible soybean meal. ⁴SBS + RSM = soybean silage and responsible soybean meal.

used to plant and harvest maize can be used for soybean (Seiter et al. 2004). Moreover, the large seeding window of soybean silage allows maximising yields of CP/ha and the succession to winter crops. Also for ME, the environmental impact of soybean silage was higher than lucerne hay, i.e. 25 and 13 kg Neq/ton CP, respectively. Overall, the results of GWP and ME were greatly influenced by the CP content: the greater the content, the lower the impact with the exception for maize silage for which the high amount of biomass leads to high CP yield (ton CP/ha, Table 1) and consequently to lower environmental impact, in terms of CP, compared to the other forage sources (i.e. barley silage, high moisture ear maize, and Italian ryegrass).

Global warming potential of lactating cow diets based on different soybean sources

The GWP of individual daily TMR was calculated as the sum of GWP of each feed ingredient; the average value was pared to 17.8 kg CO₂eq, similar to the results reported by Gislón et al. (2020a), i.e. 13.7 kg of CO₂eq, with a wide variation among farms. As suggested by these authors, the variability of GWP among diets is directly related to their feed composition and to the GWP of each feed. In particular, there is a linear correspondence between increasing daily diet GWP (kg of CO₂eq) and increasing the amount of soybean meal in the ration (Gislón et al. 2020a). This mainly explained the higher values of GWP obtained in the

present study for CON and SBS diets as compared to diets including RSM, mainly due to LUC of conventional soybean meal. The impact of soybean meal on the total diet GWP was 43% and 31% for CON and SBS, where part of the soybean meal was replaced by soybean silage. On the contrary, the impact of soybean meal, coming from responsible soy cultivation, contributed only for the 11% and 7% to the GWP of CON + RSM and SBS + RSM diets, respectively (Figure 3). The impact of soybean meal in the four diets considered was 9.81, 6.34, 1.48, 0.96 kg CO₂eq, for CON, SBS, CON + RSM, and SBS + RSM diets, respectively (Figure 3). Therefore, the highest value of individually daily diet GWP was observed with the CON diet (23.0 kg CO₂eq), but this value was reduced when the soybean meal was substituted either with the responsible soybean meal (CON + RSM, 13.4 kg CO₂eq) or soybean silage (SBS, 20.8 kg CO₂eq, Figure 3).

For all four diets, maize (forages and concentrates) gave an important contribution to the GWP by providing, on the whole, about 7 kg CO₂eq (Figure 3). In this regard, it is important to apply crop management strategies that can lower the GWP. For example, as Adom et al. (2012) suggested, fertiliser best management practices such as precision application of farm nutrients may significantly reduce maize GWP. Despite the high environmental impact of high moisture ear maize (Table 5), SBS diet, characterised by a higher inclusion of this feed than CON, showed lower GWP than CON. Therefore, the partial replacement of conventional soybean meal with soybean silage, even

combined with the inclusion in the diet of high moisture ear maize, gave an interesting result in reducing global daily diet GWP. These results, therefore, encourage the inclusion of these soybean sources into lactating cow diets rather than conventional soybean meals. In addition, the partial replacement in the diet of maize silage with high moisture ear maize allowed to reduce the inclusion in the diet of maize meal (Table 2). This may be favourable in terms of daily diet GWP since reduced dietary concentrates might reduce total net emissions (Ogino et al. 2007). Furthermore, excessive use of maize meal in the diet is not related to any productive advantage for the animals (Gislon et al. 2020a).

Environmental impact of milk production on the basis of different scenarios

The dietary formulation is an interesting way to reduce the GWP of diets for dairy cows and, as a consequence, the overall environmental impact of milk production (Wilkinson and Garnsworthy 2017). Following this suggestion, the environmental impact of milk from animals fed diets based on different sources of soybean was evaluated (Table 6). The partial replacement of conventional soybean meal with soybean silage and the total replacement of conventional soybean meal with responsible soybean meal allowed the reduction of the environmental impact of milk production for all the categories studied (Table 6). Therefore, the GWP of milk decreased from 1.38 kg CO₂eq/kg FPCM of the CON scenario to 1.17 and 1.13 kg CO₂eq/kg FPCM of the SBS and CON + RSM. In terms of GWP, the best result was reached by combining soybean silage with responsible soybean meal: 1.01 kg CO₂eq/kg FPCM (Table 6). Overall there was a wide variation of GWP among scenarios, despite the similar milk production. This variation for GWP per kg of FPCM was also observed by Battini et al. (2016), analysing 4 dairy farms in the Po Valley: the values ranged from 1.18 to 1.60 kg CO₂eq/kg FPCM, when LUC and C sequestration were not considered, and from 1.56 to 1.89 kg CO₂eq/kg FPCM when they were considered. In the study of Uddin et al. (2020), two diets with an inclusion of soybean meal similar to CON (i.e. 11.9% on average) had also similar GWP with CON: 1.44 kg CO₂eq/kg FPCM, on average (Uddin et al. 2021).

For those scenarios involving conventional soybean meal, CON and SBS, even if partially replaced with soybean silage for the latter, feed production, on farm and off farm, accounted for 47% (CON) and 42% (SBS)

of milk GWP, even slightly higher than the contribution given by animal housing, i.e. 30% and 32% of total GWP. By replacing conventional soybean with responsible soy (CON + RSM and SBS + RSM scenarios), the GWP contribution from feed production decreased to 35%, with a share related to animal housing of 37% of milk GWP.

Values of GWP obtained for CON and SBS scenarios are mainly linked to purchased protein sources, particularly soybean and LUC. The LUC is identified (Castanheira and Freire 2013) as the main source of GHG emissions from this crop. Thus, increasing farm protein self-sufficiency by producing high quality forages, such as soybean silage, may increase the environmental sustainability of the milk chain. These findings were confirmed in March et al. (2021), where the scenario with a diet based on home-grown forages, in particular with legume beans and silages as protein sources (no soybean meal included), was the one with lower GWP (1.18 kg CO₂eq/kg FPCM). Otherwise, reducing the reliance on imported soybean meal in EU would require deep changes in dietary patterns, crop and livestock production, and world trading (Karlsson et al. 2021).

Besides the favourable use of soybean silage, the present study demonstrated the great potential of responsible soybean meal to increase the sustainability of milk production (Table 6). Results obtained for NLT were also influenced by conventional soybean included in the scenarios, showing lower values as this is reduced (Table 6). Results are consistent with Vagnoni and Franca (2018), highlighting that diets characterised by larger use of soybean-based feed result in higher emissions related to the land transformation from the forest. This is also confirmed by Mueller et al. (2014), showing a close relationship between land transformation and soybean meal for intensive milk production systems.

HT was mainly related to the feed production, both on farm and off farm, for all the scenarios considered (Table 6). The slight differences detected among the scenarios were mainly due to emissions related to purchased feed. In particular, a greater contribution from maize meal emerged, which, in fact, was almost halved in SBS and SBS + RSM scenarios (Table 2), showing the lowest values for HT (Table 6).

No differences occurred in terms of TA and ME, among the scenarios considered (Table 6). This is mainly related to the fact that these impact categories are mainly linked to manure management. In the present study it was assumed that the same mode of

animal housing, manure storage, and spreading were implemented at the farm for all the scenarios.

Data normalisation

A normalisation of the data was carried out with Recipe Midpoint (H) using European normalisation references (the average European inhabitant environmental load, for each impact category, Figure 4). The normalisation step provides adimensional scores, useful to understand the relative importance of category indicator results for a single product system (Guinée et al. 2002). Results obtained from normalisation allow identifying possible improvements in the environmental performance of milk production since it addresses the activities of major contributors to environmental impact. According to these outcomes, the impact category that can be regarded as highly significant is NLT, regarding CON and SBS scenarios, due to the utilisation of conventional soybean. Total substitution of soybean meal with soybean silage and responsible soy (SBS + RSM and CON + RSM) reduced the impact of NLT (Figure 4).

The other significant impact categories were TA and ME, for all the scenarios considered, consistent with the results of Hospido et al. (2003). Since crop production for animal feed is responsible for an important percentage of several impact categories, such as ME and TA (Hospido et al. 2003), some alternatives to reduce the environmental impact of milk production can be proposed. Increasing efficiency of forage production and use are examples of sustainable intensification and contribute to improve the environmental sustainability of milk production (Gislon et al. 2020a).

ALO, GWP and HT can be classified as impact categories that did not have a significant effect (Figure 4).

Conclusion

The high environmental impact of imported soybean meal mainly due to intensive and destructive use of land in the country of origin creates the urgency to find alternative feed ingredients. An alternative option is the inclusion of soybean silage into lactating cow rations. The use of soybean silage contributed to a reduced GWP of the daily diet and the environmental impact of milk production, due to the reduction of soybean meal inclusion. However, compared with lucerne hay, the most utilised self-produced protein feed in Italian dairy farms, soybean silage showed higher GWP, ME and HT mainly due to the high

contribution of mechanical operations in the field (e.g. tillage).

In addition, the substitution of conventional soybean meal with responsible soybean allows the opportunity to achieve high sustainability of milk production when considering GWP, ALO, NLT, and HT. The normalisation of impact categories highlights the negative effect of conventional soybean meal on NLT and puts in evidence the positive effect of the inclusion in lactating cow diets of responsible soybean.

In conclusion, the use of soybean silage is an interesting option to reduce environmental impact of milk production besides maximising yields of DM and CP per hectare if grown in succession to different winter crops and be able to be grown instead of lucerne. Responsible soybean meal resulted to be another interesting protein feed choice to increase sustainability of milk chain.

Ethical approval

The experiment was conducted according to the University of Milan Welfare Organism (OPBA) and with authorization number 954/2016-PR from Italian Ministry of Health.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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Data availability statement

The data that support the findings of this study are available from the corresponding author, G.G., upon reasonable request.

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