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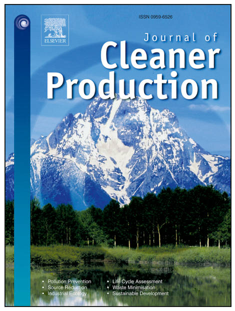

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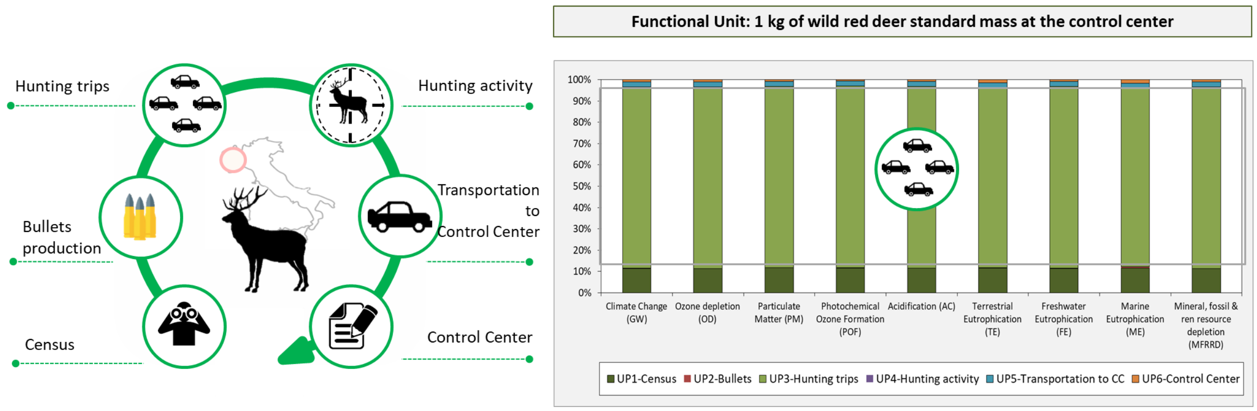
Hunting trips
Hunting activity
Bullets production
Transportation to Control Center
Census
Control Center
Functional Unit: 1 kg of wild red deer standard mass at the control center
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Climate Change (GW)
Ozone depletion (OD)
Particulate Matter (PM)
Photochemical Ozone Formation (POF)
Acidification (AC)
Terrestrial Eutrophication (TE)
Freshwater Eutrophication (FE)
Marine Eutrophication (ME)
Mineral, fossil & ren resource depletion (MFRRD)
UP1-Census
UP2-Bullets
UP3-Hunting trips
UP4-Hunting activity
UP5-Transportation to CC
UP6-Control Center

LCA and wild animals: results from wild deer culled in a northern Italy hunting district

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Authors' contributions

DM, ED, LN and RV collected and created the raw dataset, DM and MF performed the LCA and wrote the paper, AG revised the paper, MF -as LCA scientific responsible- supervised the paper.

Abstract

Although the research of innovative and sustainable environmental alternatives to meat consumption is increasing, little attention has been given to hunting activity, which has traditionally provisioned food products from wild animals. Given this gap, the present study aims to quantify the environmental impacts of wild red deer culling (*Cervus elaphus*) through selective hunting in a mountainous Italian district, adopting a *cradle-to-gate* life cycle assessment (LCA) approach. Nine impact categories are evaluated using the International Reference Life Cycle Data System (ILCD) v1.09 impact assessment method, with climate change filling a special role. The results highlight that the long distances covered by the hunters to cull wild red deer is the hotspot of the supply chain representing almost 85% of the impact in every considered impact categories. Focusing on climate change, the outcomes show that the emissions of greenhouse gases (GHGs) per functional unit (4.85 kg CO_{2eq}) are largely influenced by the hypothesis considering the wild red deer as an elementary flow entering the system and, thus, not including enteric methane emissions. In this case, the hunted red deer meat appears to be an environmentally sustainable alternative to conventional beef. The representativeness of the findings has to be increased both within the same species and in association with other wild ungulates (e.g., roe deer, wild boar or chamois) to better understand the potential role of traditionally hunted wild products in more sustainable diets.

1. Introduction

The world average greenhouse gas hierarchy across different food categories reports that plant-based foods (grains, fruits and vegetables) have lower environmental impacts than do animal-based products (meat, milk and derivatives) (Barilla Center for Food and Nutrition, 2016; Clune et al., 2017). Specifically, meat from ruminants (beef, lamb) is recognized as the food product with the greatest carbon footprint (CF) throughout the entire supply chain, with the predominant role played by breeding activities (feed production, manure management) and enteric emissions (Djekic and Tomasevic, 2016; Poore and Nemecek, 2018). The latter, arising as byproduct of the digestion process that converts feed into energy, additionally contributes to climate change, resulting in food products with higher GHGs emissions per unit of mass or protein than that from non-ruminant livestock (pigs and poultry) (de Vries and de Boer, 2010; Poore and Nemecek, 2018). Moreover, the relevant environmental burdens of producing animal-based protein (beef meat especially), which include other issues such as acidification (AC), eutrophication (EU), land-use change (LUC) and freshwater withdrawals (WU) (de Vries and de Boer, 2010; Recanati et al., 2015), have encouraged the research of possible sustainable alternatives for protein production, such as plant-based products (e.g., legumes or whole-grain cereals) (Neacsu et al., 2016), insects (Halloran et al., 2016) and cultured meat (Tuomisto and Teixeira De Mattos, 2011). However, little attention has been paid to free-ranging wild animal hunting based on harvesting plans adopted to reduce conflicts with human activities. This traditional activity has provided meat in rural and mountainous areas, and currently, thanks to the low fat content and optimal ratio of unsaturated to saturated fatty acids (Valencak et al., 2017), hunting products could address the needs of the modern consumers (Demartini et al., 2018; Hoffman and Wiklund, 2006; Marescotti et al., 2019; Tomasevic et al., 2018). Indeed, in addition to the health and taste aspects, free-ranging animals with no need for feed production could suggest meat from wild animals (venison) as an environmental-friendly alternative to—or integration with—conventional meat consumption.

As underlined by some recent studies (Gaviglio et al., 2018; Giacomelli and Gibbert, 2018), Italian hunting activity relates more to relaxing or to wildlife management activities (control of wild-animals population's growth) than to a food supply chain. The situation is likely due to the facts that (i) hunters do not recognize themselves as primary producers of food, (ii) the quantity of meat derived from hunting is very low compared to that from other meat supply chains, and (iii) many other types of food are available to consumers. The rapid increase of large wild ungulates (deer, wild boar, and roe deer) which can possibly raise conflicts with human activities (Fratini et al., 2016; Giacomelli et al., 2018; Ramanzin et al., 2010), has led to an increase of the hunting culling rate to limit population growth. Consequently, in rural and mountainous areas, the creation of professional food supply chains for wild game meat seems crucial to offer consumers (not only hunters' relatives) high-quality products (Gaviglio et al., 2018; Tomasevic et al., 2018). Within the present framework, the "*Processi di Filiera Eco-Alimentare*" project, which proposes the implementation of a certified large wild ungulate meat supply chain in the Italian province of Verbano-Cusio-Ossola (VCO), is a local effort seeking the efficient use of renewable resources (FAO, 2015) and their sustainable conversion into products with added value (food).

Given that only two reports have performed a life cycle assessment (LCA) of venison (Findlay et al., 2015; Saxe, 2015), new studies are absolutely essential to deepen the investigation of the environmental performances of wild game meat supply chains and to discuss the methodological issues that still arise. Consequently, the aim of the present work is twofold. First, the goal is to identify hotspots and to quantify the environmental performance related to wild red deer hunting in the Northern Alpine Hunting District (HD) of the VCO province during the 2015 hunting season. Second, after scenario analysis of the environmental hotspots, the main methodological issues and the overall results are discussed to provide to LCA practitioners useful information for analogous forthcoming assessments.

Among the large wild ungulates inhabiting the case study area (red deer, wild boar – *Sus scrofa*, roe deer – *Capreolus capreolus*, and chamois – *Rupicapra rupicapra*), the focus on the red deer is motivated by the facts that (i) its population is increasing in the territory and it is listed as the category of "Least Concern" in the IUCN Red List (International Union for Conservation of Nature and Natural Resources, 2000), (ii) selective red deer hunting is strictly regulated by the Piemonte Region and exclusively used to control population growth, (iii) its meat is traditionally used for human consumption and culinary preparations and, finally, (iv) modern consumers show positive attitudes towards this product (Demartini et al., 2018; Marescotti et al., 2019). A *cradle-to-gate* LCA is performed without embracing the carcass slaughtering and the final consumption. The analysis is mostly built on a detailed inventory created with the cooperation of different stakeholders that contributed to the entire data collection of the "*Processi di Filera Eco-Alimentare*" project (veterinarians, hunting technicians).

2. Materials and methods

The environmental impacts of wild red deer hunting during the 2015 hunting season in the VCO are assessed through the LCA, a standardized methodology that observes and analyses a product over its entire life cycle (ISO, 2006a, 2006b). In the following paragraphs, the four stages of the LCA study (goal and scope definition, life cycle inventory or LCI, life cycle impact assessment or LCIA, and interpretation of results) are performed.

2.1. Goal and scope definition

The goal of the study is to evaluate the environmental impacts of wild red deer hunting while providing a set of data and information about hunting activities in the mountainous area of VCO (transportation distances, firing bullets). A *cradle-to-gate* LCA is performed, and the system is modeled as a static technosphere (*attributional LCA*). The inventory (LCI), results (LCIA) and discussion could be useful (i) to wildlife technicians, hunters and all stakeholders involved in the "*Processi di Filiera Eco-Alimentare*", (ii) to LCA practitioners and, more generally, (iii) to stakeholders interested in meat sustainability issues.

2.2. Functional Unit and System Boundaries

The functional unit (FU) is a quantified performance of a product system used as a reference unit (ISO, 2006a, 2006b). According to the objective of the project "*Processi di Filiera Eco-Alimentare"*—i.e., the creation of a large wild ungulate meat supply chain—the hypothesis is that the production of food is the prevailing function of the system, even if other functions could be associated with the selective hunting method for wild red deer (i.e., the reduction of conflicts between wildlife and anthropogenic activities and the "passion and tradition" for hunting activities) (Saxe, 2015). Consequently, the FU is defined as "*one kilogram of wild red deer standard mass at the exit gate of the Control Center; m_{std}, 1 kg STD*".

The wild red deer standard mass (m_{std}, kg) corresponds to the mass of the red deer when completely eviscerated (m_{ce}, kg). This is the animal mass (m_w, kg) excluding (i) the digestive system (intestines and stomach; m_v, kg), (ii) blood (m_b, kg), and (iii) lungs, liver and heart (termed offal from now on; m_o, kg): $m_{std} = m_{ce} = m_w - (m_v + m_b + m_o)$. The head, paws and eventual trophy are included in m_{std} (for further details, see Supplementary Material and Table S.1).

Figure 1 shows the system boundaries (SB) and the unit processes (UPs) considered in this LCA study. Specifically, the wild red deer carcass supply chain includes: the red deer census, the bullet production, the hunting trips, and the hunting game, as well as the transportation of the animal to an equipped space—the Control Center (CC)—located in Trontano, along with the production of auxiliary materials and the activities carried out in the CC.

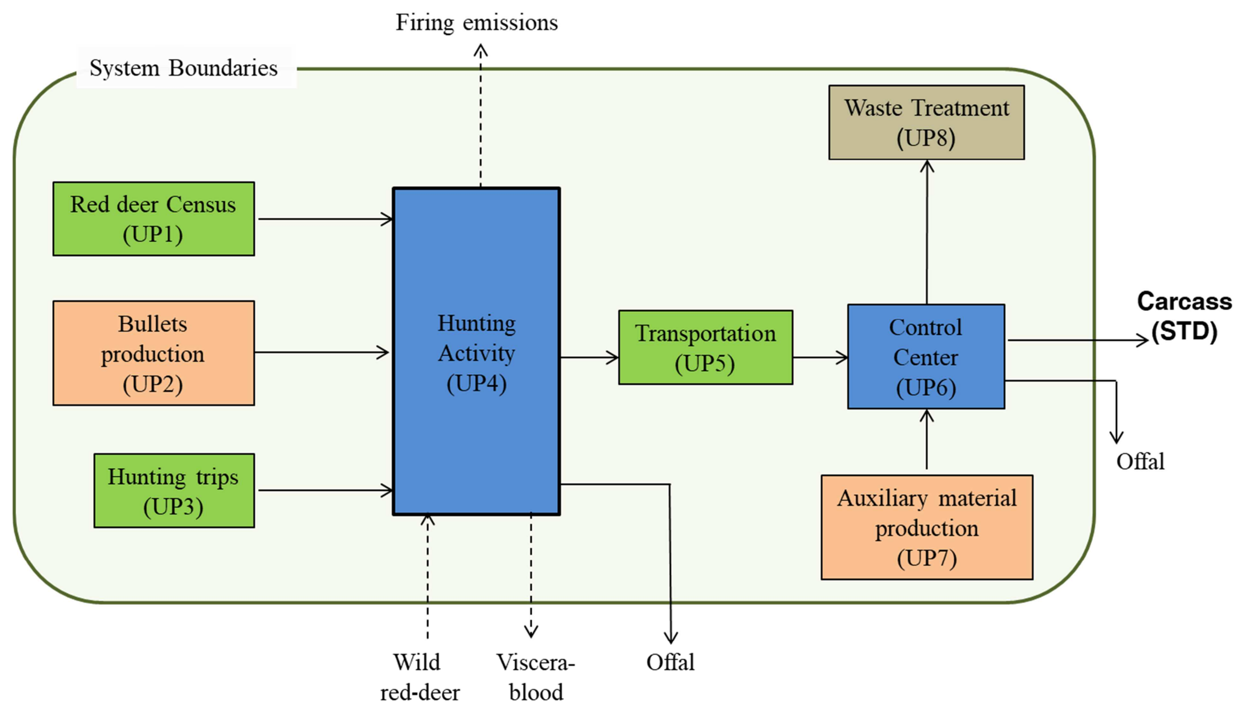

Figure 1. System boundaries of the LCA study. The elementary flows are shown as dotted lines.

Since in the HD, (i) the red deer are born and live wild, (ii) they have not been reintroduced by humans and (iii) their feeding behavior and mobility is negligibly influenced by humans—in fact, no food is provided to the deer, and no fences are implemented in the area where they live—the wild ungulates are considered "naturally occurring biotic resources" (Crenna et al., 2017) and, consequently, as elementary flows (ISO, 2006a) entering the system from the ecosphere or natural system (Alvarenga et al., 2013).

A census of the wild red deer living in the HD (UP1) is carried out every year before the hunting season, with the main purposes of estimating the number of animals living in the area and defining the yearly culling rate according to the regional (Piedmont Region) laws and regulations (Table S.2 and S.3). During the red deer hunting season (18th October-29th November 2015), hunters drive to different hunting zones with the expectation of identifying and hunting red deer, respecting the approved regulations (UP3). Among the local hunting regulations, each hunter has a maximum number of hunting days (13 days) and potential prey (4 red deer). The hunting activity is carried out by foot, using specific ammunition (UP2), and without the support of any infrastructure (e.g., shooting towers) (UP4). The hunters must bleed and eviscerate the animal as soon as possible to preserve the hygienic and sanitary meat quality. Each culled red deer is then mandatorily transported to the CC (UP5), where trained technicians (e.g., veterinaries) verify the cull correctness and monitor some biometric parameters of selectively hunted ungulates (weight, sex, age class)

(Becciolini et al., 2016). The availability of those data is fundamental both for knowledge of the current and future status of the population and for characterization of the population living in the mountainous area (Italian National Institute for Environmental Protection and Research - ISPRA, 2013). The boundaries of the system are set at the gate of the Trontano CC, the "bottleneck" of the supply chain in which all hunted wild ungulates have to be registered, because large variability in the carcass destination and processing has been detected starting from this point. In fact, according to Gaviglio et al., 2017, the destinations of the red deer carcasses are (i) self-consumption by hunters (54%), (ii) donation to relatives/friends (32%), (iii) selling to restaurants (7%), and (iv) discarding (6%).

Excluding the bullets production (the unique total-wear material), the remaining hunter equipment (rifle, hunting optics and boots) is outside the SB because (i) those goods have a useful lifetime generally higher than three years (Environdec, 2015) and (ii) no primary data were available for the allocation of the relative production impacts on wild red deer. Moreover, the limitations of the definition of SB are represented by the exclusion of (i) activities linked to the obtainment of the hunting license, practice in firing ranges and training of hunters, (ii) the transportation distance covered to buy the ammunition (Ferreira et al., 2016), and (iii) the transportation of waste from the CC to the final treatment.

2.3. Data source and quality

To evaluate the performance of wild red deer culling, both primary and secondary data have been used (Table 1). The primary data were directly collected at the Trontano CC during the 2015 hunting season. In addition to compulsory information on biometric parameters, the data collection planned for the "*Processi di Filiera Eco-alimentare*" project was enlarged to include the (i) evisceration procedure (complete or partial), (ii) abatement site, (iii) typology, caliber and number of fired shots in the 140 *exits-with-cull* (i.e., exits in which a hunter killed a wild animal), (iv) hunting effort, and (v) material and energy consumption at the CC. In the case of hunting exits, the inventory was integrated during the 2017 hunting season with consultation of the 2015 "regional hunter card" (see Supplementary Material). The Ecoinvent Database v3.3 was the technical support used to model the different UPs included in the SB (Wernet et al., 2016).

Table 1. Main sources and data quality included in the LCA (Legend: T = technological flow, E = elementary flow).

LIFE CYCLE PHASE	UNIT PROCESS	FLOW (T/E)	SOURCE	DATA TYPE
Census	UP1	Travelled distance (T) Transportation means	Estimate (Google Earth) Ecoinvent v3.3	Primary Secondary

Bullets production	UP2	Lead and lead-free bullets (T)	Ferreira et al., 2016 and Ecoinvent v3.3	Secondary
Hunting effort	UP3	Travelled distance (T) Transportation means	Estimate (Google Earth) Ecoinvent v3.3	Primary Secondary
Hunting activity	UP4	Wild red deer (E) Shots fired (T) Emissions to soil (E) Emissions to air (E)	Control Center Control Center Estimate (Andreotti and Borghesi, 2012) Ferreira et al., 2016	Primary Primary Primary Secondary
Transportation to the Control Center	UP5	Travelled distance (T) Transportation means	Estimate (Google Earth) Ecoinvent v3.3	Primary Secondary
Control Center	UP6	Energy, water and material consumption (T)	Control Center	Primary
Production of ancillary materials	UP7	Ancillary material (T)	Ecoinvent v3.3	Secondary
Waste treatment	UP8	End-of-life of material (T)	Ecoinvent v3.3	Secondary

2.4. Allocation procedure

Wild red deer selective hunting, as defined in the *goal and scope*, is considered as primary production of food (Findlay et al., 2015; Saxe, 2015). Therefore, all the activities carried out before the hunting activities (census) are completely associated with the wild red deer carcass, without allocating any environmental impacts to other hunting purposes ("joy of hunting" and wildlife management) (Saxe, 2015). The allocation procedure has been applied in three additional processes (UP3, UP4 and UP6) of the LCA. Concerning the hunting exits (UP3), the distance covered - during the hunting season - by the hunters which can cull the red deer was totally allocated to the red deer, excepting hunting exits in which other wild animal species were eventually culled (roe deer, chamois). By contrast, in the case of wild boar culling, the hunting exit is associated with the "original target" of the exits, which were red deer (see Supplementary Materials) (Giacomelli et al., 2018). In UP4 and UP6, when the production of co-products (offal) occurred, the total impacts were allocated to wild red deer carcasses, since the offal fraction is not commercialized and could be considered a surplus exiting from the SB. Finally, all primary data collected at the Trontano CC (UP6), excepting latex gloves, are associated with the activities carried out in the center from September 16th to November the 29th 2015, including the entire period during which all large wild ungulates are culled through a selective method. The UP6 electricity, water and material requirements are allocated to red deer, adopting the "kilogram of STD mass" as the mass criterion (Table 2). Specifically, the total STD mass marked in the 2015 season at the Trontano CC (red deer, wild boar, chamois and roe deer) was m_{tot} = 16,205 kg, whereas the contribution of red deer was m_{rd} = 9,761 kg. Therefore, 60% of the flows entering and exiting the UP6 are allocated to wild red deer (40% to all remaining wild animals).

Table 2. Mass allocation of energy and material consumption at the Control Center (year 2015).

SPECIES	INDIVIDUALS (n)	STD MASS (kg)	ALLOCATION (%)
Chamois	194	3,724	23
Roe deer	86	1,390	9
Red deer	140	9,761	60
Wild boar	29	1,330	8
Total	**449**	**16,205**	**100**

2.5. Impact assessment method

The material and energy inflows and outflows included in LCI have been implemented in the SimaPro 8.3.0 software and translated into environmental impacts through the ILCD 2011 Midpoint v1.09 (Wolf et al., 2012). The midpoint impact categories analyzed were: climate change (GW, kg CO_2eq), acidification (AC, mol H^+_{eq}), terrestrial eutrophication (TE, mol N_{eq}), freshwater eutrophication (FE, kg P_{eq}), marine eutrophication (ME, kg N_{eq}), ozone depletion (OD, kg CFC-11_{eq}), photochemical ozone formation (POF, kg $NMVOC_{eq}$), particulate matter (PM, kg $PM_{2.5eq}$) and mineral, fossil and renewable resources depletion (MFRRD, kg Sb_{eq}).

3. Life Cycle Inventory

3.1. Red deer census (UP1)

The wild deer census was carried out both at night and during the day. The night census, carried out with the participation of local hunters, consisted of travelling standard linear paths in off-road vehicles equipped with spotlights to identify the wild animals. Nine crews of three people travelled a total of D_{Cn1} = 436 km to realize the night census. In addition, a medium distance of 17 km/hunter (distance from the hunter residence to the census meeting point) was considered (D_{Cn2} = 918 km), resulting in a total night census distance of D_{Cn} = 1,354 km.

Differently from the night census, the whole hunter group (n_h = 168; n_{h1} = 139 coming from the VCO district and n_{h2} = 29 from outside) contributed to the day census. To quantify the distance related to this census, for each hunter tour—from the residence (HM) to the hunting zone (HZ)—has been accounted for. Therefore, for the day census, the total distance was D_{Cd} = 12,618 km (Supplementary Material, Table S.4).

Among the different passenger car datasheets included in the Ecoinvent v3.3 Database, off-road vehicle transfers (D_{Cn1}) were modeled as *transport, passenger car, large size, diesel, EURO 3 {RER}*, whereas for the remaining transfers (D_{Cn2} and D_{Cd}), the assumption is that 50% of the total distance was covered by a EURO3 diesel passenger car and 50% by a EURO3 petrol passenger car (*transport, passenger car, medium size, petrol, EURO 3 {RER}*). On one hand, the hypothesis on the emission standards goes along with a worst-case strategy, and on the other hand, the share between petrol and diesel cars reflects the Italian car fleet in the 2015 (Automobile Club Italia, 2017). These datasheets are not site-specific: they simply model transportation in a passenger car in Europe, taking into account (i) the average fuel consumption, (ii) an unspecific driving cycle, and (iii) average emissions (Simons, 2016).

3.2. Bullets production (UP2)

In the HD—excluding some special protection areas —there are no limitations on either the type of bullets (lead or lead-free) or the number of shots fired during the hunting activities. Primary data collected at the Trontano CC (2015 season) report information about (i) the type of bullet used and (ii) the mass of the bullets used in the n_{rd} = 140 *exits-with-cull*.

Although it considers military ammunition, the study of Ferreira et al., 2016, was chosen as the reference to model ammunitions manufacturing (Supplementary Material, Table S.7). The reasons behind this choice are that (i) the manufacturing phase of selective hunting (one standalone projectile) and military ammunitions could be considered similarly, whereas they could widely differ in terms of the consequences of the bullet on the target (Andreotti and Borghesi, 2012) and (ii) to the authors' knowledge, the study seems to be the only one modeling the production of different typologies of bullets from an LCA perspective, considering four different components (cartridge, projectile, primer and propellant) for lead and lead-free ammunitions. In this LCI, only the materials requirement associated with the projectile and the cartridge, as well as the total energetic and water consumptions, were considered (Supplementary Material, Table S.5) because the influence of the primer and the propellant was assessed as negligible in the life cycle of ammunitions (Ferreira et al., 2016).

3.3. Hunting trips (UP3)

UP3 includes the total distance travelled in the 2015 hunting season by the whole group of hunters (n_h = 168) to cull n_{rd} = 140 wild red deer. Hunter trips have been subdivided into: (i) *exit-with-cull* and (ii) *exit-no-cull* (the hunter did not cull any wild animal).

Although the outward trip is considered the same in both situations, in an *exit-with-cull*, the return trip is always calculated as the distance from the Trontano CC to the hunter's residence, whereas in an *exit-no-cull*, the return trip distance is equal to the outward trip distance. The transportation from the hunting zone to the Trontano CC is excluded from UP3 and included in UP5 (Figure 1). The methodology adopted for the calculation of individually travelled distances is widely described in the Supplementary Material. The total distance covered by the hunters resulted in D_{tot} = 105,139 km (751 km·culled red deer^{-1}). Almost 55% of the D_{tot} (58,036 km) was travelled by hunters with no prey during the year (hunter class H0), 33% (34,305 km) by hunters with one prey (hunter class H1) and the remaining 12% by H2, H3 and H4 hunter classes to cull 78 wild red deer (Table 3). Each hunter spent an average of n_E =10.0 exits to reach the HD (covering an average distance of 62.6 km·hunter^{-1}·exit^{-1}), but the total average specific distance (km·hunter^{-1}) shows a wide range of values between different hunter classes (from 162 for H4 to 910 for H3).

Given that no information was available about the types of vehicles used to reach the hunting areas or the variability in the transportation means (due to social and age differences in the hunter groups, Gaviglio et al., 2017), the transportation was modeled using two different database sheets from Ecoinvent v3.3 (see paragraph 3.1). Each hunter was considered to drive individually to the hunting zone (HZ): 50% of hunter cars were modeled by "*Transport, passenger car, large size, diesel, EURO 3 {RER}*", and the remaining half by "*Transport, passenger car, medium size, petrol, EURO 3 {RER}*" (Saxe, 2015).

Table 3. Distance covered by the hunters during the red deer hunting season (year 2015).

HUNTER CLASS	HUNTERS (n)	TRAVELLED DISTANCE (km)	(% tot)	(km·hunter^{-1})	HUNTING EXITS (n)	(% tot)	(n·hunter^{-1})
H0	71	58,052	55.2	818	721	43.1	10.2
H1	62	34,305	32.6	553	565	33.8	9.1
H2	29	8,818	8.4	304	321	19.2	11.1
H3	4	3,640	3.5	910	42	2.5	10.5
H4	2	324	0.3	162	25	1.5	12.5
TOTAL	**168**	**105,139**	**100**	**626**	**1,674**	**100**	**10.0**

3.4. Hunting activity (UP4)

UP4 models the wild red deer withdrawn from the ecosphere and entering into the supply chain. From an LCA perspective, it is relevant to quantify the amount of "*naturally occurring biotic resource*" prevailing from nature (Crenna et al., 2017). According to previous research (Viganò et al., 2017) carried out in the same hunting district, the ratio between the wild red deer standard mass (m_{std}) and the whole mass (m_w) equals $k_{p1} = m_{std}/m_w = 0.72$. This index is comparable to the values shown in Becciolini et al., 2016, for adult male (73-78%) and adult female (70-72%) wild red deer living in the Northern Apennine and Central Alps. Consequently, the wild red deer elementary flow entering the system can be estimated as: $m_w = m_{std}/k_{p1} = 9{,}761/0.72 = 13{,}556$ kg. This means that 1.39 kg of m_w must enter into the system to produce 1.0 kg of m_{std} (FU).

The main outflows of UP4 are the n_{rd}=140 STD carcasses (both CE and PE) of wild red deer culled. Viscera (intestines and stomach) and blood components removed from the ungulates and left on the field have been quantified in $m_v + m_b$ = 3,023 kg·year^{-1} (22.3% of the m_w, primary data). Due to the unknown interactions between visceral and blood components and the surrounding environment, these natural outflows are considered as elementary flows exiting the system. In the case of CE red deer, a surplus offal flow of m_{o1} = 377 kg exiting UP4 can be computed (5.7% of the m_w, primary data).

To cull 140 wild red deer, 195 bullets were shot in *exits-with-cull*, resulting in 1.4 bullets/animal, of which 65% were lead bullets and 35% lead-free. No primary data were available for the bullets eventually shot in the *exits-no-cull*, and consequently, they were not included in the LCI. The emissions linked with the firing of shots influence both the air and the soil environmental compartments. The air emissions were computed using the data reported in Ferreira et al., 2016, which referred to the same ammunition used to model the production phase (Table S.6). Regarding the soil emissions, the assumptions were: (i) all fired shots passed through the wild red deer (both missing and striking shots) and (ii) all the metal composing the projectiles (lead or copper) entered the soil. To estimate the amount of metal emissions to soil, the method proposed in the ISPRA report (Andreotti and Borghesi, 2012) for the quantification of lead dispersed during hunting activities was applied for both lead and lead-free ammunitions. The amounts of lead and copper (m_m, g·year^{-1}) entering the soil were calculated multiplying: (i) the annual number of red deer entering the Trontano CC ($n_{rd,}$, -), (ii) the average number of shots by an individual (n_b, -), and (iii) the average bullet mass (m_b, g). This mass was derived from primary data collected at the CC (the projectile mass is the only component that exits from the rifle during the shooting phase)[1]. The results showed that 1,270 g·year^{-1} of lead and 670 g·year^{-1} of copper were emitted to the soil of the HD during the 2015 wild red deer hunting season (Table 4).

Table 4. Input values and estimated soil emissions due to fired shots during the wild red deer hunting season (year 2015).

PARAMETERS	SYM	UM	LEAD	FREE-LEAD
Annual n. red deer culled (#)	n_{rd}	-	96	43
Average n. shot/animal	n_b	-	1.32	1.55
Average bullets mass	m_b	g	10	10
Annual amount of metal	$\mathbf{m_m}$	**g·year^{-1}**	**1,270**	**670**

Note: (#**)** For one red deer, there was no information about the type or number of fired shots.

[1] The brass cartridge remains inside the rifle, and normally, it could be reused by the hunters or conserved at home. In this assessment, neither the final treatment nor the recycling of material is considered.

3.5 Control Center (UP5-UP8)

The transportation of the CE and PE n_{rd} = 140 red deer from the HZs to the Trontano CC (UP5) was modeled as the hunting exits (with 50% of the distance individually travelled in diesel cars EURO3 and 50% in petrol cars EURO3). The total distance amounted to D_{CC} = 2,893 km, which is equivalent to 20.7 km·culled red deer^{-1} and 0.29 km·kg^{-1} STD.

Excluding the electricity used for lights, hook scales and electronic devices, all material inputs entering UP6 are linked to the maintenance of hygienic conditions during the red deer carcass management (Table 5). Three pairs of latex gloves (10 g rubber·pair^{-1}) are used for red deer, whereas the consumption of other inputs (tap water, electricity, paper and soap) at the CC was allocated to the red deer by adopting a mass criterion (Table 2). The outputs of UP6 are m_{std} = 9,760.5 kg STD of red deer carcass and m_{o2} = 393 kg of offal (associated with PE red deer). The total offal flow of the product system from UP4 and UP6 was $m_o = m_{o1} + m_{o2}$ = 770 kg.

Since no primary data were available for waste production, the hypothesis is that the amount of waste (paper, rubber) is equal to the input. The waste treatment (UP8) is modeled through Ecoinvent v3.3, supposing the municipal incineration of solid wastes. The transportation of wastes to the incinerator is not included in the SB, and no benefits from energy recovery are considered (Environdec, 2015).

Table 5. Main inventory inputs and outputs of the Trontano CC (UP6) (year 2015).

INPUT (UP6)				
FLOW	**UM**	**TOTAL**	**FU (1 kg STD)**	**DATABASE Sheet**
Red deer culled	kg	10,153	1.04	-
Tap water	m^3	3.3	3.4E-4	*Tap water {Europe without Switzerland}| market for| Alloc Rec, U*
Electricity	kWh	964.7	0.1	*Electricity, medium voltage {IT}/ market for| Alloc Rec, U*
Paper	kg	6.87	7.0E-4	*Tissue paper {GLO}| market for| Alloc Rec, U*
Rubber	kg	4.20	4.2E-4	*Synthetic rubber {GLO}| market for | Alloc Rec, U*
Core board	g	252	3.0E-2	*Core board {GLO}| market for| Alloc Rec, U*
Sodium hypochlorite	l	1.81	1.8E-4	*Sodium hypochlorite, product in 15% solution state {GLO}| market for| Alloc Rec, U*
OUTPUT (UP6)				
FLOW	**UM**	**TOTAL**	**FU (1 kg STD)**	**ALLOCATION of impacts**
Red deer carcass (STD)	kg	9,761	1	100%
Offal	kg	392.9	0.04	0%
WASTE (UP8)				
FLOW	**UM**	**TOTAL**	**FU (1 kg STD)**	**DATABASE Sheet**
Rubber	kg	4.2	4.2E-4	*Treatment of municipal solid waste, incineration {IT}, alloc, Rec*
Paper/core board	kg	7.12	7.3E-4	

Wastewater	m^3	3.3	3.4E-4	*Wastewater, average {Europe without Switzerland}| treatment of wastewater, average, capacity 1E9l/year | Alloc Rec, U*

4. Life Cycle Impact Assessment

The contributions of the different UPs to the LCIA results and the absolute values of nine selected impact categories are shown in Figure 2 and Table 6, respectively.

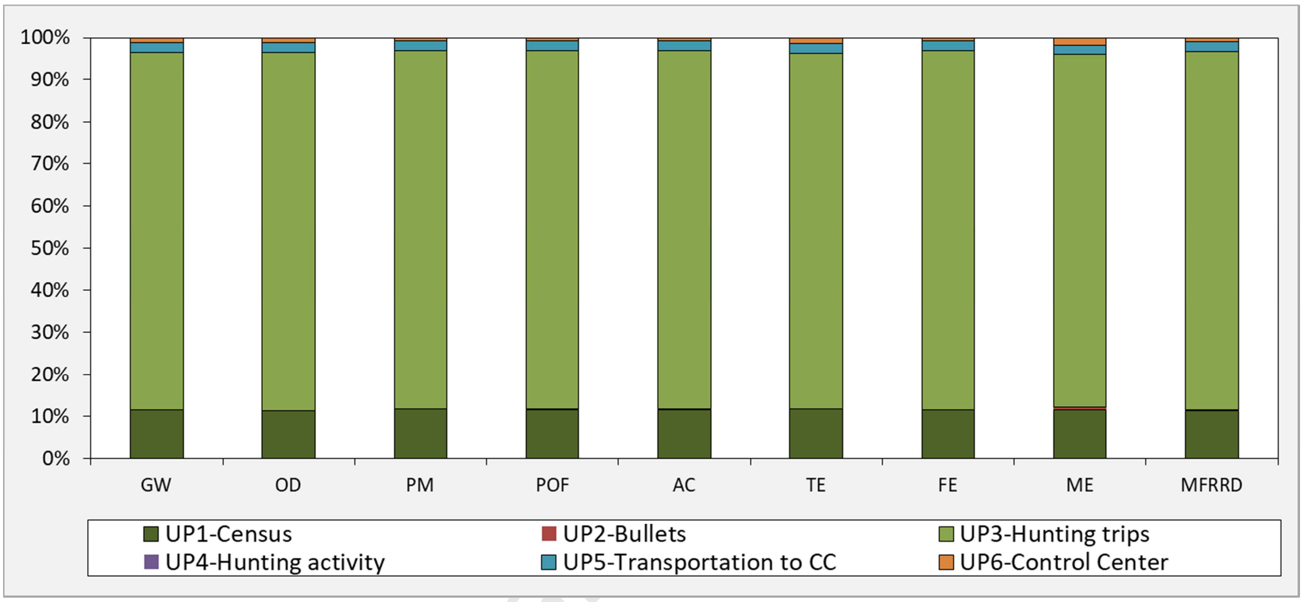

Figure 2. LCIA results referring to the FU in nine impact categories. The values referred to UP6 include both UP6, UP7 and UP8. GW: climate change; OD: ozone depletion; PM: particulate matter; POF: photochemical ozone formation; AC: acidification; TE: terrestrial eutrophication; FE: freshwater eutrophication; ME: marine eutrophication; MFRRD: mineral, fossil and renewable resources depletion.

Table 6. Absolute results of the study in twelve impact categories (referred to the FU = 1 kg STD carcass). The values referred to UP6 include both UP6, UP7 and UP8.

IMPACT CATEG. (#)	UM	CENSUS (UP1)	BULLETS (UP2)	HUNTING TRIPS (UP3)	HUNTING ACTIVITY (UP4)	TRANSP. TO CC (UP5)	CONTROL CENTER (UP6)	TOTAL
GW	kg $CO_{2\ eq}$	5.57E-01	1.20E-03	4.13E+00	1.59E-06	1.14E-01	5.62E-02	4.85E+00
OD	kg CFC-1 1_{eq}	8.74E-08	1.04E-10	6.56E-07	0.00E+00	1.81E-08	6.44E-09	7.68E-07
PM	kg PM2.5 $_{eq}$	4.00E-04	2.05E-06	2.89E-03	4.15E-09	7.95E-05	2.40E-05	3.40E-03
POF	kg NMVOC $_{eq}$	1.87E-03	6.51E-06	1.37E-02	1.78E-07	3.77E-04	1.22E-04	1.61E-02
AC	molc H+ $_{eq}$	2.38E-03	2.94E-05	1.72E-02	1.87E-07	4.74E-04	3.02E-04	2.04E-02
TE	molc N $_{eq}$	5.49E-03	2.33E-05	4.00E-02	9.29E-07	1.10E-03	4.01E-04	4.70E-02
FE	kg P $_{eq}$	1.10E-04	5.26E-06	8.12E-04	0.00E+00	2.23E-05	1.66E-05	9.66E-04
ME	kg N $_{eq}$	5.13E-04	2.75E-06	3.73E-03	4.07E-08	1.03E-04	4.62E-05	4.40E-03
MFRRD	kg Sb $_{eq}$	1.29E-04	1.13E-05	9.68E-04	0.00E+00	2.66E-05	2.11E-06	1.14E-03

Note: (#) GW: climate change; OD: ozone depletion; PM: particulate matter; POF: photochemical ozone formation; AC: acidification; TE: terrestrial eutrophication; FE: freshwater eutrophication; ME: marine eutrophication; MFRRD: mineral, fossil and renewable resources depletion.

The results clearly show the predominant role of transportation (mainly UP1 and UP3) in the product system, putting in the background the production of bullets (UP2), the Control Center activities (UP6) and the hunting activity (UP4). The potential environmental impacts of the FU are closely related to the hunter trips, with 84-85% of the contributions in all the impact categories being due to this reason. Considering the climate change category (GW), 4.85 kg CO_{2eq} are associated with the culling of 1 kg STD (the FU) of wild red deer carcass. A total of 81% of the impacts on the category is exclusively due to CO_2 emissions during the hunting exits. Specifically, direct CO_2 emissions from car engine-exhausted gas contribute 50% of the total impact in the category, whereas indirect CO_2 emissions, connected with fossil fuel production and material components, as well as passenger car manufacturing, generate 30% of the total impact. The crude oil extraction process and the production of fuels generate Halon-1301 emissions, causing 85% (6.56E-07 kg CFC-11_{eq}) of the impact on the OD category (Wernet et al., 2016). The influence of UP3 on the AC is connected to the direct (fuel combustion) and indirect (material production and car manufacturing) emissions of SO_2 and NO_x. A total of 27%-29% of the impacts on the AC category is due to the indirect SO_2 emission occurring during fuel production for petrol and diesel cars, respectively. Moreover, transportation by diesel cars joins the indirect SO_2 emissions to the direct NO_x emissions (20% of the total impact on the AC). NO_x emissions are also the main contributors to the impacts on the POF, TE and ME, and in these categories, the influence of diesel passenger cars ranges from 55-62% of the total impact, against 24-30% from petrol cars. The use of passenger cars for 105,139 km of travel, corresponding to almost the 2/3 of the vehicle lifespan presented in the Ecoinvent Database (Wernet et al., 2016), generated the highest share of the impact (85%) on the MFRRD category, which was the only input-related category considered in the assessment. Specifically, 23%, 18% and 15% of MFRRD are linked to the utilization of lead, zinc and gold necessary for vehicle production and maintenance. Coherently, with the small dimensions of bullets, only 0.3% of the total impact on the MFRRD category is due to lead and zinc extraction for ammunitions manufacturing. Moreover, since the selected impact categories do not assess the roles of metals emitted within the shooting phase, a preliminary evaluation of human and eco-toxicity categories was carried out through the ILCD. The outcomes, which are included in the Supplementary Material, report that transportation activities (UP1 and UP3) cause more than 90% of the impact on the toxicity category, with negligible influence linked to shooting emissions (Figure S.1 and Table S.8).

Each hunter class contributes differently to the environmental burden of the supply chain. The exits of hunters with no (class H0) and only one prey (H1) contribute to approximately 55% and 33% of the overall impacts of UP3 and 47% and 28% of the impacts related to the FU, respectively. Moreover, even if the H2 class causes 7.1% of impacts on different environmental categories and the H3 class causes 2.9%, the distance covered by each hunter per deer are lower for the H2 hunters (152 against 303 km·hunter^{-1}·red deer^{-1}, per H2 and H3, respectively).

5. LCA interpretation and discussion

The first phase of the results interpretation consists in a scenario analysis focused on the transportation means adopted in the LCI in order to test the results of the hotspot analysis (i.e., UP3 is the hotspot) (par. 5.1). Later, the identification of wild red deer as an elementary flow was investigated and a comprehensive discussion of the overall results with respect to existing wild meat literature has been carried out (par 5.2). Finally, the position of wild red meet in the GHGs hierarchy of conventional meat was explored (par. 5.3) and feasible future research for LCA practitioners was presented (par. 5.4)

5.1 Transportation alternative scenarios

Since no primary data were available, the potential environmental impacts connected with red deer hunting in the base scenario (BS) are largely affected by the assumptions made about transportation means. Therefore, after calculating the total distance travelled in the day census and in the hunting exits, the BS scenario was compared with four alternative scenarios (AS), characterized by cars with different emissions standards and fuel types:

- AS_1: 100% distance covered by EURO3 diesel passenger cars;
- AS_2: 50% distance covered by EURO4 diesel and 50% by EURO4 petrol cars;
- AS_3: 50% distance covered by EURO5 diesel and 50% by EURO5 petrol cars; and
- AS_4: 100% distance covered by EURO5 petrol cars.

The results of the comparison, which referred to the FU and were obtained through the ILCD 2011 impact assessment method, show that the exclusive use of a diesel EURO3 passenger car (AS_1) generates higher impacts on every impact category, ranging from +3.5% (vs. BS) on the GW category to +181% (vs. AS_4) on the TE category (Figure S.2). As expected, the potential environmental impact on the categories largely affected by the use phase (PM, POF, TE and ME) is reduced by choosing a passenger car with higher emission standards. For instance, AS_3 and AS_4 generate 76% and 70% of the total BS results in the PM category and 91% and 66% in the POF category (Figure S.3). Finally, the GW and OD categories are more influenced by the production and combustion of specific fuels (Simons, 2016). The selection of EURO4 and EURO5 cars led to a reduction of the impact (i) in the GW category, ranging from -4% (AS_2 vs. BS) to -11% (AS_4 vs. BS) and (ii) in the OD category, ranging from -5% (AS_2 vs. BS) to -13% (AS_4 vs. BS).

In conclusion, the scenario analysis highlighted that the selection of transportation means in the BS modeling was quite conservative. Specifically, the results show more influence on impact categories associated with emissions standard limits (-49% AS_4 vs. BS in the TE; +43% AS_1 vs. BS in the ME) compared to the impact on categories mostly connected to fuel consumption (from -11% to +3% in GW; from -13% to +4% in OD). Focusing on climate change, the overall impact ranges from 4.3 to 5.0 kg $CO_{2eq} \cdot kg^{-1}$ STD, depending on the transportation means (Table S.9).

5.2 Wild red deer in LCA

Considering the limited existing LCA literature that applies to wild red deer supply chains (and hunted wild game meat in general), it is possible to note large differences in both the hotspot analysis and the overall results (Table 7). On one hand, Findlay et al., 2015 reported a CF ranging from 6.7 to 21.1 kg $CO_{2eq} \cdot kg^{-1}$ of deer carcass, with enteric CH_4 emissions responsible for approximately of 80% of the overall result. On the other hand, a weighted average of 28.6 kg $CO_{2eq} \cdot kg^{-1}$ of red deer meat (from 11.3 to 44.8 kg $CO_{2eq} \cdot kg^{-1}$ of red deer meat) was assessed by Saxe, 2015, highlighting foraging on farmers' fields and food production as the most relevant phases of the Danish venison LCA. By contrast, the environmental burden of wild red deer hunting in the northern Italy is almost completely caused by hunting exits, resulting in 4.3-5.0 kg $CO_{2eq} \cdot kg^{-1}$ of STD carcass. The lack of guidelines, the site-specificity of the studies and the continuous development of the LCA methodology could have affected to a great extent the authors' choices of system boundaries, the goal and scope (including the FU) and the impact assessment method, so that a robust comparison of the present study with the two abovementioned appears problematic. However, it is possible to note that the main differences between the three LCA studies occur in the inclusion (or exclusion) of foraging and CH_4 emission in the assessments. In the present study, wild red deer foraging on farmers' fields, even if grazing occurred and caused conflicts with some local human activities, was not included. On one hand, this is due to the lack of reliable primary data both on damages to crops and on the total wild red deer population, and on the other hand, it is due to the lack of a proper way to quantify the foraging. Shifting the focus to enteric CH_4 emissions, that has resulted as the environmental hotspot in Findlay et al., 2015, in the case of the LCAs of wild ruminant meat it seems fundamental to identify and specify the boundary between the ecosphere and technosphere. Indeed, according to Crenna et al., 2017, a (truly) wild animal has to be considered as a "*naturally occurring biotic resource*" and, consequently, an elementary flow entering the system (*material or energy entering the system being studied that has been drawn from the environment without any previous human transformation*, ISO, 2006a, 2006b). Therefore, according to the identification of wild red deer living in the VCO as an elementary flow, CH_4 emissions, even if naturally occurring, were excluded from the assessment. Some issues might be faced in case studies in which human transformations considerably influence wildlife (feeding animals), and "*man-made*" wild ruminants might be recognized as part of the technosphere (breeding wild animals). The consequences would not only affect the identification of wild ruminants as technological flows, but would also require the inclusion of enteric emissions in the assessment. To accomplish the quantification of CH_4 emissions, supplementary uncertainties could be generated by (i) the selection of a suitable emissions factor (EF) and (ii) the definition of the time horizon during which the enteric emissions are summed. Indeed, (i) the examined literature presents different EFs for red deer, depending on their actual dietary components (naturally foraged or cultivated feedstuff) or derived from the EFs of higher CH_4 producers (e.g., cattle) (Crutzen et al., 1986; EMEP/EEA, 2016; Hongmin Dong, Joe Mangino, 2006; Jackson et al., 2009; Pérez-Barbería, 2017; Swainson et al., 2007). Finally, (ii) it should be assessed whether all wild ruminant CH_4 emissions from birth to the killing date or only those produced during the analyzed period, as in Findlay et al., 2015, should be included in the assessment.

To understand the potential role of these emissions in the overall assessment, the GW result of this study has been re-quantified including the CH_4 emitted (characterization factor of 25 kg $CO_{2eq}\cdot kg^{-1}$ CH_4, Wolf et al., 2012) during the entire lifetime of the culled wild red deer (3.2 years is the average culled red deer lifetime, primary data). The GW ranged from 14.3 kg $CO_{2eq}\cdot kg^{-1}$ STD (+196% vs. BS; CH_4 contributes to 69% of the result) when using a weighted wild red deer EF (8.3 kg $CH_4\cdot head^{-1}\cdot year^{-1}$) (Pérez-Barbería, 2017) to 33.6 kg CO_{2eq} kg^{-1} STD (+593% vs. BS; CH_4 contributes to 87% of the result) when using an EF derived from farmed cattle (25.0 kg $CH_4\cdot head^{-1}\cdot year^{-1}$) (EMEP/EEA, 2016) (see Supplementary Material for details).

Table 7. Red deer LCAs: comparison of the goal-and-scope phase of the present study with those of existing literature.

TECHNICAL FEATURE		DANISH (Saxe, 2015)	SCOTTISH (Findlay et al., 2015)	ITALIAN (this study)
Functional Unit		(kg venison meat)	(kg dressed carcass)	(kg STD carcass)
Impact Assessment Method		Stepwise 1.05 method	Different Emission Factor Databases	ILCD 2011 Midpoint v. 1.09
Impact Categories		Multiple	Only Climate Change	Multiple
System Boundaries (Main UPs)	Feed or Foraging	x	*Not included*	*Not included*
	Bullets Production	x	*Not included*	x
	Culling Activities	x	x	x
	Methane Emission	*Not included*[2]	x	*Not included*

[2] Methane is cited in the report, but to the Authors' comprehension it is not included in the assessment.

5.3 Wild red deer meat supply chain

Considering the potential environmental impacts associated with wild red deer hunting and the assumption concerning enteric CH_4 emissions, it seems interesting to estimate where the wild red deer meat could potentially fall within the common food products GHGs hierarchy (Barilla Center for Food and Nutrition, 2016; Clune et al., 2017; Poore and Nemecek, 2018). Thus, starting from the STD carcass mass (primary data; m_{std}, kg), the environmental impacts have been referenced to the bone-free meat mass (m_{bfm}; kg). First, the ratio (primary data) $k_{p2} = m_{crc}/m_{std} = 0.87$ is considered, wherein m_{crc} (kg) is the carcass mass (meat and bones only), followed by the ratio $k_{p3} = m_{bfm}/m_{crc} = 0.82$ (BFM: bone-free meat, secondary data referenced to cattle, according to the Barilla Center for Food and Nutrition, 2016). The result for the GW category shows an impact of 6.85 kg $CO_{2eq}\cdot kg^{-1}$ BFM, highlighting (i) a positioning in the hierarchy close to that of mono-gastric meat (poultry, pigs) and (ii) environmental benefits (minus 73-76%) compared to those of average conventional beef meat, as in Findlay et al., 2015 and Saxe, 2015 (Table 8). From a LCA perspective, the improvement of the wild red deer supply chain appears strictly related to the hunter primary production efficiency. Even if hunting is, by definition, a lower-efficient activity compared to livestock production, the environmental load of the wild red deer meat supply chain could be strongly mitigated by reducing the total distance travelled and increasing the number of culled red deer per hunter, with a category upper bound equal to that reported in the Annual Harvesting Plan (192 wild red deer for the 2015; Table S.2 and S.3 in Supplementary Material). Indeed, not accounting for "unproductive hunters" (H0 class), the minimal distance to be covered in the 2015 to cull 140 red deer would be approximately 47,000 km, linked to a reduction of 47-52% of the overall impact, depending on the category (2.5 kg $CO_{2eq}\cdot kg^{-1}$ STD or 3.5 kg $CO_{2eq}\cdot kg^{-1}\cdot$ BFM). These results could be achieved by increasing hunting training, as also suggested by Gaviglio et al. (2017).

Table 8. Carbon footprint of different typologies of meat.

SOURCE	UM	POULTRY	PIG	BEEF	WILD RED DEER	WILD RED DEER (if methane is included)
Barilla Center for Food and Nutrition, 2016 (#)	kg $CO_{2eq}\cdot kg^{-1}$ BFM	3.9	5.3	25.7	-	-
Clune et al., 2017 (#)		4.1	5.9	28.7	-	-
This study		-	-	-	6.9	20.1 – 47.1

Note: (#) The results refer to the mean values found in the document.

5.4 Implications and future research for LCA practitioners

When dealing with wild ruminant supply chains, practitioners should be aware that the identification of the "wilderness" of ruminants is a remarkably challenging step that could lead to contrasting results and hotspots. For instance, if animals are fed and they can not be considered as belonging to the ecosphere, additional unit processes referred to feed production and enteric methane emission shall be included in the assessment. Furthermore, although selective hunting is a method by which to control the wildlife population and, theoretically, does not put pressure on the future availability of natural resources, it seems highly relevant to quantify the biotic resources depletion through new impact categories –now missing- and related characterization factors as suggest, for instance, in Crenna et al., 2017.

The results of this study are site- and time-dependent, and further steps towards a more strong assessment might concern:

- the quantification of results variability in the HD due to the different annual ratios between travelled distance during hunting exits and the total STD carcass mass provided and a more accurate estimation of transportation distances and means (e.g., fuel type, emission standard) (Maroušek et al., 2015). This advice could be useful to create a robust LCI in assessments with system boundaries similar to the one presented.
- the comparison "*from-field-to-fork*" (Notarnicola et al., 2017) of locally hunted red deer meat with imported meat from abroad, stressing the detection of the main differences in the LCA between the same-wild or farmed-food product (e.g., raw meat, long-cooked meat, sausages). In fact, referring to the case study, in many restaurants of the VCO district, it is possible to find venison (mainly farmed) coming from New Zealand or Eastern Europe, whereas locally hunted meat is discarded (Gaviglio et al., 2018).

Finally, when comparing wild red deer meat with farmed red deer meat or even conventional meats, it seems necessary to widen the investigation and support the LCA with nutritional, taste and quality information and animal welfare assessments. Further assessments are strongly recommended.

6 Conclusion

Considering public concern about environmental issues linked to meat production and the lack of LCA literature analyzing wild game meat, the present research focused on wild red deer meat produced during one hunting season in a mountainous Italian hunting district.

Despite that the case study focuses on only one species and covered little information on the Italian hunting sector, some interesting results emerged. First, the distance covered by the hunters is the main hotspot of wild red deer meat production, regardless of the impact category. Second, wild red deer meat hunted in the VCO cannot be considered a *"zero-impact"* meat. However, highlighting the influence of naturally occurring CH_4 emissions on the results, this type of wild venison appears to be an environmentally friendly alternative to conventional beef meat, ranking near conventional pig and poultry meat.

The overall results pointed out that a key strategy by which to mitigate the environmental loads of future wild supply chains should focus on the hunters. A transition towards *"professional hunting"* (trained hunters aiming at high-quality food provisioning) could reduce the driven distances and total impacts, but it is still not allowed by national law ("Legge 11 febbraio 1992, n.157- Norme per la protezione della fauna selvatica omeoterna e per il prelievo venatorio. G.U. Serie generale n. 46 del 25-02-1992- Suppl. Ordinario n.41," n.d.). Consequently, on one hand, it seems pivotal to increase hunter training and the awareness of their role in the environmental sustainability of wild meat provisioning, and on the other hand, it is important to improve the regulations, according to the national law, to foster efficient hunting (*"professional hunting"*).

The data collection, modeling and outcomes, as well as the methodological issues faced, could furnish a new relevant background to LCA practitioners approaching analogous case studies. However, the low representativeness of the findings seems to be a weak point of the research. Broadening the results to other hunting districts should be undertaken with caution, especially in territories where hunting regulations largely differ from those of the VCO. Enlarging the view to (i) multiple wild animals (red deer, roe deer, chamois, boar) with different sizes and harvesting plans and to (ii) the national situation seems crucial to facilitate going beyond the basic comparison between products (conventional and wild meat) and to test and quantify the potential role of wild meat consumption as an action through which to tackle climate change (FAO, 2013; Hyland et al., 2017; Poore and Nemecek, 2018).

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Highlights

- The environmental burdens of a hunting supply chain have been investigated
- Wild red deer is considered as an elementary flow entering the system
- The distance covered by hunters for hunting represents the environmental hotspot (85%)
- Wild red deer can not be considered as a *zero-impact* food