Dipartimento di Scienze Agrarie e Forestali

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GREENHOUSE GAS ASSESSMENT OF AGRO-SILVO-PASTORAL SYSTEMS OF THE MEDITERRANEAN COAST: THE CASE OF CASTELPORZIANO RESERVE

AGR/18 - Animal Nutrition and Feeding

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Table of Contents

Abstract

Despite some deniers still persist, the evidences of climate change (CC) are currently growing before our eyes, and global warming is one of the major threats to public global health. The world is way behind on its commitment to reduce greenhouse gas (GHG) emissions, and in the next decades, nations must make an unprecedented effort to cut their levels of GHG to avoid climate chaos.

By providing food to about 7.7 billion of people, agriculture contributes to a significant share (11-12%) of the global GHG emissions, especially because of methane (CH_4) and nitrous oxide (N_2O) emissions sources. However, if it is true that agriculture is a part of the CC problem, it is equally true that agriculture could be a part of the solution.

Carbon sequestration in the agriculture sector is the capacity of agricultural lands and forest to remove CO_2 from the atmosphere. Specifically, CO_2 is absorbed by trees, plants and crops through photosynthesis, and stored as cellulose, hemicellulose and lignin in tree trunks, branches, foliage, roots and soils. As a result, soils are the largest terrestrial carbon sink in the planet. Therefore, if on one hand a release of just 0.1% of the soil organic carbon (SOC) currently stocked in European soils would be equal to the annual emissions from 100 million cars, on the other hand, a small increase of its content would significantly reduce the CO_2 concentration in atmosphere.

The dynamics (i.e., increase and decrease) of SOC are highly influenced by agricultural practices, climate and soil. In this context, by employing farming practices that involve minimal disturbance of the soil and the use of organic fertilizers, farmers may be able to increase the amount of SOC in their fields, and thus contribute to both soil fertility maintenance, and global GHG mitigation. However, although SOC sequestration could be a great ally in the fight against CC, the sustainability of the agricultural sector cannot be achieved by focusing solely on the upstream processes of the system, and GHG mitigation opportunities must be identified also at later stages of the supply chain.

In this regard, by allowing the evaluation of the overall environmental impacts generated along a product/service life cycle (i.e., from raw material acquisition, through production and utilization phases, to waste management), the Life Cycle Assessment (LCA) is a useful tool that could help in defining effective mitigation strategies.

Nowadays, the need for verified and credible information on GHG emissions is increasing, with pressure coming from a wide range of interest groups (e.g., governmental and non-governmental organizations) aimed on reducing greenwashing. In this respect, the environmental labels based on LCA studies are valuable tools to establish credible green marketing claims.

This thesis is composed of three studies which have used the LCA approach to investigate the GHG emissions arising from different systems involving anthropogenic activities.

In the first study, the LCA approach was used to quantify the overall GHG emissions (from cradle-to-grave) generated by a local organic beef supply chain. The study identifies the main GHG hotspots, and suggests some mitigation practices that could be applicable along the short supply chain.

In the second study, the LCA approach allowed the evaluation of the GHG emissions (from cradle-to-farm-gate) arising from a farm that rears native beef cattle within a Mediterranean natural reserve of Italy. Specifically, in this study different agronomic practices, grazing management and climate scenarios were evaluated for their contribution on the soil GHG emissions and sinks, and thus the overall farm carbon footprint.

Finally, the third and last study aimed at developing a standard (LCA-based) guideline to be followed when assessing the GHG emissions (from cradle-to-grave) generated by all the common activities taking place within a National park. Particularly, the feasibility and applicability of the guideline proposed, was tested using a Mediterranean natural reserve of Italy as case study. Although GHG hotspots and mitigation strategies were discussed within the paper, the final aim of the work was to propose a widely accepted LCA-based guideline to be followed in order to obtain an environmental declaration for natural parks.

The results of this PhD thesis provide interesting insights about the GHG emissions arising from typical beef systems of the Mediterranean area, and about some possible related mitigation strategies. Although the livestock and soil emissions resulted as the main GHG hotspots of the beef supply chain, home consumption and retail phases have also shown potential room for improvement. The adoption of conservation tillage practices and the use of organic fertilizers were shown to be effective in mitigating the GHG emissions arising from the beef farm system. While, by providing a granular picture of the Mediterranean natural reserve' GHG emission sources and hotspots, the proposed LCA-based guideline shown to feasible and suitable in achieving the planned objectives.

Riassunto

Nonostante l'insistenza di qualche instancabile negazionista, i cambiamenti climatici (CC) stanno avendo, e ancor di più avranno in futuro, rilevanti impatti sugli ecosistemi e sulle attività umane. Secondo l'ultimo report (2019) del Gruppo Intergovernativo sul Cambiamento Climatico (IPCC), il riscaldamento globale provocherà un aumento di siccità e piogge estreme in tutto il mondo, pregiudicando la produzione agricola e la sicurezza delle forniture alimentari. A pagarne le conseguenze saranno soprattutto le popolazioni più povere di Africa e Asia, con guerre e migrazioni.

Attualmente, il mondo è indietro rispetto agli impegni presi per ridurre le emissioni di gas serra (GHG) e le nazioni devono compiere uno sforzo senza precedenti per ridurre i loro livelli di GHG nei prossimi decenni, solo così saremo in grado di evitare il caos climatico.

Fornendo cibo a circa 7,7 miliardi di persone nel mondo, l'agricoltura contribuisce ad una quota significativa (11-12%) delle emissioni globali di GHG, soprattutto a causa delle importanti fonti emissive di metano (CH_4) e protossido di azoto (N_2O). Tuttavia, se è vero che l'agricoltura contribuisce al cambiamento climatico, è altrettanto vero che la stessa agricoltura può diventare parte della soluzione.

Con il termine sequestro di carbonio, si fa riferimento alla capacità delle terre e delle foreste di rimuovere la CO_2 dall'atmosfera. Attraverso il processo della fotosintesi infatti, la CO_2 assorbita da alberi, piante e colture, viene immagazzinata nella biomassa di tronchi, rami, radici e suolo. Di conseguenza, i suoli rappresentano il più grande magazzino di carbonio del pianeta. Pertanto, se da una parte il rilascio dello appena 0,1% del carbonio contenuto attualmente nei suoli Europei può essere paragonabile alle emissioni annuali generate da 100 milioni di automobili, dall'altra, un altrettanto piccolo incremento di questo contenuto può avere effetti significativi sulla riduzione di CO_2 nell'atmosfera.

Le dinamiche (ovvero incremento e decremento) del carbonio organico contenuto nel suolo (SOC) sono fortemente influenzate dalle pratiche agricole, dal clima e dalla tipologia di terreno. In questo contesto, tramite l'impiego di pratiche agricole che comportano un disturbo minimo del suolo e l'utilizzo di fertilizzanti organici, gli agricoltori possono contribuire sia al mantenimento della fertilità del suolo, sia alla mitigazione globale dei GHG.

Tuttavia, nonostante il sequestro di SOC rappresenti un grande alleato nella lotta al CC, la sostenibilità del settore agricolo non può essere raggiunta concentrandosi esclusivamente sui processi a monte del sistema, ma le opportunità di mitigazione dei GHG devono essere valutate e intraprese anche nelle fasi successive della catena di approvvigionamento.

A questo scopo, consentendo la valutazione degli impatti ambientali generati lungo il ciclo di vita di un prodotto o di un servizio (ovvero, dall'acquisizione delle materie prime, passando per le fasi di produzione e utilizzo, arrivando fino alla gestione del rifiuto generato), la valutazione del ciclo di vita (LCA) è una tipologia di analisi che può essere di aiuto nel definire efficaci interventi e strategie di mitigazione.

Al giorno d'oggi, la necessità di informazioni verificate e credibili sulle emissioni di GHG è in costante aumento, con pressioni provenienti da una vasta gamma di gruppi di interesse (es., organizzazioni governative e non governative) determinati a ridurre le strategie di comunicazione ingannevoli (greenwashing) che le imprese spesso utilizzano per creare una falsa immagine positiva sotto il profilo ambientale. A questo proposito, le etichette ambientali basate su studi LCA diventano strumenti preziosi per tutte le aziende che vogliono intraprendere operazioni credibili e verificate di marketing ambientale.

Questa tesi di dottorato si compone di tre studi che, tramite l'utilizzo dell'approccio LCA, hanno investigato le emissioni di GHG provenienti da diversi sistemi antropogenici.

Nel primo studio la metodologia LCA è stata coinvolta nella quantificazione delle emissioni GHG (dalla culla alla tomba) generate lungo una catena di approvvigionamento locale di carne bovina biologica, con lo scopo di: identificarne i principali punti emissivi (hotspots) e suggerire interventi di mitigazione applicabili lungo tutta la filiera.

Nel secondo studio, l'analisi LCA è stata applicata alla quantificazione delle emissioni GHG (dalla culla al cancello della fattoria) derivanti da un'azienda agricola che alleva bovini di razza Maremmana all'interno di una riserva naturale Mediterranea del centro Italia. Nello specifico, in questo studio sono state analizzate le dinamiche con cui l'adozione di diverse pratiche agronomiche, gestione del pascolo e scenari climatici futuri, possono influenzare le emissioni di GHG e gli stoccaggi di SOC, e di conseguenza l'impronta emissiva (impronta di carbonio) totale prodotta dall'azienda.

Infine, il terzo ed ultimo studio è stato incentrato allo sviluppo di una linea guida standard (basata sull'approccio LCA) da adottare al fine di valutare le emissioni di GHG (dalla culla alla tomba) generate da tutte le attività che prendono luogo generalmente all'interno di un parco/riserva nazionale. In particolare, l'applicabilità della linea guida proposta è stata testata in un caso studio che ha interessato la riserva naturale Mediterranea menzionata precedentemente. Sebbene nel documento siano stati discussi anche hotspots e possibili strategie di mitigazione, lo scopo finale del lavoro è stato quello di sviluppare una linea guida in grado di fornire un approccio LCA standardizzato da poter essere impiegato dai parchi naturali per intraprendere operazioni di marketing ambientale.

I risultati di questa tesi di dottorato forniscono interessanti spunti sulle emissioni di GHG derivanti dai tipici sistemi di allevamento di carne bovina dell'area del Mediterraneo, e su alcune delle possibili correlate strategie di mitigazione. Sebbene le emissioni di GHG generate dagli animali e dal suolo siano risultate le principali fonti di emissione lungo la catena di approvvigionamento della carne, sia i consumi domestici che la vendita al dettaglio hanno mostrato potenziali margini di miglioramento. L'adozione di pratiche agronomiche meno invasive e l'uso di fertilizzanti organici hanno dimostrato di essere efficaci nel mitigare le emissioni di GHG derivanti dal comparto agricolo. Infine, avendo fornito un quadro dettagliato dei principali hotspots della riserva naturale Mediterranea, la linea guida proposta in questa tesi ha dimostrato di essere adatta all'utilizzo dei suoi risultati per operazioni di marketing ambientale da parte dei parchi nazionali.

Ringraziamenti

Ci siamo, sono le 18:55 del 30.06.2020, in questo preciso momento ho completato la tesi che racchiude il lavoro, il sudore, le esperienze e le ansie di questi ultimi tre anni e mezzo di percorso formativo.

Fra poco sottometterò, definitivamente, l'elaborato alla coordinatrice del corso…ovviamente non prima di aver riletto e ricontrollato tutto fino alla nausea (povero me).

Anche se questa che state leggendo (rispetto a tutto il resto) è sicuramente la parte più semplice da scrivere, le cose che vorrei dire e le persone che vorrei ringraziare sono talmente tante che, dividerla in capitoli (es. famiglia, colleghi, amici, supervisori, professori, etc.) non sarebbe una brutta idea. Tuttavia, considerando che mi separano solo poche ore dal termine di consegna… beh, questa è decisamente una brutta idea.

Due sono i ringraziamenti che ci tengo a fare in particolar modo. Il primo lo voglio rivolgere a te che ti sei soffermato a leggere queste poche righe. Ti ringrazio perché se stai leggendo questa parte significa che hai voglia di conoscere qualcosa che va al di là di ipotesi di ricerca, analisi dei dati e presentazione dei risultati. Se stai leggendo queste righe vuol dire che sei curioso di conoscere qualcosa che mi riguarda più personalmente, qualcosa che fa parte della mia sfera emotiva, qualcosa di me… e per questo voglio dirti grazie.

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List of Tables

List of Figures

List of Abbreviations and Acronyms

C	Carbon
CB	Cooked organic beef
CC	Climate change
Cf	Current rate of fertilization
CFC	Chlorofluorocarbon
CFP	Carbon footprint
Cg	Continuous grazing
CH_4	Methane
CO_2	Carbon dioxide
CO_{2e}	Carbon dioxide equivalents
Ct	Current tillage
CtCf	Current tillage & current fertilization
CtHf	Current tillage & high fertilization
CtLf	Current tillage & low fertilization
DE	Digestible energy
DM	Dry matter
DNDC	Denitrification-Decomposition
EC	European commission
EF	Emission factor
EU	European union
FU	Functional unit
GEI	Gross energy intake
GHG	Greenhouse gas
Gt	Giga tonnes
GWP	Global warming potential
HCFC	Hydrochlorofluorocarbon
HDPE	High-density polyethylene
Hf	High (+50%) fertilization
HFC	Hydrofluorocarbon
ISO	International organization for standardization
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LDPE	Low-density polyethylene
Lf	Low (-50%) fertilization
LU	Livestock unit
LW	Live weight
Mt	Minimum tillage
MtCf	Minimum tillage & current fertilization
MtHf	Minimum tillage & high fertilization
MtLf	Minimum tillage & low fertilization
N	Nitrogen
NO_3^-	Nitrate

N_2O	Nitrous oxide
NCC	Current climate
NGV	Natural gas vehicle
NH_3	Ammonia
NO	Nitric oxide
Nt	No-tillage
NtCf	No-tillage & current fertilization
NtHf	No-tillage & high fertilization
NtLf	No-tillage & low fertilization
OEFSR	Organizational environmental footprint sector rules
PEFCR	Product environmental footprint sector rules
PFC	Perfluorocarbons
PhD	Doctor of Philosophy
ppm	Part per million
RCP	Representative concentration pathways
Rg	Rotational grazing
SB	System boundary
SOC	Soil organic carbon
UN	United Nations
VS	Volatile solids

Chapter 1

General Introduction

1.1. Background

Despite some deniers persist, the evidences of climate change (CC) are currently growing before our eyes, and global warming is one of the major threats to public health worldwide. The concentration of carbon dioxide (CO_2) in the atmosphere has increased from approximately 277 part per million (ppm) in 1750 (the beginning of industrial era) to 412 ppm at the beginning of 2020 (Dlugokencky and Tans, 2020). As a result, anthropogenic activities are estimated to have caused approximately 1°C of global warming above pre-industrial levels, an increase which is likely to reach 1.5°C between 2030 and 2050 if it continues to increase at current rate (IPCC, 2018).

The consequences of global warming include far-reaching and long-lasting changes to the natural environment and ecosystems. Indeed, about 6% of insects, 8% of plant and 4% of vertebrates are projected to lose over half of their climatically determined geographic range for a global warming of 1.5°C, compared with about 18% of insect, 16% of plants and 8% of vertebrates for a global warming of 2°C. High-latitude tundra and boreal forest are particularly at risk of climate change-induced degradation and loss, with woody shrubs already encroaching into the tundra (IPCC, 2018).

In recognition of this, in December 2015, 195 nations adopted the Paris agreement. The first instrument of its kind aiming at strengthening the global response to the threat of CC by holding the increase in the global average temperature to well below 2°C above pre-industrial levels, and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels. The visualization presented in Figure 1.1 shows a range of potential future scenarios of global greenhouse gas (GHG) emissions (measured in gigatons of CO_2 equivalents) based on data from Climate Action Tracker (CAT, 2019). Particularly, the figure shows how the world is not on-track to meet its agreed target of limiting warming to 2°C, and under the current policies, expected warming will be in the range 3.1-3.7°C by 2100 (Figure 1.1). Consequently, although we still have some potential pathways to follow that are compatible with limiting average global warming to 1.5-

2°C within this century (Figure 1.1.), these require an almost immediate sharp decline of GHG emissions, which is impossible to reach without including a reduction of non-CO_2 GHG and an increase of CO_2 removals measures (IPCC, 2018).

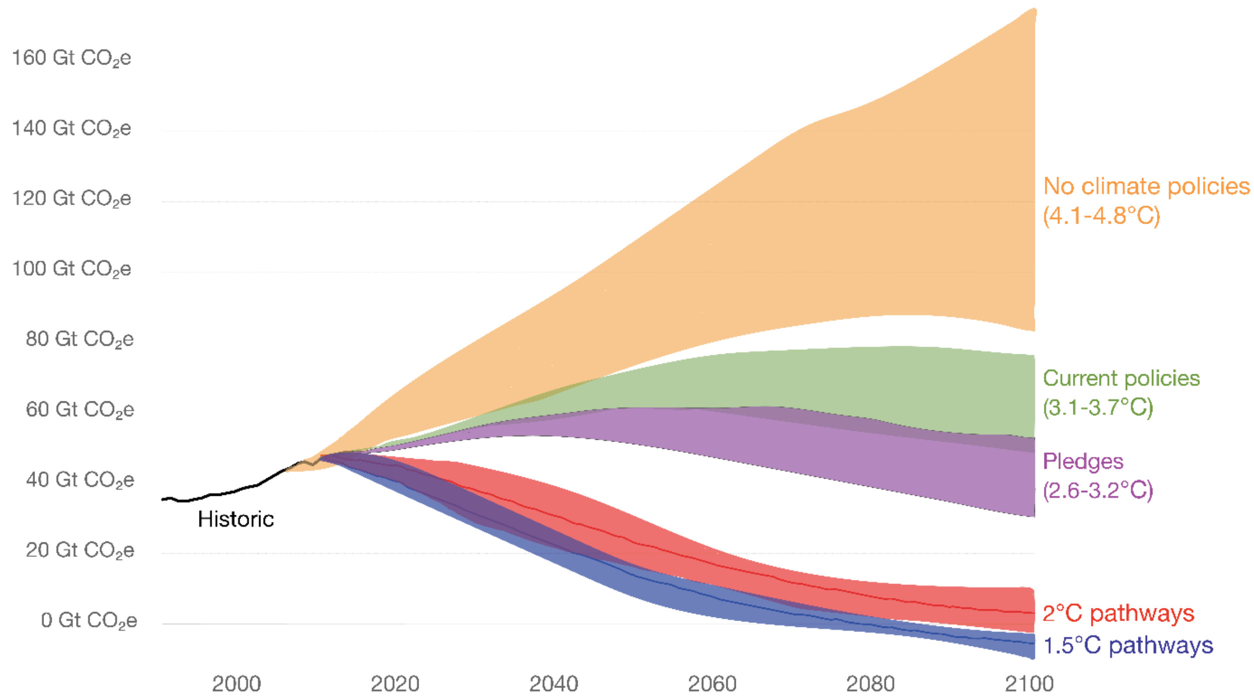

Figure 1.1 Projections of future global greenhouse gas emissions scenarios. High, median and low pathways represent ranges for a given scenario. Temperature figures represent the estimated average global temperature increase from pre-industrial, by 2100. Figure adapted from Hannah and Max Roser, (2020). CO_{2e} = Carbon dioxide equivalents; Gt = gigatons

Being responsible for around 40% of methane (CH_4) and 60% of nitrous oxide (N_2O) emitted globally, agriculture is the biggest source of non-CO_2 GHG emissions. Therefore, with an overall contribution between 10-12% of the total anthropogenic GHG emissions, agriculture will have to participate actively to achieve the CC goals: on the one hand by increasing biomass supply for fossil fuel substitution, and on the other hand, through direct GHG emissions cuts and removals (Frank et al., 2018).

Nonetheless, in the last revision of the world population prospects, the United Nations (UN) projected that the world's population would grow from 7.7 billion in 2019 to reach 8.5 billion in 2030 and 9.7 billion in 2050 (UN, 2019). Consequently, feeding this overgrowing population using the current land area and agricultural practices seems unimaginable. An improvement of the mitigation and adaptive capacity of the agricultural sector will be crucial for enhancing food security and limiting the increase of global average temperature (Dubey et al., 2020).

Despite this overall challenging scenario, it is no time to be pessimistic, and recent events (e.g., global climate strikes) have highlighted an increase of people' environmental awareness which is pushing governments to take actions against global warming. Sustainable development is now on the national and international agendas, it requires many things, but above all it requires rapid improvements in the efficiency of energy use, natural materials extraction, transport, and food production.

Nowadays, it is widely recognised that any producer works with "chains" of suppliers "upstream", and chains of customers "downstream". Companies and governments alike have started to look at products and services from cradle to grave, and simultaneously, Life Cycle Assessment (LCA) has become widely recognized as an effective tool for assessing the resource use, environmental burdens, and human health impacts connected with the complete life cycle of products, processes, and activities (EC, 2013).

Food production and consumption have a significant impact on the environment, with food systems contributing 19-29% of global anthropogenic GHG emissions, with meat and dairy products accounting for a significant share of this quota (Muller et al., 2019). The need for verified and credible information on GHG emissions is increasing, with pressure coming from a wide range of interest groups (e.g., governmental and non-governmental organizations) aimed at reducing greenwashing (Torelli et al., 2019). In this respect, the environmental labels are valuable tools when looking at actions to establish credible green marketing claims (Taufique et al., 2019).

Specifically, sustainable labels that show consumers the life cycle impact of the product converted to a standardised measure of carbon dioxide emissions (CO_2 equivalents), are referred to as Carbon Footprint of Products (CFP) labels. The rationale for these labels, when applied to food products, is that they may help to direct the consumer towards buying more GHG saving agricultural products, thus mitigating agriculture's contribution to global warming (Canavari and Coderoni, 2020).

1.2. Agricultural sources and sinks of greenhouse gases

Of the total 47.6 gigatons (Gt) of carbon dioxide equivalents (CO_{2e}) emitted on 2017 by the global anthropogenic activities (Gütschow et al., 2019), about 5.4 Gt of CO_{2e} (i.e., 11.4%) came from the agricultural sector (FAO, 2019). According to the data provided by FAO, (2019), in Figure 1.2 are shown the GHG contribution of the categories involved within this sector.

By including the incidence of enteric fermentation, manure left on pasture and manure management, the livestock sector accounts for around 60% of the GHG generated from the agricultural sector (Figure 1.2). While, except for the quota of the burning savannah (5%), which could be attributable to both crop cultivation and livestock farming, the remaining 35% is the share of the GHG linked to agricultural soil cultivation for food and feed purposes.

In the following sections the main agricultural GHG sources and the related mitigation strategies were briefly introduced.

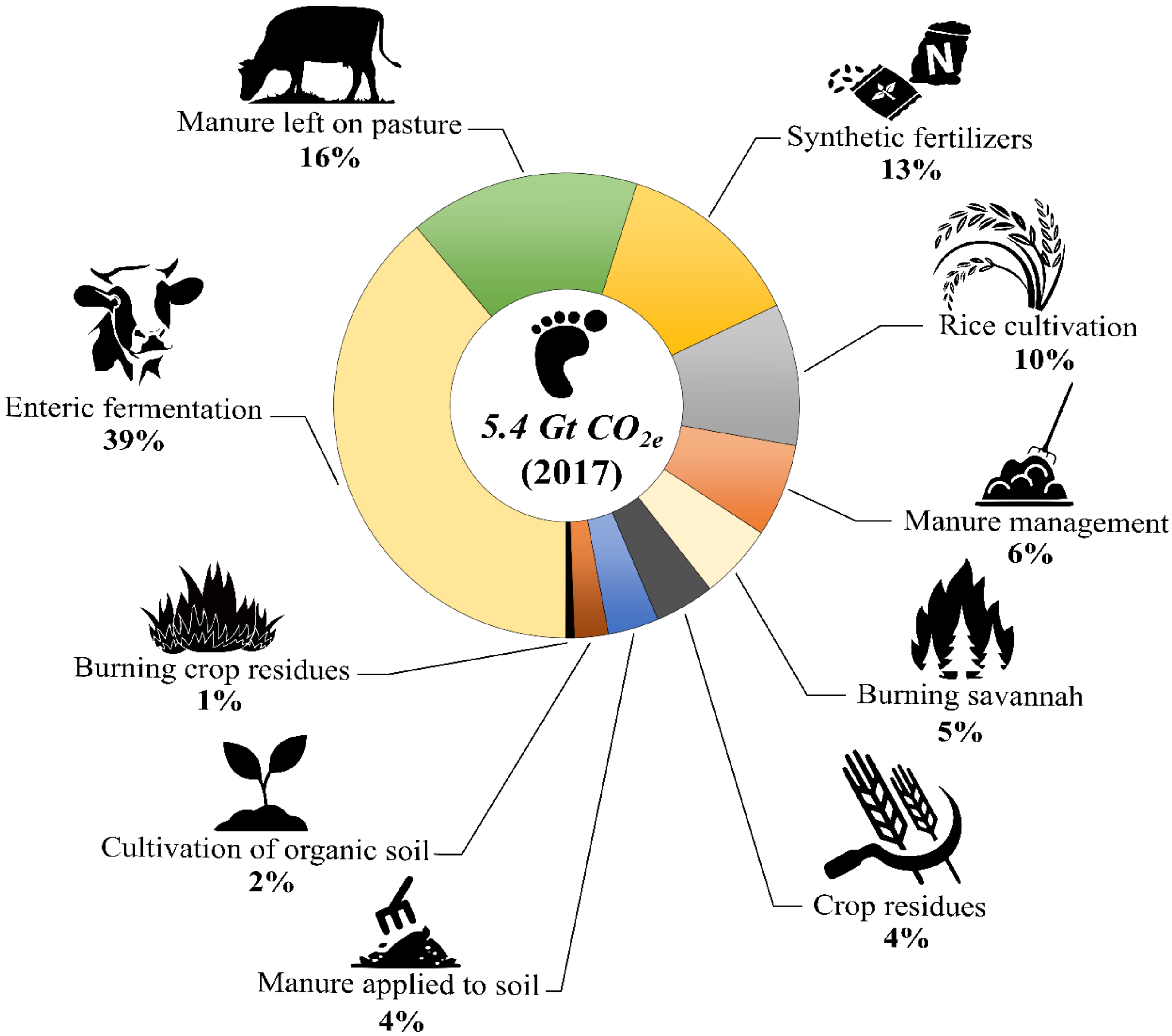

Figure 1.2 Breakdown of the GHG emissions generated by the agricultural sector. Figures adapted from FAO, (2019) data

1.2.1. Enteric fermentation

Enteric fermentation is a natural part of the digestive process of ruminants where bacteria, protozoa, and fungi contained in the fore stomach of the animal (rumen), ferment and break down the plant biomass eaten by the animal. Plant biomass in the rumen is converted into volatile fatty acids, which pass the rumen wall and enter the liver through the circulatory system. This process supplies a major part of the energy needs of the animal and enables the high conversion efficiency of cellulose and semi-cellulose, which is typical of ruminants. The gaseous waste products of enteric fermentation, CO_2 and CH_4, are mainly removed from the rumen by eructation. CH_4 emission in the reticulorumen is an evolutionary adaptation that enables the rumen ecosystem to dispose hydrogen, which may otherwise accumulate and inhibit carbohydrate fermentation and fibre degradation (McAllister and Newbold, 2008). The emission rate of enteric CH_4 varies according to feed intake and digestibility.

1.2.2. Manure emissions

Manure acts as an emission source for both CH_4 and N_2O, and the quantity emitted is linked to environmental conditions, type of management and composition of the manure. Organic matter and nitrogen content of excreta are the main characteristics influencing emission of CH_4 and N_2O, respectively. Under anaerobic conditions, the organic matter is partially decomposed by bacteria producing CH_4 and CO_2. Storage or treatment of liquid manure (slurry) in a lagoon or tank promotes an anaerobic environment which leads to an increase in CH_4 production. Long storage periods and warm and wet conditions can further increase these emissions (EPA, 2010). On the other hand, N_2O emissions need a combination of aerobic and anaerobic conditions to be produced. Therefore, when manure is handled as a solid (dung) or deposited on pastures, N_2O production increases while little or no CH_4 is emitted. N_2O is generated through both the nitrification and denitrification processes of the nitrogen contained in manure, which is mainly present in organic form (e.g., proteins) and in inorganic form as ammonium and ammonia. Nitrification occurs aerobically and converts ammonium and ammonia to nitrites and then nitrates, while denitrification occurs anaerobically converting nitrates to N_2O and nitrogen gas (Saggar, 2010). The balance between ammonium and ammonia is highly affected by pH, with ammonia increasing as pH increases.

1.2.3. Soil emissions

Generating CO_2, CH_4 and N_2O, soil and its use contribute substantially to the greenhouse effect (Smith et al., 2018). The GHGs produced from the soils are result of microbial activity, root respiration, chemical decay processes, as well as heterotrophic respiration of soil fauna and fungi. The capacity of the soil to produce or consume CO_2, CH_4 and N_2O is strictly connected to soil water content (humidity), soil temperature, nutrient availability, pH-value, and land-cover related parameters (Muñoz et al., 2010). The release of CO_2 from the soil comes mainly from anaerobic and aerobic decomposition of soil organic matter by soil microbes, and respiration from plant roots. The decomposition of the organic matter by methanogens under anaerobic conditions leads to production of CH_4, however, it can be also consumed under aerobic conditions by microorganism that use oxygen and CH_4 for their metabolism. Finally, the releases of N_2O are driven by nitrification and denitrification processes, which in turn are significantly influenced by agricultural practices (e.g., N application rate, crop type, fertilizer type, etc.) and soil conditions (e.g., soil moisture, soil organic C content, texture, etc.) (Oertel et al., 2016).

1.2.4. Livestock GHG mitigation strategies

The extreme heterogeneity of the agricultural sector needs to be considered when defining the overall sustainability of a mitigation strategy, which can vary across different livestock systems, species, and climates. To meet future needs of an expanding population, animal productivity needs to increase and GHG emission intensity per unit of product need to decrease. One of the principal ways to achieve this environmental standard is to adopt effective mitigation strategies, which may act directly by reducing the amount of GHG emitted, or indirectly through the improvement of production efficiency (Grossi et al., 2019).

To increase the effectiveness of these strategies, it is important to choose those that are synergic (win-win) with adaptation and avoid the conflictual ones (trade-off). Indeed, the sustainability of animal-agriculture practices in CC context is a wicked problem, and the best achievements require multidisciplinary holistic approaches. For example, high producing dairy cows are more susceptible to heat stress than low producing cows. Using lower production cows could reduce heat stress, lower milk output and lower input costs. However, there would be a concentration of maintenance costs with a reduction in efficiency and increased GHG intensity per unit of product (Gaughan et al., 2019).

Unfortunately, there is not a standard procedure to follow. Generally, no measure in isolation will encompass the full emission reduction potential, while a combination selected from the full range of existing options will be required to reach the best result (Llonch et al., 2017). The majority of the mitigation strategies aim to increase productivity (unit of product per animal), which in most cases cannot be achieved without good standards of animal health and welfare. Optimizing animal productivity has a powerful mitigating effect in both developed and developing countries, however, the size of the effect will also depend on factors such as the genetic potential of the animal and adoption of management technologies.

The GHG mitigating potential of the main strategies involving the livestock sector have been summarized in the following Table 1.1.

Table 1.1 Potential of various GHG mitigation strategies for the livestock sector (adapted from Grossi et al., 2019)

Strategies	*Category*	*Potential mitigating effect**	
		Methane	*Nitrous oxide*
Enteric fermentation	Forage quality	Low to medium	†
	Feed processing	Low	Low
	Concentrate inclusion	Low to medium	†
	Dietary lipids	Medium	†
	Electron receptors	High	†
	Ionophores	Low	†
	Methanogenic inhibitors	Low	†
Manure storage	Solid-liquid separation	High	Low
	Anaerobic digestion	High	High
	Decreased storage time	High	High
	Frequent manure removal	High	High
	Phase feeding	↕	Low
	Reduced dietary protein	↕	Medium
	Nitrification inhibitors	↕	Medium to high
	No grazing on wet soil	Low	Medium
	Increased productivity	High	High
Animal management	Genetic selection	High	↕
	Animal health	Low to medium	Low to medium
	Increase reproductive eff.	Low to medium	Low to medium
	Reduced animal mortality	Low to medium	Low to medium
	Housing systems	Medium to high	Medium to high

*High = ≥30% mitigating effect; Medium = 10-30% mitigating effect; Low = ≤10% mitigating effect. Mitigating effects refer to percent change over a "standard practice" according to Newell Price et al., (2011); Borhan et al., (2012); Hristov et al., (2013); Montes et al., (2013); Petersen (2013); Battini et al., (2014); Knapp et al., (2014); Llonch et al., (2017); Mohankumar Sajeev et al., (2018).

† Inconsistent/variable results.

↕ Uncertainty due to limited research or lack of data.

1.2.5. Soil C-sinks

CO_2 emissions resulting from respiration in soil and vegetation are the main sources from which this gas enters the atmosphere, being 10-15 times greater than CO_2 emissions generated using fossil fuels (Raich and Schlesinger, 1992). However, constant transfer of carbon occurs through the plants between the soil and the atmosphere and vice versa. Plants absorb CO_2 form the atmosphere through the process of photosynthesis and use it to build their roots, stems or leaves. Carbon is mainly transferred into the soil through the release of organic compounds by plants roots or through the decay of plant material or soil organism when they die. Microbial breakdown of the organic matter finally releases the nutrients which plants use to grow. During this process of decomposition, part of the carbon is released as CO_2 through soil respiration, whilst another part is converted into stable soil organic carbon (SOC) that is locked into the ground. The rate of this phenomenon depends on factors including temperature and rainfall, soil water-balance, and composition of the organic material (EC, 2011). As a result, if the rate of addition of new material is less than the rate of decomposition, soil organic matter declines, conversely, if the rate of addition is greater than the rate of decomposition, soil organic matter will increase.

Soils of the world can act as sinks or sources of GHG emissions, and the net balance between the absorbance of atmospheric C and its release determines the net temporal status of soils as either C absorbers (input) or releasers (outputs). Containing an estimated total of about 75 billion tonnes of carbon in the topsoil layer alone, European soils are a huge reservoir of C, and releasing even a tiny fraction of this carbon into the atmosphere would have a significant effect on efforts to fight CC. For example, a release of just 0.1% of the carbon now contained in Europe's soils would be equal to the annual emissions from 100 million cars (EC, 2011).

However, this process can also be seen in a reverse way. The "4 per 1000" (4‰) (https://www.4p1000.org/) initiative launched by France at the COP 21 in 2015 stressed the fact that C sequestration in agricultural soil could be an effective GHG mitigation strategy. Specifically, the initiative states that an annual grow rate of 4‰ in the soil C stock in the first 30-40 cm of ground, would significantly reduce the CO_2 concentration in the atmosphere related to anthropogenic activities.

Maintaining existing SOC stocks and enhancing SOC sequestration through sustainable soil management practices (e.g., minimum tillage, organic fertilization, crop rotation, etc.) constitutes a feasible solution to offset global emissions while providing a vast set of multiple benefits for the environment, people and the economy (Minasny et al., 2017).

1.3. LCA as a sustainable assessment tool

Numerous studies have shown that the main environmental hotspots within the food supply chain are associated with upstream activities (e.g., cultivation of crops and animal husbandry) that, as a result, have received the most attention from the governmental and non-governmental organizations. Although it is tempting to focus only on those upstream activities where most of the impact arises, sustainability cannot be achieved by focusing solely on those, but must also identify opportunities and implement improvements at later stages of the supply chain (Thoma et al., 2018).

The most commonly used tool for system scale assessment is the LCA, which aims at evaluating the overall environmental impact of a product or service, taking into account all the interactions with the natural environment occurring along its life cycle, i.e., from raw material acquisition, through production and utilization phases, to waste management.

Since the first development of LCA concept, scientist and experts collaborated to develop a set of rules to harmonize and guarantee a minimum quality standard. The collection of the framework and principles of LCA is today contained in two documents certified by the International Organization for Standardization (ISO) using the code ISO 14040 and ISO 14044 (ISO 2006a; ISO 2006b). The ISO 14040 defines the framework and principles of LCA, while the ISO 14044 defines the mandatory elements that make the analysis compliant to the International standard.

The standard procedure is composed of four steps: (i) goal and scope definition, (ii) life cycle inventory (LCI), (iii) life cycle impact assessment (LCIA) and (iv) interpretation (ISO 2006a, b).

i. Goal and scope definition

At this stage, the following must be defined: the reason for executing the LCA, a detailed definition of the products and its life cycle, the functional unit (FU), and the system boundaries (SB) that will be considered. The FU is a key element of an LCA study and represents a reference to which the inputs and outputs can be related. As per the system boundaries, it determines which unit processes will be included in the assessment, and it is partly based on a subjective choice when the boundaries are initially set (i.e., cradle-to-gate, gate-to-gate, cradle-to-grave, gate-to-grave).

ii. Life cycle inventory (LCI)

Within this phase all the inputs and outputs flow associated with the product or service being assessed must be determined and quantified. Usually, the development of the inventory is done by using input (e.g., raw material, energy needs, transportation, etc.) and output (e.g., final product, co-product, waste, etc.) data to construct a flow model which will help with the collection of the data, the most resource consuming part of the LCA.

iii. Life cycle impact assessment (LCIA)

The LCIA is defined by the ISO as the phase aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product or service throughout its life cycle. The LCIA is composed by three mandatory steps, which are: selection of impact categories, classification, and characterisation. In the selection phase, the environmental impacts categories to be assessed (e.g., CC, eutrophication, acidification, etc.) are selected in accordance with the goal of the study. In the classification phase, the input and output flows of the inventory are assigned to the relevant impact categories according to their ability to contribute to different environmental problems. In the characterization phase, each elementary flow assigned to an impact category is multiplied by a characterization factor that quantitatively represents the importance of that flow for a specific impact category.

iv. Interpretation

Within this final step, the result from the inventory analysis and impact assessment are summarized. Generally, the outcome of the interpretation phase is a set of conclusion and recommendations for the intended audience of the LCA. These are accomplished by identifying the life cycle stages at which mitigation interventions can substantially reduce the environmental impacts of the system or product.

1.3.1 GHG accounting approaches

Calculating GHG fluxes can be the most challenging part of developing GHG inventories, especially when the product or service being assessed is connected to the agricultural sector. Indeed, many different types of GHG emissions sources are associated with agriculture, and understanding the qualitative difference amongst these, is crucial to many steps in inventory development. As shown in Figure 1.3, an important distinction for the GHG emissions arising from the agricultural sector is between mechanical and non-mechanical sources (Russell, 2011).

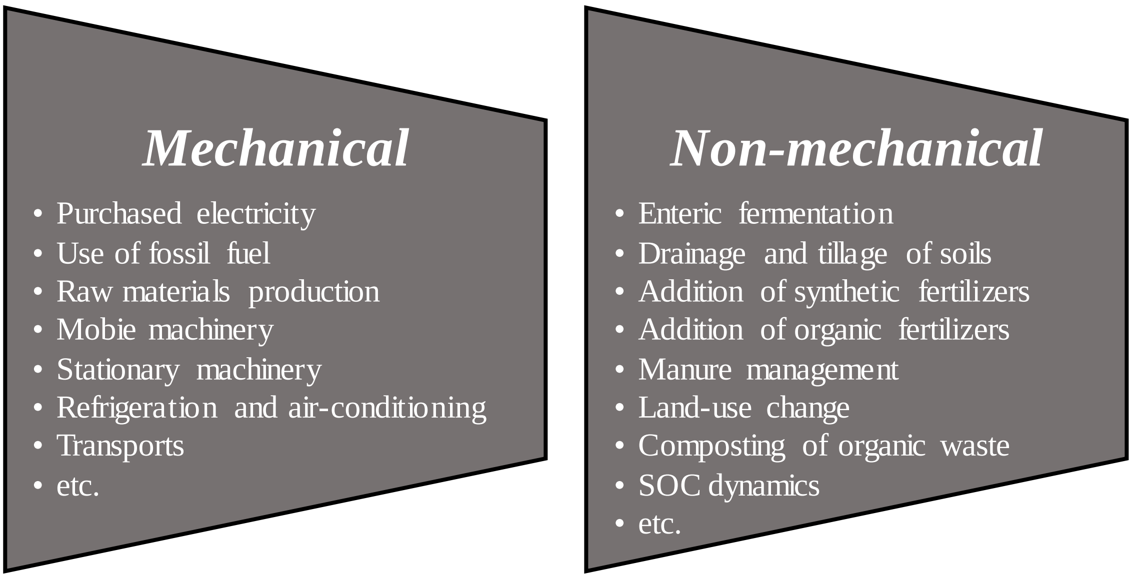

Figure 1.3 Not exhaustive list of mechanical and non-mechanical agricultural GHG emission sources (adapted from Russel, 2011)

Specifically, the non-mechanical GHG sources are either biological processes shaped by climatic and soil conditions, and are often connected by complex patterns of N and C flows through the farms.

As described above, CO_2 fluxes are mostly controlled by uptake through plant photosynthesis, and released via respiration, decomposition and the combustion of organic matter. N_2O emissions result from nitrification and denitrification processes, while CH_4 emissions result from methanogenesis under anaerobic conditions in: soil manure storage, enteric fermentation, and the incomplete combustion of organic matter.

The mechanical sources are, instead, equipment or machinery operated on farms, such as mobile machinery (e.g., tractors), stationary equipment (e.g., milking parlour), refrigeration and air-conditioning equipment which emit CO_2, CH_4 and N_2O, but also hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs) in some cases.

Globally, the non-mechanical sources are larger in magnitude than the mechanical ones, with enteric fermentation, manure and soil emissions, being the largest sources (FAO, 2019). The distinction between these two sources becomes paramount when calculating GHG fluxes and the associated levels of uncertainty. Generally, GHG emissions from non-mechanical sources can be calculated with lower accuracy than mechanical ones. Indeed, the complex interactions between management practices and variable environmental conditions, result to higher uncertainty of the GHG flux estimations, regardless of the calculation approach chosen.

There are plenty of LCA database available (e.g., Ecoinvent, Agri-footprint, Agribalyse, etc.) that can be used to account for mechanical GHG source of emissions. While there are three types of calculation approaches that can be used for non-mechanical sources: (i) field measurement, (ii) emission factors, and (iii) empirical model and process-based model.

i. Field measurements

Many GHG emission sources in agriculture can be measured using either direct or indirect measurement techniques. Direct techniques include controlled livestock chambers that measure the CH_4 emission from enteric fermentation (Castelán Ortega et al., 2020), flux chambers that measure the N_2O and CO_2 emissions from plots of land (Lognoul, et al., 2017), and gas flux meters that measures the CH_4 emissions from certain livestock waste management systems (Scotto di Perta et al., 2019). Indirect techniques include the measurement of carbon stocks before and after change in management practices or land use (Conant et al., 2011). However, although being useful for research, both direct and indirect techniques are often too costly for developing corporate inventories.

ii. Emission factors

The simplest approach involves the multiplication of management activity data by relevant emission factors (EFs), which are coefficients describing the amount of GHG flux per unit of activity (Tubiello et al., 2013). The accuracy of this approach depends not only on the accuracy of the activity data, but also on how specific the factor is with respect to the combination of environmental factors and management activities. Default EFs are largely based on field measurement at individual research sites or represent average values across a range of sites (Russell, 2011).

iii. Empirical and process-base models

Empirical models use field measurements to develop statistical relationships between GHG fluxes and agricultural management factors. While, process-based models mathematically link important biogeochemical processes that control the production, consumption, and emission of GHGs. Some model may only require one or several inputs to estimate GHG fluxes, while others might have extensive data requirements that span across different spatial and temporal scales. The accuracy of models is variable and depends on the robustness of the model, and the accuracy of the inputs (Hillier, et al., 2016).

1.3.2 The IPCC methodologies for GHG emissions inventories

The Intergovernmental Panel on Climate Change (IPCC) has developed a comprehensive set of methodologies (IPCC, 2006) to guide the preparation of National GHG inventories. The guideline defines three general Tiers of methodologies based on their complexity and data requirements. Generally, the use of EFs or simple empirical models (i.e., IPCC Tier 1 and 2) are the easiest and least resource-intensive approaches to use. But they are not very effective in capturing the geographical variation and biological processes influencing the GHG fluxes, and they may not be sensitive to many changes in farm management practices. In contrast to EFs and simple empirical models, field measurements (i.e., Tier 3) and more refined empirical or process-based models (i.e., Tier 2 and 3), which integrate and link multiple sources, allow a whole farm analysis of GHG fluxes. They are, therefore, particularly suited in understanding GHG emissions trade-offs. However, they can require expertise, data and time, that are often not available.

1.3.3 Eco-labelling

The communication of LCA results to stakeholders, is a relevant topic for businesses that work on improving their products and organization's environmental image. To support this, environmental certifications and labels are useful tools for transmitting information about the environmental performance of products to stakeholders (Minkov et al., 2020).

The type III environmental certifications are declarations that provide information to the final consumers through a logotype, or other type of communication tools (e.g., annual reports), on the life cycle of a product or service provided by a company or organization which is committed to environmental improvements. The ISO 14025 (ISO, 2006c) defines the type III environmental certifications presenting environmental information to enable comparisons between products fulfilling the same function.

In 2013, the European Commission (EC) published a recommendation on the use of a common methodology to measure and communicate (e.g., eco-labelling) the environmental performance of products and organizations (EC, 2013). The basis of this common methodology is the LCA.

Particularly, the initiative from the EC aimed at setting specific guidelines for LCA studies, called: Product Environmental Footprint Category Rules (PEFCR) when relating to products, and Organizational Environmental Footprint Sector Rules (OEFSR) when involving organizations. Such definite guidelines for measuring environmental performance throughout the life cycle of a specific-category product or organization, should then facilitate the comparability between LCA studies and provide principles for communicating the environmental performance, such as transparency, reliability, completeness, and clarity (EC, 2013).

Labelling has been given an increasingly important role in achieving sustainability goals, providing consumers with the opportunity to consider the environmental, social and ethical impacts of their food choices (Van Loo et al., 2014). As an example, the European Union (EU) eco-label has been recently awarded to thousands of different products in Europe, and in 2019 has registered an 88% of increase in the number labelled products/service since 2016 (EC, 2019).

1.4. Objective of the thesis

The main overall objective of this PhD thesis was:

- ✓ To quantify the GHG emissions arising from a Mediterranean pasture-based beef farming system located within an Italian National park, and to evaluate its contribution on the overall annual GHG emissions generated by all the park activities.

The specific objectives were:

- ✓ To provide an insight of the GHG emissions generated along a short beef supply chain involving an extensive-organic beef farm system located in Central Italy;

- ✓ To incorporate the process-based Denitrification-Decomposition (DNDC) model (i.e., Tier 3 approach) into the CFP (cradle-to-gate) of the beef cattle reared within the Italian National park, in order to improve the quality of the LCI and to include SOC dynamics;

- ✓ To model the agricultural soil GHG emissions and sinks of the Italian National park, because of a potential introduction of alternative agronomic practices (i.e., tillage, fertilizing and grazing managements) under current, and future CC pathway scenarios; and

- ✓ To propose a methodological (LCA-based) approach and guideline to follow in order to assess a CFP (cradle-to-grave) of a National park and test its applicability with a practical case study.

1.4.1 *Thesis structure*

The outline of the thesis is presented in Figure 1.4. The first part of the **Chapter 1** provides general information regarding the contribution of the agricultural sector on the total anthropogenic GHG emissions, giving an insight of the biological processes at the base of its GHG hot spots. The second part of the chapter provides a brief introduction of the major mitigation strategies involving the livestock sector and SOC sequestration. While in the last part are described the leading method and tools to assess and communicate the environmental performance of a product or service. The chapter highlights also the main and the specific objectives of the thesis. **Chapter 2** quantifies the cradle-to-grave CFP of an organic beef meat produced and consumed within a local supply chain, identifying its main GHG hotspots and the opportunities to implement improvements along the supply chain. **Chapter 3** reports a cradle-to-gate CFP of a pasture-based beef farm located within an Italian National park. In this study, a process-based model was used to estimate the GHG emissions and sinks from the agricultural soil. Furthermore, the model was used to estimate the beef CFP changes as a consequence of different tillage practices, organic fertilization rates, grazing managements, and future CC scenarios. In **Chapter 4**, it is presented an LCA-based guideline to quantify a cradle-to-grave CFP of a National park. Particularly, the feasibility and suitability of the proposed LCA guidelines was tested on a practical case study. The guideline developed aims at establishing a standard procedure that works as objective foundation for credible green marketing claims of National parks. In **Chapter 5** a synthesis and summary of the results from the previous chapters are presented along with the main conclusion drawn from the research undertaken during the PhD. Finally, in **Chapter 6** are summarized all the activities (e.g., seminar presentations, conference participations, courses, etc.), as well as a list of all the publications directly and indirectly related to the PhD program undertaken.

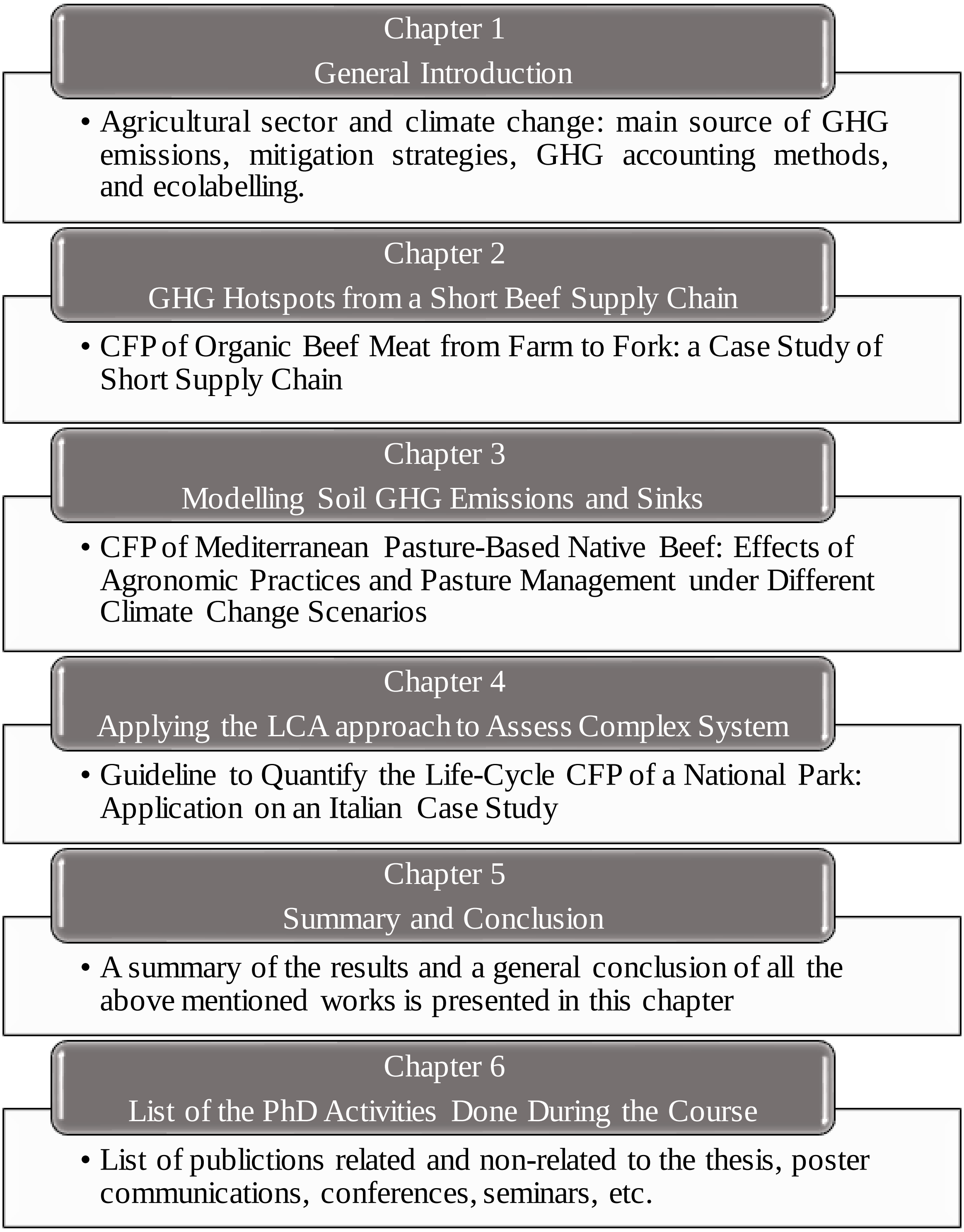

Figure 1.4 Structure of the thesis

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Chapter 2

GHG Hotspots from a Short Beef Supply Chain

Carbon Footprint of Organic Beef Meat from Farm to Fork: A Case Study of Short Supply Chain

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The results presented in this chapter are completely based on the article:

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2.1. Abstract

Food production and consumption have a significant impact on the environment, and its supply will be one of the major priorities of the humankind in the 21st century. Local food networks, especially those using organic methods, are proliferating worldwide, and little is known about their carbon footprints (CFPs). This study aimed to assess greenhouse gas (GHG) emissions associated to a local organic beef supply chain using a cradle-to-grave approach.

The CFP assessment determined an overall burden of about 24.5 kg CO_{2e} per kg of cooked organic beef. Contributing for about 86% of the total GHG emissions, the breeding and fattening phase was the main source of emission, followed by home consumption of meat (9%), retail (4%), and slaughtering activities (1%). Accounting for 47% of the total CFP, the enteric fermentation was both the leading cradle-to-grave hotspot, and the main source of emission within the breeding and fattening phase. As regard to the home consumption of meat instead, contributing for 72%, the cooking process was the larger source of GHG.

The identification of the major sources of GHG emissions associated to the short organic beef supply chain, may stimulates debate on environmental issues, helps in determining the contribution of local food network to climate change, and facilitates the adoption of more sustainable practices.

Keywords: Organic beef meat; local food network; LCA; GHG emissions; climate change

2.2. Introduction

Food production and consumption have a significant impact on the environment, with food systems contributing 19-29% of global anthropogenic GHG emissions, with meat and dairy products together accounting for a significant share of this quota (Muller et al., 2019).

Food supply will be one of the major priorities of the humankind in the 21st century. Indeed, due to both growths in world population and per capita consumption, human demand for animal proteins is expected to increase over the next decades (Nardone et al., 2010). To satisfy the growing food demand, farmers worldwide will need to increase their production, which in turn will results in higher consumption of resources (e.g., land, water and energy) and greater release of pollutants into air, water and soil (Steinfeld et al., 2006). Within this context, bovine meat production has been identified as the main source of GHG emissions among food products (Carlsson-Kanyama and González, 2009).

In order to evaluate the environmental profile intensity of beef production, it is important to adopt a whole system modelling approach. The life cycle assessment (LCA) methodology (ISO, 2006a, 2006b) allows to identify and analyse the environmental impacts and hotspots of product and service systems and should be the basis of any decision-making strategy for environmental improvements in a life cycle perspective (González-García et al., 2009). However, the comprehensiveness of the LCA methodology, due to the inclusion of a wide spectrum of environmental indicators, presents weakness when results are communicated to stakeholders and the general public (Weidema et al., 2008b). In this regard, the application of a single-issue indicator, such as carbon footprint (CFP) has become increasing popular (Rugani et al., 2013).

CFP is a term used to describe the measurement of GHG emissions from a product or an organization. Wiedmann and Minx, (2008) define the CFP as a measure of the total amount of CO_2 emissions that is directly and indirectly caused over the life stages of a product or activity. However, as most of the anthropogenic activities emit other GHG than CO_2 (e.g., CH_4, N_2O, HFCs, etc.), the term carbon dioxide equivalent (CO_{2e}) is commonly used in CFP assessments. Specifically, the term equivalent means that the global warming factor of the GHG other than CO_2, it is calculated to show their potential compared to that of CO_2, and then included in the assessment (Tjandra et al., 2016).

Although several studies have been carried out to evaluate the environmental impact of beef production considering all activities up to the farm gate (Ogino et al., 2004; Williams et al., 2006; Beauchemin et al., 2010), only few have included the further stages such as slaughtering, processing, retailing and consumption (Desjardins et al., 2012; Roy et al., 2012; COOP, 2013). Specifically, these studies were mainly at country level or related to large scale retail distribution. To the best of our knowledge, no studies have been carried out to calculate GHG emissions associated to organic beef production and its consumption in a local food network.

There is no a clear and simple definition of “local food network” or a “short supply chain” (Galli and Brunori, 2013). In this paper, it is intended as a supply chain characterized by both short distance between producer and consumer (proximity), and by few intermediaries involved.

The aim of this study was to quantifies the cradle-to-grave CFP of an organic beef meat produced and consumed within a local supply chain, identifying its main GHG hotspots, and the opportunities to implement improvements along the stages of the chain.

2.3. Materials and methods

2.3.1 Functional unit and system boundaries

The functional unit (FU) was 1 kg of cooked organic beef (CB), including waste disposal, evaluated at the consumer's home. No distinction was made between different cuts of meat (e.g., steak, loin, or fillet). The burdens associated with the short beef supply chain were evaluated with a cradle-to-grave approach (ISO, 2013). As shown in Figure 2.1, the system boundaries (SB) included the (i) breeding and fattening of animals, (ii) slaughtering operations, (iii) meat processing including production of packaging, (iv) retail activities, (v) transport, (vi) home storage, (vii) cooking, and (viii) waste disposal.

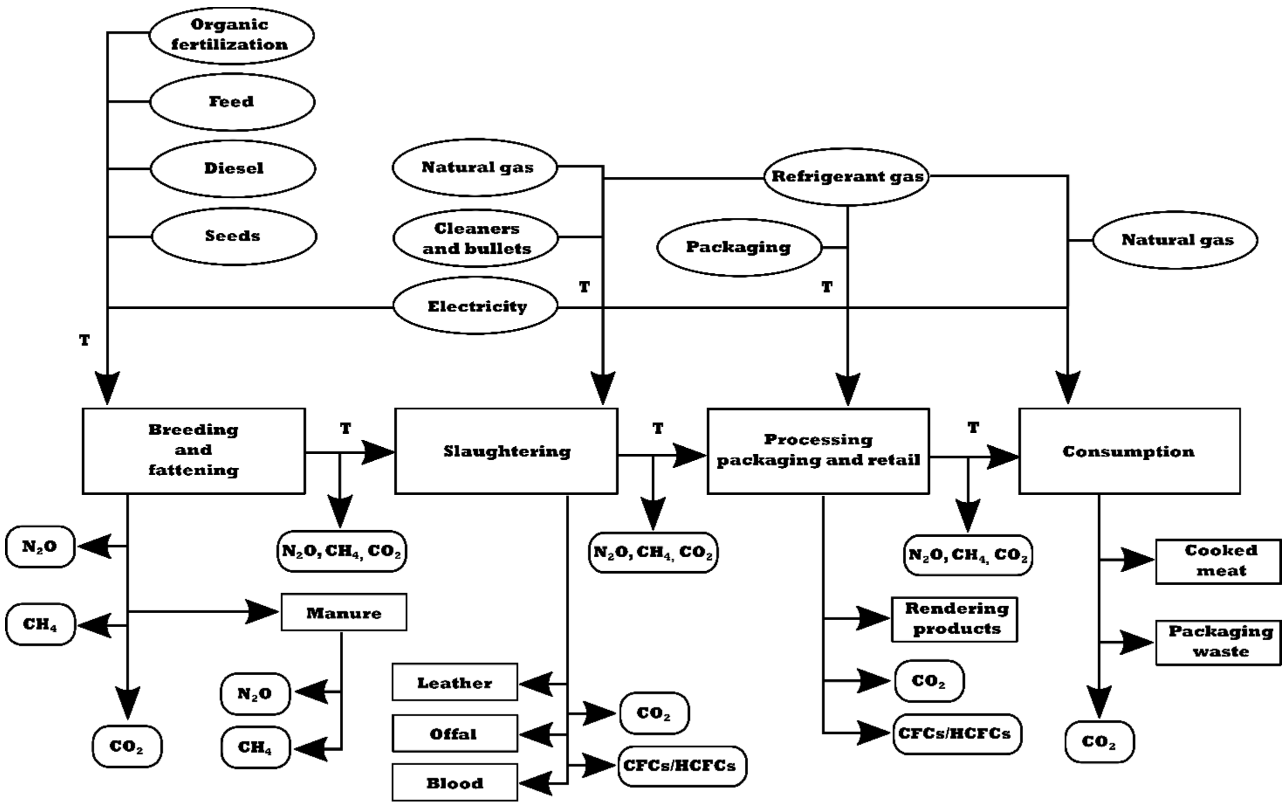

Figure 2.1 System boundaries (SB) of the short organic beef supply chain. T indicates the transports between and within processes

2.3.2 Life cycle inventory

Data refer to 2014 and were collected directly from the processes included in the system. When this was not possible, data were obtained from international databases that support environmental assessments (Frischknecht et al., 2007), calculated using appropriate models indicated by the guidelines for national greenhouse gas inventories (IPCC, 2006), or provided from literature. A summary of the data is reported in Table 2.1.

Table 2.1 Life cycle inventory of the short organic beef supply chain

Process	Categories of input	Data	Unit
Breeding and fattening	Seeds	7.4	t
	Land use	106	ha
	Organic fertilizers	3268	t
	Cows	71	heads
	Bulls	2	heads
	Calves (0-6 months)	58	heads
	Heifers for breeding (6-24 months)	23	heads
	Growing bulls (6-12months)	19	heads
	Fattening bulls (12-24 months)	33	heads
	Average slaughter weight	700	kg
	Slaughtered bulls/year	31	heads
	Slaughtered cows/year	6	heads
	Fuel	21,684	L
	Electricity	56,059	kWh
Slaughterhouse	Animals transported to plant*	2,442	km
	Natural gas	37,060	kg
	Electricity	292,433	kWh
	Refrigerant gas	180	kg
Butcher's shop	Transport of input	4,584	km
	Beef sold	9,536.7	kg
	Electricity	11,319	kWh
	Refrigerant gas	5.6	kg

*The total distance was considering 37 animals leaving the farm, 33 km form farm to slaughterhouse and a round-trip journey

2.3.3 Breeding and fattening

This study involved an organic Italian farm breeding and fattening native Chianina beef cattle. The investigated farm represents in terms of animals, land size and management, a typical organic beef farming system of central Italy.

The Chianina breed is characterized by somatic gigantism, long trunk, lightweight skeletal structure, great ease of calving, resistance to harsh environments, and modest feeding requirements. Fattened bulls were slaughtered at an age between 20 and 24 months, and at 700 kg of live weight (LW). Farming consisted of two phases: breeding cows and heifers for calf production and fattening of bulls. All animals were fed with a total mixed ration.

The farm cultivated 106 ha, no extra-farm feed was purchased, and organic manure (3,268 t year^{-1}) was mechanically spread as organic fertilizer. Slaughtered animals leaving the farm refers to fattened bulls, heifers (those not used for breeding) and culled cows; no distinction was made between these types of meat.

2.3.4 Slaughtering, retail and consumption

All animals were slaughtered in the same abattoir, 33 km from the farm. The abattoir received different livestock species and a total of 25,601 animals were slaughtered in 2014, including: 3,304 cattle, 8,923 pigs and 13,374 lambs. The primary products were meat carcasses, with offal, blood and leather as co-products. The carcasses are usually stored at 0-2°C for 2 days at the plant, and then transported to retail outlets for aging and processing operations. The storage system at the plant used 180 kg R-434a (a blend of refrigerant gas composed by pentafluoroethane, tetrafluoroethane, triflouroethane and isobutane).

Within the slaughtering operations were considered: transport of cattle from farm-to-plant, energy consumption (electricity and natural gas), refrigerant gas leaks, manure produced by animals waiting to be slaughtered, cleaners and bullets used for captive bolt.

The butcher's shop received beef only from the farm considered (butcher's shop owned by the farm). Within the retail activities were accounted: transport of beef carcasses from slaughterhouse-to-butcher's shop, electricity consumption, refrigerant gas leaks and packaging production.

The storage system at the butcher's shop consisted of a climate-controlled chamber for meat aging, and a meat display fridge using a total of 5.64 kg of R-404a and 0.4 kg of R-134a (tetrafluoroethane).

The total meat sold at the butcher's shop was 13,176 kg year^{-1}, which included: 9,536 kg of beef, 1,938 kg of pork, 1,049 kg of lamb, 574 kg of chicken, and 76 kg of rabbit. The packaging of 1 kg of meat consisted of two sheets, one made of 19 g of paper and 1 g of low-density polyethylene (LDPE), and the other made of 2 g of high-density polyethylene (HDPE). Customers usually had their own shopping bags, and then these were not considered in the study.

A sample of 50 customers was interviewed to acquire data for the meat consumption analysis. The data collected through the survey were: (i) amount, frequency and type of meat purchased, (ii) type of transport used for the shopping (e.g., on foot or by car), (iii) type of car (gasoline, diesel or GPL), (iv) distance travelled (km) per shopping trip, (v) beef cost as a percentage of the total daily shopping expenses, (vi) type (refrigeration and/or freezing) and duration of storage, (vii) cooking type (stove and/or oven) and, (viii) waste disposal (recycling or not). A summary of consumers' responses is reported in Table 2.2.

It should be noted that the survey was offered to each customer that entered the shop during several days distributed throughout the year. Those who agreed to fill out the survey were self-selected; no selection criteria (e.g., the demographic structure of the referent population) were applied.

Table 2.2 Interviews data regarding the beef consumption habits of the butcher's customers (average values)

Phases	Practice*	Data
Meat purchased	Quantity for each shopping trip/customer	2 kg
	Bovine	72%
	Others	28%
Meat transported	On foot	17%
	By car	83%
	Diesel	64%
	Petrol	28%
	NGV**	8%
	Distance travelled per shopping trip/customer	10 km
Meat stored	Refrigerator	20%
	Freezer	80%
	Time in refrigerator	2 days
	Time in freezer	21 days
Meat cooked	Gas stove	89%
	Electric oven	11%
Packaging disposal	Recycled	44%
	Not recycled	56%

*Data acquired interviewing a sample (50) of butcher's shop customers
**Natural gas vehicle

2.4. *Life cycle inventory analysis*

2.4.1 *Breeding and fattening*

Emission factors (EFs) associated with the production of seeds and the extraction of fuel were obtained from the Ecoinvent database (Frischknecht et al., 2007). Carbon dioxide (CO_2) produced as a result of electricity consumption was calculated using an EF of 0.385 kg CO_2 kWh^{-1} (ISPRA, 2014). The EFs associated to the fuel combusted for soil and animal management, as well the GHG emissions related to transports were obtained from Ecoinvent (Frischknecht et al., 2007).

Farm GHG emissions from the breeding and fattening stages were calculated. Specifically, the emissions arising from cows producing calves, and from heifers renewing the herd, were considered as breeding activities. While the GHG emitted by the growing and fattening animals were considered as fattening stage.

Enteric CH_4 emissions were calculated for each category of animal (i.e., growing bulls, cows, heifers and fattening bulls) using Tier 2 methodology (IPCC, 2006). Particularly, the approach was based on: daily gross energy intake (GEI), digestible energy (DE), and the Y_m conversion factor corresponding to the fraction of GEI converted to CH_4. The daily GEI was calculated considering LW, milk produced for calves, daily LW gain, activity (i.e., time at pasture), and cows' pregnant rate (%).

The value of Y_m adopted was 6.5% for higher forage diet (breeding) and 4.5% for higher grain diet (fattening). The values of DE adopted were 65% and 70% for breeding and fattening, respectively.

Solid manure (no liquid form was produced), volatile solids (VS), and N excretion rates, were calculated considering all animal categories (cows, heifers, beef) and their housing system as reported in the Italian guidelines for manure management (Bonazzi, 2001).

Country-specific conversion factors of 4.8 g CH_4 kg VS^{-1}, and 0.02 kg N_2O-N kgN^{-1}, were used (ISPRA, 2014) to calculate CH_4 and N_2O from manure storage, respectively. Methane emissions from dung deposited on pasture by cows and heifers (no grazing for beef) were calculated according to the total VS excreted, livestock category and annual time spent on pasture.

Direct and indirect N_2O emission resulting from soil management were estimated using the IPCC default EFs (IPCC, 2006). The method is based on total soil N inputs, which includes: organic fertilizer (land-applied manure), urine and dung deposited on pasture, mineralization of soil organic matter, and crop residue decomposition (above and below-ground). The potential of soil organic carbon (SOC) sequestration was not considered in the analysis.

2.4.2 Slaughtering, retail and consumption

EFs for electricity consumption and CH_4 combustion were obtained from the national inventory report for Italian greenhouse gas and IPCC (IPCC, 2006; ISPRA, 2014). EFs associated to different type of transport (trucks, vans and cars) were considered (Frischknecht et al., 2007). The emissions of refrigerant gases used in the storage systems were estimated considering different gas leak rates per each type of refrigeration system. Specifically, gas leaks of 50%, 25% and 15% of the total refrigerant capacity (kg $year^{-1}$) were considered for transport, slaughterhouse, and butcher's shop, respectively (IPCC, 2006; Frischknecht et al., 2007).

Electricity consumption for the home meat preservation (refrigerator and freezer) was estimated considering the volume of meat, the storage time, and the electricity consumption factors of 0.59 kWh m^{-3} day^{-1} and 0.63 kWh m^{-3} day^{-1} for refrigerator and freezer, respectively (EPD, 2013). The emissions released from cooking one kg of meat by gas stove or electric oven, were calculated considering cooking times of 15 min and 1 h, respectively.

2.4.3 Allocation

Dealing with allocation of products and co-products in a multi-stage system may become an issue. Indeed, there are different ways to handle data for products and co-products throughout the meat supply chain, and there is no a single established/validated method (Thoma et al., 2011).

In this study, the GHG emissions calculated within each phase of the supply chain have considered the allocation between co-products.

Specifically, (i) slaughterhouse, (ii) retail, (iii) retail-to-home transport, and (iv) home consumption, is where the GHG allocation between co-products occurred. Considering slaughtered animals as the only product, no allocation was made between farm activities (breeding and fattening). Furthermore, considering only the total LW leaving the farm, no distinction was made between primary (fattening bulls or heifers) and secondary (culled cows) meat.

The main products at the slaughterhouse were beef, pork and lamb carcasses. Whereas, offal, blood and leather were sold as co-products. Sales prices (provided by the plant) were 5.3€, 2.9€ and 7.5€ per kg for beef, pork and lamb, respectively. While 120€, 6€ and 12 € were the sales prices per 100 kg of leather, offal and blood, respectively. Considering the economic values, the allocation factors were 60%, 29%, 8%, 2%, 0.5% and 0.1% for beef, pork, lamb, leather, offal and blood, respectively.

Considering the different prices of the meat sold (i.e., economic allocation), the GHG emission coming from the butcher shop were allocated 87% to beef, 8% to pork and 5% to lamb. The GHG emissions coming from the shop-to-home transport were economically allocated taking into account the incidence of the beef (25.5%) on the total expenditure. And, as well for the previous stages, an economical allocation (73% to beef) was made for the GHG emissions coming from home storage (i.e., refrigerant gas leaks).

2.4.4 Impact assessment

Global warming potential (GWP) was evaluated with GHG converted to equivalent units of CO_2 (CO_{2e}) according to a 100-year time horizon (Forster et al., 2007). Considering a kg of CO_2 as reference, the GWP factors adopted per kg of CH_4, N_2O, R-134a, R-434a and R404a were 25, 298, 1,430, 3,245, and 3,922 kg, respectively. All emissions were calculated modelling data in Excel worksheets (MC, 2003).

2.5. *Results*

Table 2.3 shows the contribution to the overall CFP, of each phase involved in the short organic beef supply chain investigated in this study. The total CFP was about 24.5 kg CO_{2e} per kg of cooked beef (CB).

Table 2.3 Cradle-to-grave carbon footprint expressed as kg CO_2-equivalent (CO_{2e}) including the greenhouse gas (GHG) contributions of each phase considered in the short organic beef supply chain

Phase	kg CO_{2e}	% GHG within supply chain
Breeding and fattening	20.98	85.8
Slaughterhouse	0.27	1.1
Butchery	1.00	4.1
Consumption	2.22	9.0
Total	24.46	100

The organic farm combining breeding and fattening of native Chianina cattle emitted about 21 kg CO_{2e} per kg of LW, and it was the principal contributor, accounting for 86% of the total CFP of the supply chain. The emission of CH_4 from enteric fermentation was the greatest source of GHG arising directly from farming activities (47%). CO_2 emitted from energy use was the second major contributor (28%), while CH_4 and N_2O from manure management, and N_2O from soil management accounted for 16% and 9%, respectively. The local supply transport related to farming operations (seeds, fuel, feed and animals) accounted for less than 1% of the GHG emissions arising from the farming stage.

Slaughtering operations, which includes the transport of animals to the slaughterhouse, emitted 0.27 kg CO_{2e} per kg of beef carcass, and accounted for 1.1% of the whole supply chain. Energy use and refrigerant gas leaks were the main sources of GHG emissions within the slaughterhouse (85%). Transport of animals to the slaughterhouse accounted for 10% of GHG emitted at the plant, while CH_4 and N_2O from manure produced by animals waiting to be slaughtered accounted for about 4%. The GHG associated with the production of captive bolts and cleaners used for slaughtering operations amounted to less than 1%.

The overall GHG emitted at the butcher's shop were 1.00 kg CO_{2e} per kg of beef sold and accounted for 4.1% on the total CFP. The main contributors at this stage were refrigerant gas leaks (50%) and electricity consumption (40%). Minor contributions were associated with transport of carcasses from slaughterhouse- to-the butcher's shop (7%), and packaging production (3%).

The consumption of meat including transport-to-home, home storage, cooking and waste disposal, resulted in 2.2 kg CO_{2e} kg CB^{-1}, corresponding to 9% of the total CFP. Energy use for storage and cooking was the main GHG contributor within this stage (81.5%). Energy consumed to cook meat (82% for a gas stove and 18% for an electric oven) accounted for 1.4 kg CO_{2e} kg CB^{-1}, while 0.4 kg CO_{2e} kg CB^{-1} was attributable to the storage of meat in a refrigerator (13%) and freezer (87%). Transport of meat from shop-to-home (18.1%) was the second source of emissions, while GHGs emitted by packaging disposal were less than 1%.

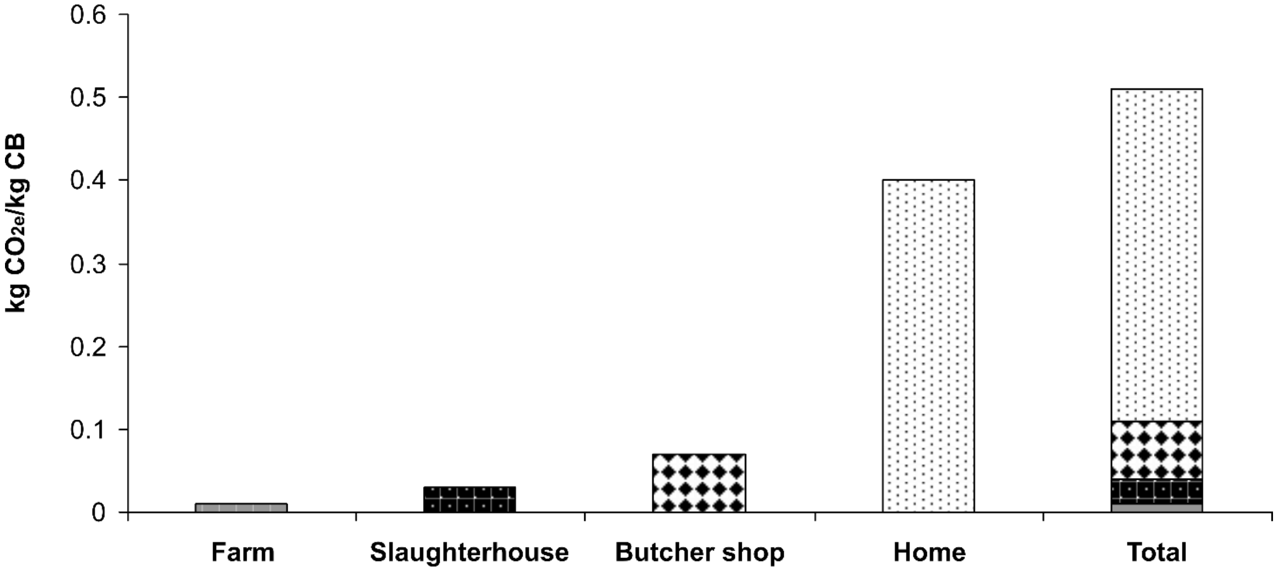

Figure 2.2 Carbon footprint expressed as kg CO_2-equivalents (CO_{2e}) per kg of cooked organic beef (CB) associated to the transport occurring along the short organic beef supply chain

Considering the whole life cycle investigated, the overall GHG emissions coming from the transports contributes for 2% of the total. As showed in Fig. 2.2, farm-to-slaughterhouse and slaughterhouse-to-butcher shop had a minor incidence compared to the shop-to-home transports.

Figure 2.3 shows the GHG emissions attributable solely to the use of energy (i.e., electricity, fuel and gas). The consumption of energy throughout the local organic beef network emitted 8.2 kg CO_{2e} kg CB^{-1}. Fuel (diesel) used for farming activities (feed production, feeding operation and animal management) accounted for 5.9 kg CO_{2e} kg CB^{-1}, and represented the main source (71%). The GHG emissions arising from storing and cooking the meat at home accounted for 1.8 kg CO_{2e} kg CB^{-1} (22% of total energy consumed), and gas combusted for cooking operations was the main source of emissions. The GHG emitted for slaughtering and retail activities accounted for 1.5% and 5% of the total GHG emitted for energy use, respectively.

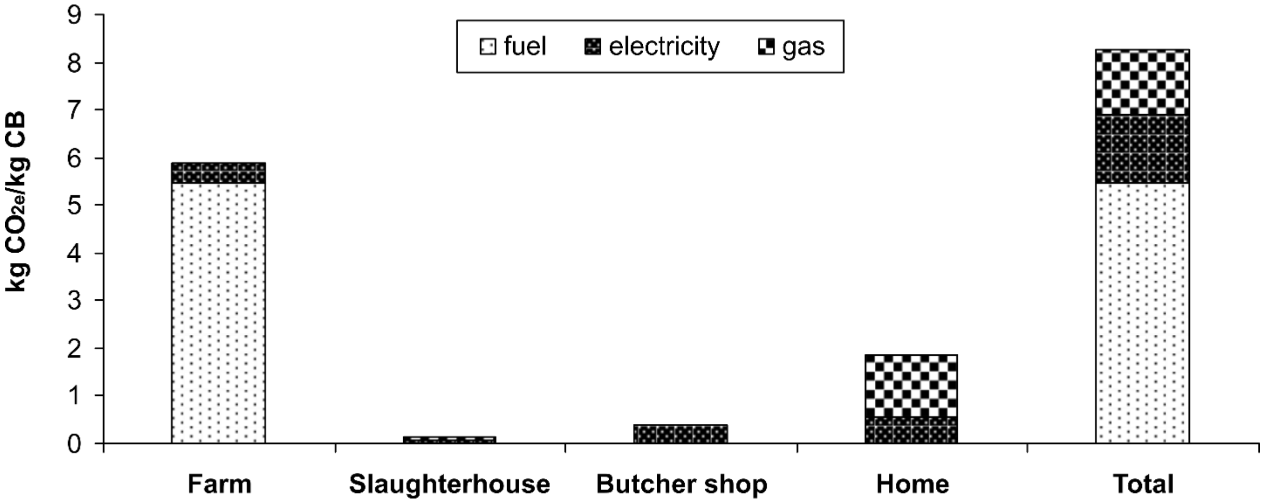

Figure 2.3 Carbon footprint expressed as kg CO_2-equivalent (CO_{2e}) per kg of cooked organic beef (CB) associated to the energy consumed along the short organic beef supply chain

2.6. Discussion

Local food networks are important retail systems in Italy as well as in the rest of the world and represent a valid alternative to large scale distribution. In addition, these food systems play a central role in guarantying the social and economic sustainability of rural communities.

However, little is known about carbon pollution produced by short food supply chains, and even less about local organic beef networks. In this study were considered the GHG contributions of the farm, slaughterhouse, farm's butcher's shop and its customers. Although the local food network investigated in this study can be considered highly representative of the beef production and consumption in Italy, not replicates of this system were analysed, therefore, the authors were careful in not to generalizing the results obtained. Nevertheless, these results may provide some interesting and useful insights into GHG emissions of local meat networks.

2.6.1 Breeding and fattening

Studies assessing beef CFPs, report values ranging between 13 and 40 kg CO_{2e} kg LW^{-1}. (Sonesson et al., 2009; Nguyen et al., 2010; Jacobsen et al., 2014). This huge variability could be mainly attributable to the differences in the production systems analysed (e.g., organic vs conventional or suckler cow-calf vs dairy bull calf) and/or to the methodological approaches adopted (i.e., FU, SB, EFs and allocation methods). Therefore, due to these substantial differences, direct comparisons between studies are often difficult.

In this study, the value of the CFP assessed at the farm gate resulted within the range indicated above, and the proportions of GHG coming from enteric fermentation and manure management agree with previously determined values (Ogino et al., 2007; Beauchemin et al., 2010). The burden associated with feed production was lower than the range (27-41%) reported in previous studies (Ogino et al., 2004; 2007). Particularly, in those studies, the emissions associated with fuel consumption and soil management for feed production were considered together, whereas were considered separately in this study. However, if considered cumulated, the contribution of feed production rise to 32% of the CFP at farm gate.

The about 21 kg CO_{2e} kg LW^{-1} (at the farm gate) arising from the organic production system investigated in this study, resulted higher (+ 0.6 kg CO_{2e} kg LW^{-1}) than those accounted by a study (COOP, 2013) evaluating beef destined to a large retail system, where breeding calves (in France) were transported to Italy for fattening. Despite the longer distance travelled by the animals in the Coop's study, the CFP was lower than a system (this study) where calves were born and bred in the same farm until reaching slaughtering age. The Coop study referred to Charolais and Limousin breeds raised in a conventional system (personal communication from Coop Italy). These widespread breeds are under genetic selection since long time, and they have higher production efficiency than less selected native breeds. Indeed, Charolais bulls show a higher feed efficiency than Chianina bulls (Giorgetti et al., 1991). In addition, organic beef cattle systems (18.2 kg CO_{2e} per kg of beef carcass) have been suggested to be more carbon polluting than conventional systems (15.8 kg CO_{2e} per kg of beef carcass) (Williams et al., 2006). This result was confirmed also when organic and conventional beef production was considered in the Italian context. Specifically, a recent Italian study showed CFP values of 24.6 and 18.2 kg CO_{2e} kg LW^{-1} for organic and conventional beef, respectively (Buratti et al., 2017). This result would seem to confirm that, rather than distance travelled by animals during breeding stages, production efficiency has a stronger effect on total GHG emissions (Schroeder et al., 2012).

While the nitrogen exported in beef carcasses it is annually balanced through N-fixing crops and by direct N atmospheric deposition, the P and K soil content needs some external input (i.e., fertilizer application) to be rebalanced. However, because not applied during the inventory year (2014), the GHG emissions related to the production and use of P and K fertilizers were not accounted in the estimation. In this regard, by considering an average P (~ 2.2 g/kg carcass weight) and K (~ 3.6 g/kg carcass weight) content per kg of carcass sold (Williams, 2007), a rough esteem was implemented in order to know the potential GHG incidence of this omission, which anyway resulted far lower than 1%.

The potential soil organic carbon (SOC) sequestration dynamics that may result by adopting a more soil conservative approach (e.g., organic system) were not investigated in this study. Indeed, because highly influenced by soil variability (e.g., texture, carbon content, drainage, etc.), climate conditions and soil managements, the quantification of SOC dynamics is challenging to estimate. However, when the C-sinks were evaluated in organic and conventional beef production systems, its contribution was limited in both (Buratti et al., 2017). Indeed, the authors of the study reported that the net C-sink decreased the CFP from 24.6 to 23.3 kg CO_{2e} kg LW^{-1} in the organic system, and from 18.2 to 17.7 kg CO_{2e} kg LW^{-1} in the conventional system. Nevertheless, SOC sequestration resulted two-and-a-half times higher in the organic system than conventional one. This suggests that organic practices have a high mitigation capacity, and that this potential should be considered when assessing their overall GHG contribution.

Considering the above discussion, we may argue that the idea which depicts local organic beef systems as more sustainable, because of the shorter transport distances and conservative practices, is not completely correct. Indeed, beyond the contribution of conservative practices in increasing SOC sequestration, other factors affecting the production efficiency of the farm should be considered when defining the sustainability of beef production.

Several practices are reported to reduce GHG emissions at farm level, and the optimum strategy should consider the interactions (e.g., trade-offs) and the cost-benefits of the potential interventions. In general, it could be stated that mitigation of GHG at farm level may be achieved by increasing farm productivity. In this regard, breeding animals with higher feed conversion ratio, reducing the unproductive animals on the farm and increasing production (e.g., slaughter weight reached at younger age, higher forage yield per unit of land), may contribute effectively to reducing GHG emissions per unit of meat produced. However, to maximize the sustainability of beef, strategies to improve production efficiency should be synergic with those aimed at increasing SOC sequestration.

2.6.2 Slaughtering, retail and consumption

The GHG emitted from slaughtering operations was less (0.27 vs 2 kg CO_{2e} per kg beef carcass) than that reported in the Coop study mentioned above (COOP, 2013). The shorter distance from farm to slaughterhouse may at least partially explain this difference. The distance between our farm and the slaughterhouse was shorter (33 km) than the 350 km reported in the Coop study. For this stage, the Coop study also included intermediate transport of carcasses from abattoir to processing plant (250 km). Finally, this discrepancy might also be related to different allocation factors adopted for bovine meat and co-products (leather, offal and blood).

A Japanese study reported 0.04 kg CO_{2e} per kg of beef carcass at the slaughterhouse gate (Roy et al., 2012). This value was calculated based on total meat yield (chicken, pork and beef) and included meat storage, and packaging activities. The lower carbon emission associated with the Japanese slaughtering activities, compared to those obtained in this study, could be attributable to the adoption of different allocation approaches. Indeed, while the Japanese study allocated GHG emissions based on the mass of products and co-products, an economic allocation was involved in the present study.

The contribution of slaughtering operations to the CFP of a Canadian beef production resulted in 0.18 kg CO_{2e} per kg of beef carcass (Desjardins et al., 2012). In this case also, the lower value may be due to the methodological (e.g., system boundary) and allocation procedures adopted. Indeed, the Canadian study did not include refrigerant gas leaks, but it did consider biogas recovery from manure and waste management. In addition, even if the Canadian study adopted an economic approach to allocate emissions between products (primary meat) and co-products (offal, blood and leather), the allocation factors involved were different from those adopted in the present study (i.e., dressing percentage, cutting yield, rendering yield, prices of primary meat and co-products).

The emissions related to butchering activities were higher than those calculated for large scale distributions (Roy et al., 2012; COOP, 2013). The differences are likely to depend on the higher energy efficiency of supermarkets compared with that of local butcher shops (Weidema et al., 2008a).

Improvements in energy efficiency may somewhat mitigate GHG emissions from slaughtering and retail activities. Furthermore, the use of refrigeration systems requiring lower volumes of refrigerant gas, and/or the use of refrigerant gases with lower GWP (e.g., ammonia, carbon dioxide, isobutene, etc.) would also help (Pedersen, 2012). Even the adoption of appropriate operations such as regular checks of the cooling systems, and/or avoiding rapid changes of temperature during carcasses loading/unloading, are likely to reduce GHG emissions generated from this phase of the beef supply chain (Garnett and Jackson, 2007).

The GHG emissions from home consumption were calculated based on the type of transport, storage time, cooking method, and waste disposal practices declared by the customers during the interviews. The value obtained in this study (2.2 kg CO_{2e} kg CB^{-1}) resulted within the range 0.8-3.3 kg CO_{2e} kg CB^{-1} reported by the Coop study (COOP, 2013), and higher than the Japanese' study (0.34 kg CO_{2e} kg CB^{-1}) from which further information was not provided (Roy et al., 2012). Energy consumed for cooking operations was the main contributor to the CFP, and it reflects the cooking habits of the customers interviewed. In general, cooking operations are shaped by the cultural and economic characteristics of the societies in which they occur, thus the development and/or implementation of more sustainable cooking practices should consider these aspects. Considering only the cooking devices, the evidence shows that electric stoves release less GHG emissions than those generated by using gas or solid fuel, with solid fuel producing the most pollution (Xu et al., 2015).

Despite the short average distance (10 km) involved, transporting meat from shop-to-home represented 20% of the GHG arising from the consumption stage, and 80% of those arising from the transports involved along the whole life cycle. This aspect seems to contradict the idea that, because avoiding intermediate transports, buying food directly from the producer is more environmentally sustainable. Indeed, the GHG produced during shopping trips may be an important source of emissions, especially in local food networks where the short distances involved do not compensate the small quantity of product transported per journey (Rizet et al., 2010).

By loading more products in the same vehicle, the GHG emissions generated by a single journey can be allocated between more goods, which in turn reduce the transport incidence per each product. Therefore, the CFP burden associated to shopping trips could be reduced with retailers offering optimized delivery services (i.e., collective orders), especially if combined with remote ordering (e.g., through the internet). Moreover, even without involving alternative distribution systems, both the frequency of shopping and the resulting overall distances driven may be reduced by providing better tools for planning food purchases, and through increased products shelf life (Schroeder et al., 2012).

Finally, in accordance with Dalgaard et al., (2007), and by considering the findings of this study, the choice of local products or "zero-miles products" is not sufficient to guarantee an environmentally sustainable food consumption, and other processes/activities involved in the supply chain should be carefully considered.

2.7. Conclusion

Local food networks are proliferating worldwide and are considered a sustainable food system even if their contribution to GHG emissions is currently not well understood. The analysis carried out in the present study allowed the identification of the GHG hot spots associated to a short organic beef supply chain. Farm activities and home consumption were the stages within the chain with the highest incidence. These results may help to determine the contribution of local food networks to CC and facilitate the adoption of more sustainable practices. Their adoption would in turn require education of farmers, retailers and consumers, and last but not least, a careful evaluation of the benefit-cost ratio. Finally, this study also points to the importance to account for SOC dynamics in future CFPs assessment, especially when evaluating GHG mitigation strategies related to agricultural products.

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Chapter 3

Modelling Soil GHG Emissions and Sinks

Carbon Footprint of Mediterranean Pasture Based Native Beef: Effects of Agronomic Practices and Pasture Management under Different Climate Change Scenarios

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3.1. Simple summary

The livestock sector requires a significant amount of natural resources and has an important role in climate change. Although the carbon footprint has become a widely accepted indicator for assessing the greenhouse gases emitted per unit of product, due to the lack of a commonly accepted methodology, there are still few studies that have included soil organic carbon sequestration in their calculations. In this study, by including soil organic carbon dynamics, the carbon footprint of a Mediterranean pasture-based beef cattle farm was estimated using current weather data and farming management policies. Subsequently, different soil management strategies, grazing systems, and climate scenarios were compared to the current ones to investigate the effects of these variables on the greenhouse gases emitted. The results showed that the current beef carbon footprint could be significantly reduced by switching to reduced tillage systems. The modelled combination of no-tillage practices with higher organic fertilizer application rates showed a greater potential carbon footprint reduction. No significant differences were found between carbon footprint values modelled under different climate scenarios and grazing systems. By including a process-based model into its carbon footprint calculations, this study highlights the climate mitigation potential of different farming practices and the importance of considering soil carbon sequestration.

3.2. Abstract

A better understanding of soil organic carbon (SOC) dynamics is needed when assessing the carbon footprint (CFP) of livestock products and the effectiveness of possible agriculture mitigation strategies. This study aimed (i) to perform a cradle-to-gate CFP of pasture-based beef cattle in a Mediterranean agro pastoral system (ii) and to assess the effects on the CFP of alternative tillage, fertilizing, and grazing practices under current (NCC) and future climate change (CC) scenarios. Minimum (Mt) and no-tillage (Nt) practices were compared to current tillage (Ct); a 50% increase (Hf) and decrease (Lf) in fertilization was evaluated against the current (Cf) rate; and rotational grazing (Rg) was evaluated versus the current continuous grazing (Cg) system. The denitrification-decomposition (DNDC) model was run using NCC as well as representative concentration pathways to investigate the effects of farm management practices coupled with future CC scenarios on SOC dynamics, N_2O fluxes, and crop yield. Within NCC and CtCf, an emission intensity of 26.9 ± 0.7 kg CO_{2e} per kg live body weight was estimated. Compared to Ct, the adoption of Mt and Nt reduced the CFP by 20% and 35%, respectively, while NtHf reduced it by 40%. Conservation tillage practices were thus showed to be effective in mitigating greenhouse gas emissions.

Keywords: greenhouse gases; soil management; mitigation; N_2O; SOC; DNDC model

3.3. Introduction

Greenhouse gas (GHG) emissions from the livestock sector amount to 14.5% of global anthropogenic emissions (Gerber et al., 2013), and this number is expected to grow as a consequence of the increased demand for livestock products from developing countries (Herrero et al., 2016). To meet the future needs of the expanding human population, an increased efficiency of animal production systems coupled with a decrease in GHG emission intensity per unit of product must be targeted (Grossi et al., 2019).

When assessing the environmental burden associated with livestock products, soil organic carbon (SOC) represents a large carbon pool sink that should be considered when evaluating the sustainability of agricultural systems (Lal, 2016).

In recent years, the promotion of less-intensive tillage practices (Haddaway et al., 2017), the use of organic fertilizers (Bhogal et al., 2009), and the adoption of rotational grazing systems (Byrnes et al., 2018) have been credited for mitigating climate change (CC) due to their positive effects on SOC preservation.

Various methods have been used to estimate GHG emissions and sinks in agriculture carbon footprint (CFP) studies, ranging from a simple Tier 1 approach (IPCC, 2006) to complex process-based models (Tier 3) capable of simulating carbon and nitrogen cycles (Ogle et al., 2013). On the one hand, the Tier 1 approach is still the most commonly used approach in the agriculture sector (Peter et., 2016), but on the other hand, by considering the interactions between (i) climate, (ii) soil, and (iii) tillage practices, process-based models have been shown to be useful tools in simulating the long-term effects that these interactions have on crop yields, SOC dynamics, and GHG emissions (Doltra et al., 2019). Currently, the adoption of more accurate methods for the estimation of land-based emissions is recommended to improve the accuracy of CFP results (Peter et., 2016).

Process-based models are based on biogeochemistry (Moore et al., 2014): among them, the denitrification-decomposition (DNDC) model (Li et al., 2000) has been applied in more than 30 countries across the world (Jiang et al., 2017) and has been validated globally in over 100 studies, demonstrating its high accuracy (Syp and Faber, 2017).

Despite the fact that SOC sequestration in agricultural practices is a highly debated topic (Mogensen et al., 2014), investigating C sinks within agriculture CFP studies still requires further research to develop a common, reliable, and robust method (Nayak et al., 2019). As a result, there have been few CFPs that have included soil C dynamics in their results (Stanley et al., 2018). When SOC sequestrations have been included in beef cattle CFP studies (Buratti et al., 2017; Lupo et al., 2013), whole-farm GHG emissions have been found to decrease by 5%-43%. These findings underline the importance of considering both GHG emissions and sinks in evaluating the CFP of an agricultural system accurately (Adewale et al., 2018).

Grazing systems are important resources in ruminant feeding, especially in areas where natural grasslands are part of the landscape. In the Mediterranean area, the livelihood of pastoral and agro-pastoral people depend largely upon rangelands, which are the major food source for their animals (Ates et al., 2014). The Mediterranean agro-pastoral system (Pardini and Nori, 2011) has evolved over time without the need for animal housing and feed supplies, but this practice has been increasingly lost due to the intensification of production. Nevertheless, because of their rusticity traits, in the Mediterranean area some native cattle breeds are still raised under this extensive pasture-based management system.

While there are several CFP studies that have investigated intensive and semi-intensive cosmopolitan beef cattle systems, less attention has been dedicated to GHG emissions coming from pasture-based farms rearing native breeds.

Thus, by including the DNDC model in an assessment of soil GHG emissions and sinks, this study aimed to (i) perform a CFP study of pasture-based native beef cattle reared in a Mediterranean agro-pastoral system and (ii) assess the impact on a CFP of different agronomic practices such as tillage, fertilizing, and grazing management under current and future CC scenarios.

3.4. Material and Methods

3.4.1 Functional unit and system boundaries

The functional unit (FU) chosen for the study was 1 kg of live weight (LW) of Maremmana beef cattle reared in a pasture all year round. Cradle-to-farm-gate system boundaries include all of the upstream processes of cattle beef farming until the animals leave the farm gate (Figure 3.1). Therefore, this study considered both direct GHG emissions coming from on-farm production processes (enteric fermentation, soil emissions, and fuel combustion) and the indirect GHG impacts related to the production and transport of auxiliary goods (seeds, organic fertilizers, extra farm feed, and fuel). GHG emissions deriving from the manufacturing of equipment (barns and sheds) as well agricultural machinery (tractors) were included. The following GHG sources were excluded from the boundaries of the system considered: the construction of fencing systems, the production of veterinary drugs, animal respiration and cultivation/harvesting machineries.

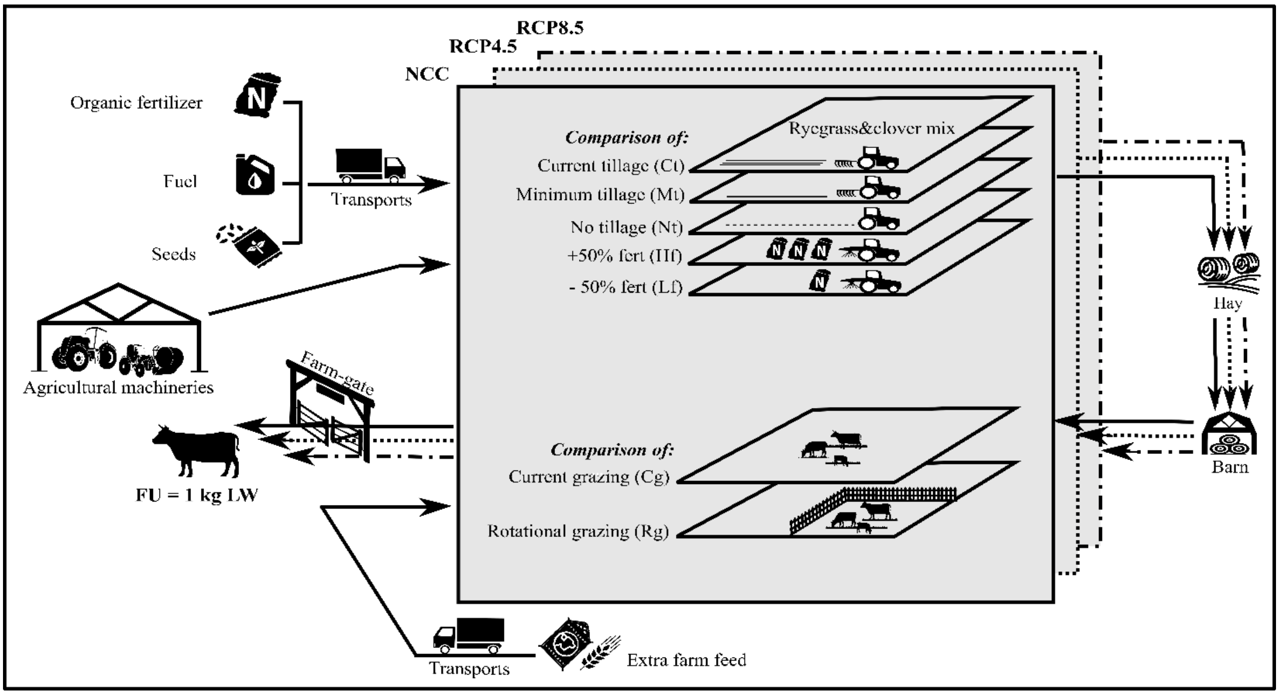


Figure 3.1 System boundaries, goods, farm management practices and climatic scenarios considered. NCC = Current climate. RCP = Representative concentration pathways. FUs = Functional units. LW = Live weight

3.4.2 The beef cattle pasture-based farming system

The beef cattle farm under study was located on the west coast of Central Italy within the Castelporziano natural reserve (41°42’50’’N - 12°24’03’’E), which also hosts one of the three Italian presidential estates. The area, with an elevation ranging from 25 to 70 m above sea level, is about 6000 ha wide and is characterized by an inferior Mediterranean thermotype climate. Different land uses coexist within the natural reserve: Mediterranean lowland mixed forests, hydrophilous retro-dune wetland zones, Mediterranean scrub, grazed meadows, cultivated fields, and anthropic environments (Trinchera et al., 2015).

Within the beef cattle farm, which extends for about 480 ha inside the natural reserve, 280 livestock units (LUs) of native Maremmana beef cattle are currently organically reared in accordance with a year-round continuous unmanaged grazing management approach (hereinafter, Cg). The extensive grassland-based system described in this study can be considered to represent a typical farming system for Maremmana beef cattle reared in Central Italy (Fratini et al., 2014).

The Maremmana breed is mainly spread throughout the Lazio and Tuscany regions, and it is an extraordinarily robust breed. Indeed, even though their slaughtering ages could be considered to be quite high (about 26-28 months old) compared to other Italian beef breeds such as Chianina, Marchigiana, and Romagnola (from 19 to 24 months old) (Sbarra et al., 2013), these animals are accustomed to living outdoors and are capable of surviving in harsh climates in which other breeds cannot adapt. After being weaned (6 months), calves are separated from cows and raised out to pasture.

As a part of pasture integration, the animals annually consume (average of 2016-2018) about 815t of dry matter (DM) ryegrass-clover hay mix produced on-farm, which amounts to about 8 kg of DM LU^{-1} day^{-1} (Table 3.1). During the two months preceding slaughter (fattening phase), the animals are finished with hay and concentrate mixes (Table 3.1) composed of (on a wet basis) 15% crude protein, 3.6% crude oils and fats, 9.7% crude fibre, 11% crude hash, and 0.4% sodium.

Table 3.1 Main herd, weather and crop management data

Animals	Unit	Data
Cows	n	146
Breeding heifers	n	13
Beef cattle	n	89
Calves	n	114
Bulls	n	5
Cows live weight	kg	655
Heifers & steers live weight	kg	350
Typical slaughter ages	months	27
Fertility rate	%	80
Replacement rate	%	10
Age at the first calving	months	36
Fattening period	months	2
Hay at pasture	kg DM LU^{-1} day^{-1}	8
Hay at fattening	kg DM LU^{-1} day^{-1}	6
Concentrates at fattening	kg DM LU^{-1} day^{-1}	7
Average animals slaughtered per year	n	74
Average weight of the slaughtered animals	kg LW $head^{-1}$	585
Stocking rate on free-range pasture	LU ha^{-1}	1.3
Pasture area	ha	220
Cropping (CtCf)	**Unit**	**Data**
Yield	kg DM ha^{-1}	3,000
Amount of organic fertilizer spread	t ha^{-1}	1.3
Fertilizer N content	%	4
Fertilizer organic C content	%	50
Planting	month	October
Harvesting	month	May
Cropping area	ha	260
Weather	**Unit**	**Data**
Mean max. temperature	°C	21.5
Mean min. temperature	°C	11.6
Mean annual precipitation	mm	945

Animals and cropping values represent the 2016-2018 mean. Weather values represent the 2009-2018 mean. n = Number; DM = Dry matter; LW = Live weight; LU = Livestock unit; CtCf = Current tillage and current fertilization.

3.4.3 Alternative farm management practices and climate scenarios

In order to assess the potential impact of different agronomic practices on GHG emissions, two tillage alternatives (minimum tillage (Mt), including pre-sowing ploughing (10 cm) coupled with Cf application rates (hereinafter, MtCf), and no-tillage (Nt) coupled with Cf application rates (hereinafter, NtCf)) were modelled as alternatives to the current CtCf. To assess the effects of organic fertilization on GHGs with respect to the organic fertilizer amount currently spread under Cf, a 50% increase (Hf) as well as a 50% decrease (Lf) were modelled for each tillage practice (Ct, Mt, and Nt).

Compared to fuel consumption under CtCf, a reduction of 13% and of 39% for MtCf and NtCf, respectively, was considered (Fathollahzadeh et al., 2009).

Furthermore, because on-farm hay production was affected when modelling the above alternative soil management strategies, resulting in hay yield deficits (CtLf), a certain amount of extra farm hay was assumed, and the related GHG emissions arising from its production and transportation (assuming 100 km of distance) were accounted for. On the other hand, when a yield surplus occurred, the hay was assumed to be sold and an economic allocation between cattle LW and hay leaving the farm was adopted.

As for grazing management, by considering the annual growth rate (Sharpe and Rayburn, 2019) and yield (2t of DM ha^{-1} yr^{-1}) (Cavallero et al., 2002) of the grasslands, rotational grazing (hereinafter, Rg) was assumed to replace the current Cg.

Of the entire grazing area (220 ha), six paddocks (~35 ha each) were assumed to be grazed twice from March to June (~10 days per turn and 45 days between turns), with a stocking rate of about 8.5 LU ha^{-1}, while from July to February the whole area was assumed to be continuously grazed (1.3 LU ha^{-1}).

Finally, in order to assess the interactions between current and alternative farm management practices and future climatic change, all of the management methods mentioned were modelled under three different long-term (from 2019 to 2089) climate pathways.

For the first one (using in loco weather station climate data series (2009-2018)), no climate change was assumed to occur during the 70-year time frame considered (NCC). The second climate path reproduced Representative Concentration Pathway 4.5 (RCP4.5), which is based on the Fifth Assessment Report (IPCC, 2013) of the Intergovernmental Panel on Climate Change (IPCC); while the third one was based on the less conservative RCP8.5 pathways.

3.4.4 *Life cycle inventory*

The denitrification-decomposition (DNDC) model is made up of different sub-models: (i) a soil climate sub-model that simulates soil temperature moisture and Eh (redox potential); (ii) a plant growth sub-model that estimates crop growth and its effects on soil (e.g., temperature, moisture, and available N); and (iii) a decomposition sub-model that mainly simulates SOC and nitrogen dynamics. Depending on the derived soil environmental factors coming from the three upper-layer sub-models, the denitrification or nitrification sub-model is activated to simulate nitric oxide (NO) and nitrous oxide (N_2O) gaseous emissions and nitrate (NO_3^-) leaching. Moreover, the ammonium/ammonia (NH_3) equilibrium is included in the nitrification model to estimate NH_3 volatilization. The fermentation sub-model calculates the release of methane (CH_4) according to fermentation equations (Deng et al., 2017). The DNDC adopts biogeochemical and empirical equations to simulate carbon and nitrogen biogeochemical cycles, including soil trace gas emissions (Li et al., 2000).

The DNDC was used in this study to estimate direct and indirect N_2O soil emissions, CH_4 soil emissions, SOC dynamics, and forage crop growth. Site-specific DNDC data input on crop parameters, management activities, climate, and soil properties are reported in Table S3.1, Table S3.2, Table S3.3.

Although the DNDC has been run with a spin-up as low as two years (Zhang et al., 2015), a 20-year spin-up is recommended to assure that different SOC pools reach equilibrium (Qiu et al., 2009). Thus, in order to reduce the uncertainties related to the initial model setting, in this study a 30-year spin-up was adopted. Specifically, the 2009-2018 climatic data (daily maximum and minimum air temperatures and precipitation) were repeated during the spin-up of all scenarios assessed. However, while a 10-year sequence was repeated randomly over 70 years within the NCC scenario model, climate projections were instead used within the RCP4.5 and RCP8.5 scenarios. In particular, Consortium for Small-scale Modelling and the Climate Limited-area Modelling community (COSMO-CLM) climate projections (Bucchignani et al., 2013) were used by the Climate Model of the Euro-Mediterranean Centre on Climate Change CMCC-CM (Scoccimarro et al., 2011) with the RCP4.5 and RCP8.5 emissions scenarios, and then the results were used in the DNDC model for the next 70 years modelled.

Direct and indirect N_2O emissions, as well as CH_4 and soil carbon sources/sinks, were considered within each combination of climate scenarios per farm management policy considered. Particularly, the 70 years following the spin-up were selected for an analysis, with each combination assessed.

The annual mean of the DNDC modelled N fluxes (leached and volatilized) were converted into N_2O using the IPCC emissions factors (IPCC, 2006). The cumulative annual mean direct and indirect N_2O emissions, as well as soil methane emissions, were converted into carbon dioxide equivalents (CO_{2e}) using the IPCC 100-year global warming characterization factors of 28 for CH_4 and 265 for N_2O (IPCC, 2013). The average annual changes in the SOC (0-50 cm) were converted into CO_{2e} considering the atomic weight of C and the molecular weight of CO_2, therefore multiplying the amount of the SOC source/sink by 3.67.

The enteric CH_4 emissions were estimated using IPCC Tier 2 methodology (IPCC, 2006) based on daily gross energy intake (GEI), the feed digestibility as a percentage of GEI (DE%), and the fraction of GEI converted to CH_4 (Y_m) (Table S4). Daily GEI was calculated considering LW and the net energy required for maintenance (NE_m), activity (NE_a), lactation (NE_l), pregnancy (NE_p), and growth (NE_g) of the different animal categories (e.g., cows, bulls, heifers, and fattened beef) (Table S3.4). The Y_m value adopted was 6.5% for grazing animals and 4.5% for those on fattening.

The environmental burdens associated with the production of fertilizers, fuel, packaging, seeds, extra farm feed, and durable goods (tractors and barns and sheds for the equipment) were considered (Figure 3.1). Because no electricity is involved in beef cattle rearing, fuel was the only input associated with energy consumption in the system. The transportation needed to support beef production was included, and for this reason, 3.5-7.5t or 7.5-16t lorries were considered.

The emission factors (EFs) adopted in this study (Table 3.2) were obtained from the Ecoinvent v3 database (Wernet et al., 2016) and from the literature. Detailed farm input data are listed in Table S3.5 of the supplementary materials.

Table 3.2 Emission factors (EFs) list

Input	Unit	EF (kg CO_{2e} Unit^{-1})	Data source
Compost (4% N content)	1 kg	0.03	(Havukainen et al., 2018)
Fuel production	1 kg	0.51	(Wernet et al., 2016)
Fuel combustion	1 kg	3.17	(Wernet et al., 2016)
Ryegrass-clover seeds	1 kg	1.62	(Wernet et al., 2016)
Extra farm feed (concentrate)	1 kg	0.6	(Adom et al., 2013)
Extra farm hay	1 kg	0.28	(Sonesson et al., 2009)
Packaging paper	1 kg	0.88	(Wernet et al., 2016)
Low density Polyethylene (LDPE)	1 kg	2.98	(Wernet et al., 2016)
Buildings (lifespan: 50 years)	1 mq	168.9	(Wernet et al., 2016)
Tractor (lifespan: 7,000 working hours)	1 kg	5.73	(Wernet et al., 2016)
Transports (Lorry 3.5-7.5t)	1 tkm	0.52	(Wernet et al., 2016)
Transports (Lorry 7.5-16t)	1 tkm	0.22	(Wernet et al., 2016)

tkm= ton per km; CO_{2e} = Carbon dioxide equivalents

3.4.5 Statistical Analyses

The one-way analysis of variance (ANOVA) approach was adopted considering the tillage (Ct, Mt, and Nt), fertilization (Cf, Hf, Lf), grazing (Cg and Rg), and climate scenarios (NCC, RCP4.5, and RCP8.5) as fixed factors. Within each climate scenario, different combinations of tillage, fertilization, and grazing systems were modelled. The dependent variables were direct N_2O, SOC, forage crop yield, and total CFP. The differences were tested using Tukey's statistic and were considered significant for $p < 0.05$. Significant differences reaching a threshold lower than 5% (e.g., 0.01 or 0.001) are also highlighted in the text and in the figures according to conventional rules. All statistical tests were performed using Statistica® 10 (Statsoft, Inc., Tulsa, OK, USA).

3.5. Results

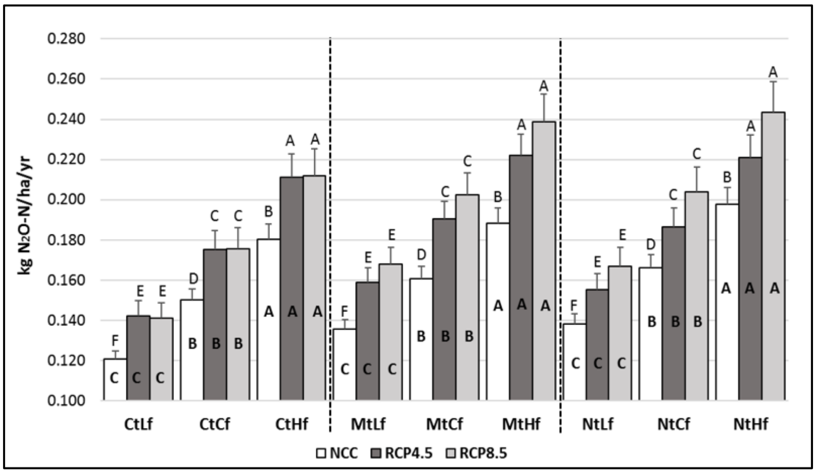
The soil GHG emissions included within the total CFP values reported in this study were direct N_2O fluxes, indirect N_2O fluxes (the NO_3^- leached and NO and NH_3 volatilized), net CH_4 soil emissions, and SOC dynamics. However, because of the low incidence of net soil CH_4 (almost null) and indirect N_2O emissions (~3%) in total soil emissions, only the main sources of soil GHGs (direct soil N_2O fluxes) and sinks (SOC dynamics) are discussed on the next paragraphs. The uncertainty values reported alongside the averages represent the standard error (±se).

3.5.1 Impact of management and climate on direct soil N_2O fluxes

The DNDC outputs showed a significant ($p < 0.001$) dose-effect relationship between direct N_2O emissions and the organic fertilization rates applied (Figure 3.2a), while the tillage system results were not significant.

Independently from the tillage and fertilization rate adopted, future climate RCP4.5 and RCP8.5 scenarios showed higher N_2O emissions than did the ones occurring within the NCC ($p < 0.001$). As an example, the N_2O emissions arising from the CtCf increased by about 15% (from 0.150 to 0.175 kg N_2O-N ha^{-1} yr^{-1}) when the RCP4.5 and RCP8.5 scenarios were modelled (Figure 3.2a). The N_2O emissions differences between RCP4.5 and RCP8.5 were never significant.

No significant differences resulted between the two grazing management policies or between the different climate scenarios (Figure 3.2b).



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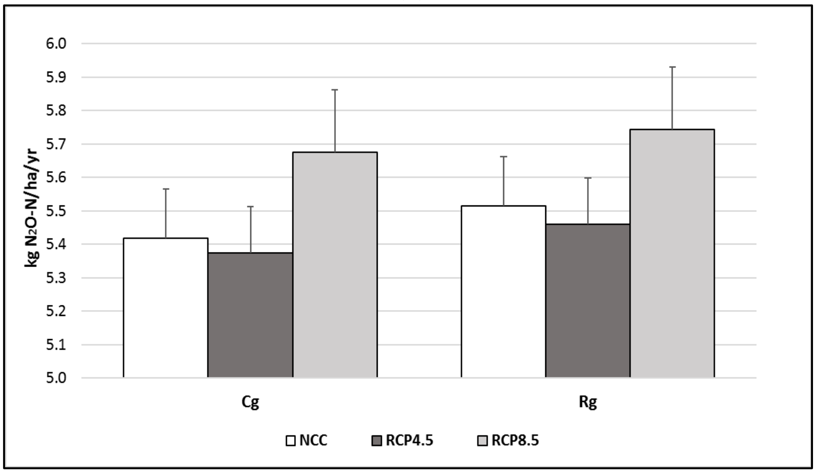

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Figure 3.2 Denitrification-decomposition (DNDC)-modelled mean annual soil direct N_2O fluxes (±se) from 2019 to 2089, as a result of different (a) farm management policies under diverse climate scenarios and different (b) grazing systems under diverse climate scenarios. Cf = current fertilization (50 kg N ha^{-1} yr^{-1}); Cg = continuous grazing; Ct = current tillage; Hf = higher fertilization rate (+50% Cf); Lf = lower fertilization rate (−50% Cf); Rg = rotational grazing; NCC = current climate; RCP4.5 and RCP8.5 = Representative Concentration Pathways 4.5 and 8.5. The letters above the bars indicate differences between climate scenarios within each tillage per fertilization rate combination. The letters in bold inside the bars indicate differences between fertilization rates applied within each tillage per climate scenario combination. Different uppercase letters indicate statistical differences from Tukey's test ($p < 0.001$). Different lowercase letters indicate statistical differences from Tukey's test ($p < 0.05$).

3.5.2 Impact of management and climate on soil organic carbon (SOC) dynamics

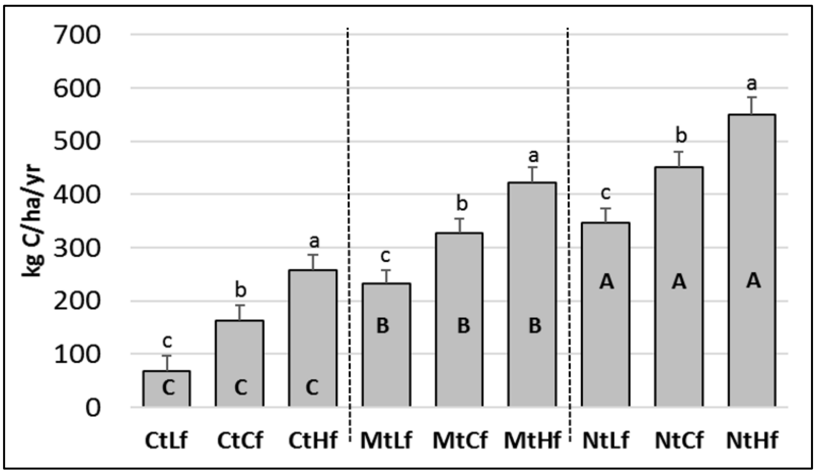
Figure 3.3a shows the SOC sink effect (0-50 cm) from the interactions of each tillage system per fertilization rate tested. The fertilization rates showed a significant ($p < 0.05$) dose-dependent effect on the SOC content, where Lf was the lowest and Hf was the highest within each tillage modelled.

The SOC sinks estimated under Mt were higher than those modelled under Ct and lower than the ones simulated under Nt ($p < 0.001$).

The combination NtHf had the greatest effect on SOC sinks. The annual SOC sink amounts ranged from CtLf (the lowest value; 65 ± 21 kg C ha^{-1} yr^{-1}) to NtHf (the highest value; 527 ± 23 kg C ha^{-1} yr^{-1}).

The climate scenarios (NCC, RCP4.5, and RCP8.5) did not show significant effects on SOC sink rates within the farm management combinations modelled (result not shown).

No significant differences were observed between the two grazing management policies tested or between the different climate scenarios (Figure 3.3b).



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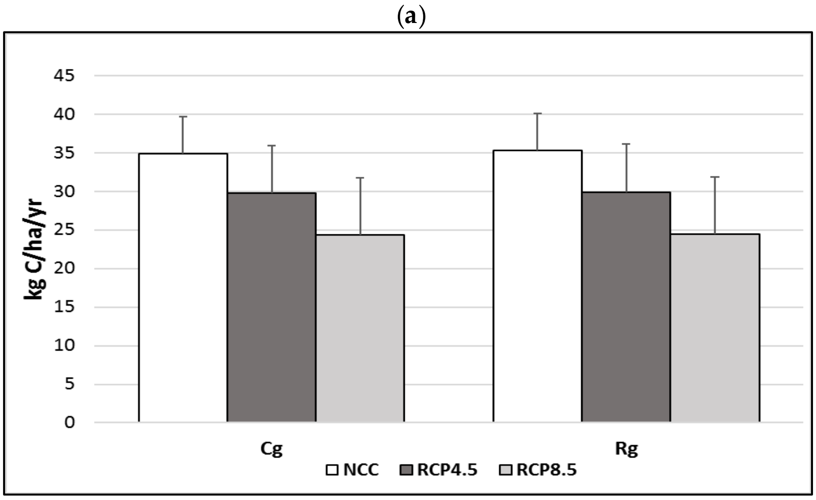

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Figure 3.3 DNDC-modelled mean annual soil organic carbon (SOC) dynamics (0-50cm) (±se) from 2019 to 2089 as a result of different (a) farm management policies and (b) grazing systems under diverse climate scenarios. Cf = current fertilization (50 kg N ha^{-1} yr^{-1}); Cg = continuous grazing; Ct = current tillage; Hf = higher fertilization rate (+50% Cf); Lf = lower fertilization rate (-50% Cf); Rg = rotational grazing; NCC = current climate; RCP4.5 and RCP8.5 = Representative Concentration Pathways 4.5 and 8.5. The letters above the bars indicate differences between fertilization rates, applied within each tillage. The letters in bold inside the bars indicate differences between each tillage per fertilization rate combination. Different uppercase letters indicate statistical differences from Tukey's test ($p < 0.001$). Different lowercase letters indicate statistical differences from Tukey's test ($p < 0.05$).

3.5.3 *Impact of management and climate on the carbon footprint of the pasture-based cattle beef system*

Considering the current climate scenario (NCC), tillage system (Ct), fertilization rate (Cf), and grazing management system (Cg), the overall carbon footprint associated with the production of native Maremmana beef cattle (evaluated at the farm gate) was estimated to be 26.9 ± 0.7 kg CO_{2e} kg LW^{-1}. With a 53% incidence, enteric fermentation was the main hot spot, followed by net soil GHG emissions (29%), fuel consumption (8%), transportation (6%), and concentrate (2%). The GHG emissions associated with seed production (1.3%), tractors (0.5%), and barns and sheds (0.2%) had only a marginal role (data not shown).

The adoption of less-invasive soil tillage systems has the potential to significantly reduce the overall CFP of pasture-based beef. Indeed, without considering the results of the modelled forage crop yield surplus, switching from CtCf to MtCf or NtCf reduced the CFP by 14% and 26%, respectively ($p < 0.001$) (data not shown). The CFP reductions (from switching to MtCf or NtCf) were more marked (20% and 35%, respectively) when the related crop yield surpluses were taken into account (Figure 3.4a). The climate scenarios did not induce any significant differences on the CFP resulting from the farm management combinations modelled (result not shown). With regard to fertilization rates, significant differences impacting total CFP ($p < 0.05$) were modelled (the lowest and highest rates of fertilizer application within each tillage) (Figure 3.4a).

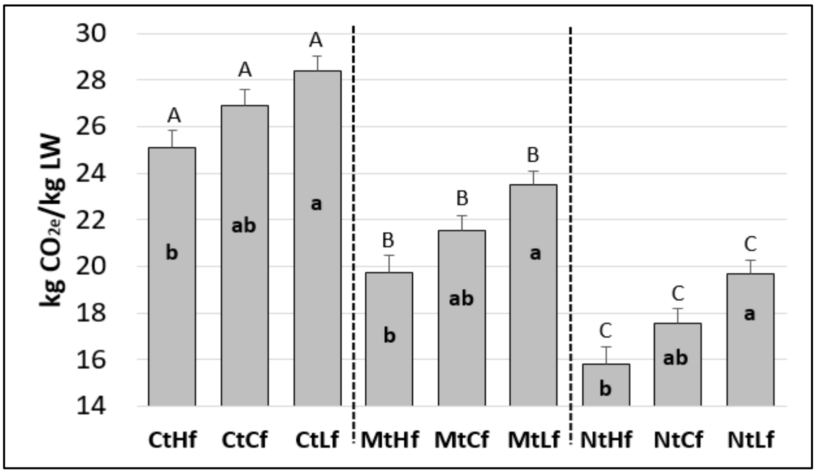
Compared to current tillage (Ct), less-invasive tillage practices had a positive effect ($p < 0.001$) on the modelled crop yield, which increased under Mt and even further under Nt.

Except for the Ct scenario, where significant ($p < 0.05$) differences in crop yield occurs only comparing the extreme of the modelled fertilization rates (i.e., Lf vs Hf), within Mt and Nt scenario each fertilization rate (i.e., Lf, Cf and Hf) has shown significant differences (Figure 3.4b). Particularly, when compared to Cf rates (i.e., 50 kg N ha^{-1} yr^{-1}), increased (+50%) rate of N organic fertilizers induced crop yield increases (6-8%), while reduced organic N rates (-50%) induced crop yield decreases (6-8%).

The climate scenario RCP8.5 induced a significant increase ($p < 0.001$) in crop yield compared to the crop yields modelled under NCC and RCP4.5 (significance not shown in figure).

Overall, the NtHf management combination showed the lowest CFP value for the beef production system under investigation. Considering the environmental benefits from crop yield surpluses, the GHG emissions arising from the NtHf combination (15.8 kg CO_{2e} kg LW^{-1}) were about 40% lower than those computed under the CtCf (Figure 3.4a).

The modelling comparing the Cg to the Rg system did not highlight significant effects on the CFP (data not shown).



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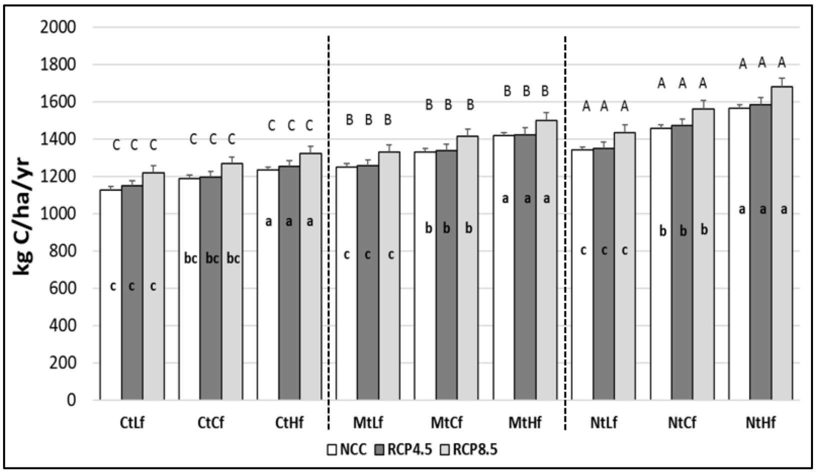

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Figure 3.4 Mean annual (from 2019 to 2089) (a) overall carbon footprint (±se) as a result of different tillage types and fertilization rates and (b) crop yield (±se) as a result of different tillage types, fertilization rates, and climate scenarios. Cf = current fertilization (50 kg N ha^{-1} yr^{-1}); Ct = current tillage; Hf = higher fertilization rate (+50% Cf); Lf = lower fertilization rate (-50% Cf); NCC = current climate; RCP4.5 and RCP8.5 = Representative Concentration Pathways 4.5 and 8.5. In (a), the letters above the bars indicate differences between each tillage per fertilization rate combination. The letters in bold inside the bars indicate differences between fertilization rates, applied within each tillage. In (b), the letters above the bars indicate differences between tillage types for each fertilization rate per climate scenario combination. The letters in bold inside the bars indicate differences between fertilization rates, applied within each tillage per climate scenario combination. Different uppercase letters indicate statistical differences from Tukey's test ($p < 0.001$). Different lowercase letters indicate statistical differences from Tukey's test ($p < 0.05$).

3.6. *Discussion*

3.6.1 N_2O emissions arising from the system

As expected, the DNDC showed N_2O emissions that were N-dose-dependent. Particularly, 0.12% of the N added as organic compost volatilized as N_2O emissions. Although comparisons to other studies were difficult due to the several factors involved in soil N_2O emissions (e.g., management history, climate condition, and soil type), the results obtained in this study fell within the 0.01%-0.37% range found by other studies evaluating compost application N fluxes (Dalal et al., 2009; Ding et al., 2013; Li et al., 2016).

Due to the highly variable effects that conservation tillage practices have on N_2O emissions, there is a considerable debate concerning the role of these practices in climate change (CC) (Mei et al., 2018). Indeed, studies have reported that N_2O emissions increase (Lognoul et al., 2017) or decrease (Feng et al., 2018). In this study, compared to conventional tillage, the modelled conservation tillage practices did not show significant improvements, which has also been found in other studies (Guardia et al., 2016).

Limited information exists about the possible impacts of CC on soil N_2O emissions. A recent study (Álvaro-Fuentes et al., 2017) found that CC could induce a slight decrease in overall N_2O emissions under different land use scenarios in the Mediterranean area. On the contrary, an Australian study that used the DNDC model to evaluate the N_2O fluxes of rain-fed agricultural systems under RCP4.5 and RCP8.5 climate projections (Ma et al., 2018) found an increase in N_2O emissions ranging from 34% to 75% compared to those occurring within the current climate scenario. In line with those findings, in this study, the RCP4.5 and RCP8.5 climate projections increased N_2O emissions (15%-21%, respectively) in comparison to those occurring under the NCC scenario. The reason for these increased trends could be attributable to the warmer soil temperature modelled in the RCP4.5 and RCP8.5 scenarios. Indeed, increased soil temperature, which the model predicted under CC conditions, is expected to stimulate microbial activity and nitrification and denitrification processes (Smith et al., 1997).

According to the DNDC outputs, the mean annual N_2O emissions arising from the conventional grazing system, Cg, amounted to about 5.4 kg N_2O-N ha^{-1}, and no differences resulted from switching to the Rg management system. The complex interactions between short-term weather conditions (e.g., warming and precipitation), land management practices (e.g., N inputs and tillage operations), and soil properties (e.g., bulk density, clay content, and water retention) make N_2O emissions highly variable both temporally and spatially (Grant et al., 2016). As a matter of fact, N_2O emissions from grazed pastures have been reported to range from null in arid and infertile regions to up to 38.5 kg N_2O-N ha^{-1} yr^{-1} in peat soils (Oenema et al., 1997; Sakadevan and

Nguyen, 2017). A study carried out on clay soil in Ireland reported a range of 1.7-6.3 kg N_2O-N ha^{-1} yr^{-1} on no-graze perennial ryegrass grasslands receiving no fertilizer, and the range increased to 4.4-34.4 kg N_2O-N ha^{-1} yr^{-1} when fertilizer and grazing were taken into account (Burchill et al., 2014).

The results obtained for the long-term timeframe modelled in this study allow us to state that the adoption of conservation tillage practices such as Mt and Nt did not induce significant soil N_2O emissions differences compared to those occurring under Ct. The 70-year time period modelled using the RCP4.5 and RCP8.5 climate pathways showed that annual N_2O emissions did not increase under these two RCP scenarios, and because soil properties and management practices were kept unchanged during the modelled time period, the resulting increasing trend could be totally attributed to CC conditions.

3.6.2 Soil organic carbon (SOC) dynamics

Although one meta-analysis study has found that there are some beneficial effects due to switching from conventional to minimum or no-tillage practices (Aguilera et al., 2013), another study has highlighted that there is no effect from switching (Dimassi et al., 2014). In our study, according to the C sink rates (0-50 cm) obtained from the modelled tillage alternatives (Figure 3.3a), the switch from Ct to Nt increased the SOC by about 0.27t C ha^{-1} yr^{-1}. It has been reported that increases in annual carbon sequestration rates can range from 0.1 up to 1t ha^{-1} after conversion from conventional to no-tillage (Farooqi et al., 2018; Lal, 2004; Sperow, 2016).

Although the link between C input and SOC sequestration could be considered to be a measure of C sequestration efficiency (Bhogal et al., 2009; Hua et al., 2014), there is no general relationship between these two parameters. Indeed, while some studies have reported soil C saturation after long-term repeated C inputs (Chung et al., 2010; Gulde et al., 2008), others have shown a linear or logarithmical SOC sequestration (Yan et al., 2013; Zhang et al., 2012). With the tillage alternatives modelled in this study, no soil C saturation was reached at the end of the 70 years following the spin-up time, and a linear increase in SOC content with greater C input was observed. This linear trend could be partially explained by the starting low organic matter content (0.0085 kg C/kg soil) of the topsoil (0-10 cm) investigated in this study. Indeed, it has been reported that soil with depleted SOC generally indicates a long-term linear relationship between C inputs and sequestration rates (Chung et al., 2010).

The model clearly suggested that a higher proportion of compost applied to soil can significantly increase SOC stocks, which may provide an important C source of net sink both under current and future CC scenarios. Specifically, of the total organic C annually applied as compost, about 27% of it was constantly sequestered within the cultivated soil. These findings were consistent with those found by other studies that have investigated the effects of organic amendments on SOC sequestration (Bhogal et al., 2009; Hua et al., 2014).

A survey of the recent literature highlighted that there is no clear general relationship between grazing management and C sequestration (Khalil et al., 2019; Zhang et al., 2017). As a matter of fact, contrasting findings can be found from the literature, with studies showing positive (Byrnes et al., 2018), null (Sanderman et al., 2015), or even worse (Allen et al., 2013) responses in terms of SOC from rotational grazing. The results of the long-term modelling from the present study did not highlight significant SOC differences between Cg and Rg. Nevertheless, the reason behind this finding could be attributable to the fact that with both Cg and Rg, the total number of animals was kept equal, and thus the overall manure in the fields was the same under both management structures. Furthermore, the DNDC lacks the ability to model grass regrowth dynamics (i.e., higher yields), which could potentially be achieved by controlling the physiological state of the meadow under Rg management: this may have further contributed to reducing the differences between the two grazing management policies investigated. In this regard, it would be important to conduct further investigations into the effects different grazing management policies could have on carbon sink in the Mediterranean context.

3.6.3 The carbon footprint (CFP) of pasture-based cattle beef

Besides the types of production systems involved (organic vs conventional), the CFPs of beef products are also strictly dependent on the cattle breed, finishing age, and type of diet. Although all of these factors, coupled with SOC sequestration rates, make a comparison of our results to other studies challenging, some conclusions can be drawn.

Recent studies (Buratti et al., 2017; Vitali et al., 2018) investigating the CFPs of typical Italian organic beef cattle farms (Chianina breed) have found that the GHG emissions at the farm gate were in the range of 20.9-23.3 kg CO_{2e} kg LW^{-1}, lower than those obtained for the beef cattle system in the present study (26.3 kg CO_{2e} kg LW^{-1}) under current conditions. The lower CFP value obtained for the Chianina breed compared to the Maremmana breed (present study) might have been due to the different production efficiencies of these breeds. Indeed, Chianina cattle have a younger slaughter age (~22 months) and a greater weight at slaughtering (~700 kg LW $head^{-1}$) compared to the Maremmana breed (~27 months, ~585 kg LW $head^{-1}$).

Compared to both the modelled (Ryals et al., 2014) and observed (Farooqi et al., 2018) findings of other studies that have investigated the effects of compost applications, our modelling suggests that the use of organic fertilizers could result in a win-win situation where there is an increase in both C storage and the crop yield, which in turn could reduce the GHG emissions arising from on-farm forage crop production. Indeed, the greater N_2O emissions modelled were associated with higher rates of simulated fertilizer applications, a result that was totally offset by the effects of the increased carbon sequestration rates. Specifically, considering the cradle-to-grave life cycle of organic compost, the ~0.32 kg CO_{2e} emitted per kg of compost (produced, transported, and spread) was counterbalanced by the ~0.49 kg CO_{2e} stored as organic matter in soil (data not shown).

The alternative fates of the organic material used as fertilizer is important when assessing the net CFP contribution of its use. Indeed, although the use of compost can increase the soil C storage, only when this transfer (vs. other uses) increases long-term C removal from atmosphere could be considered as net C sequestration (Chenu et al., 2019). For example, the soil application of forest litter removed from another ecosystem, it will inevitably reduce the soil biomass equilibrium of this latter, which in turn will counteract the C sequestered occurring in the soil where the litter is applied. In this context, a net sequestration will occur only where: (i) the organic amendments are produced by or for, rather than repurposed to, the agroecosystem, or (ii) where the C in existing amendments would otherwise be more rapidly lost to the atmosphere, such as through burning. The latter may also be possible to achieve via reapportionment of resources to land with lower C stocks (Sykes et al., 2020). In assessing the net annual C sequestration rate coming from the organic fertilization, the case study presented in this work did not consider the potential alternative fates of the digested manure applied. However, due to the low C content (< 15g C kg soil^{-1}) of the investigated soil, this latter could be considered to have a high carbon storage potential compared to the average agricultural soils (20-50g C kg soil^{-1}) within the region (de Brogniez et al., 2015).

Furthermore, in evaluating the organic fertilization rates to be applied to N-fixing crops (i.e., ryegrass-clover), the application' effect of external N to the sward' composition should be considered. Indeed, in literature many works report that high N fertilization rates can negatively influence the prominence and productivity of clover in the sward. McDonagh et al., (2017) have shown that, under higher N fertilizer use (250 kg N ha^{-1} yr^{-1}), the competitive nature of grass restricted the clover proportion below the target for desirable agronomic performance (< 20%) over 3 years. Specifically, the detrimental N fertilizer effect on clover proportion has been attributed to the reduction in light quantity and quality available for clover. Similar results were found also by Hidalgo et al., (2015) which reported reduced sward clover content with N application rates of 240 kg N ha^{-1} yr^{-1} over 3 years, while less effects were found at N rate of 120 kg N ha^{-1} yr^{-1}.

The impact that reduced tillage practices have on crop yield is controversial. Indeed, some studies have reported crop yield increases when conventional tillage was reduced to a minimum or to no-tillage (de Cárcer et al., 2019), while others have reported similar (Büchi et al., 2017) or decreased (Pittelkow et al., 2015) yields. In this study, the switch from Ct to Mt and Nt resulted in modelled crop yield increases of 12% and 23%, respectively. The modelled yield increased to within the lower part of the range reported for rain-fed crops under dry climates (6%-41%) (Taner et al., 2015; Wang et al., 2007), which could have been attributable to both the greater soil water conservation and greater SOC concentrations modelled with the Mt and Nt tillage practices.

The DNDC model outputs did not highlight any significant differences between the crop yields occurring under the NCC and RCP4.5 climate scenarios, while greater yields (8%) were modelled under RCP8.5. The main reason behind this trend could be attributable to the higher CO_2 concentration considered within the RCP8.5 (468 ppm) scenario compared to the RCP4.5 (448 ppm) (Yu et al., 2017) and NCC (412 ppm) scenarios (NASA, 2019).

The replacement of Cg with Rg management did not lead to a significant improvement in terms of GHG emissions. However, although the DNDC model is a powerful tool for estimating the aboveground net primary production, significant uncertainties still exist when it is used to quantify the variation of the grazing effects on grasslands (Wang et al., 2016). Indeed, by affecting species composition, primary production, and root biomass, grazing could have an overall impact on standing biomass that is more direct and rapid than that exerted by management practices and climate change (Numata et al., 2007). In this regard, the validation of the model using site-specific field observations (e.g., the daily grass growth rate) needs to be explored in future work. Furthermore, on the animal side, by increasing the proximity of bulls to cows, a switch from Cg to Rg could have positive consequences (e.g., reducing the inter-calving period) that were not accounted for in this case study.

Finally, although the conditions on the assessed beef farm are representative of the typical weather, soil, and management practices of native cow-calf systems bred in the Mediterranean area, further investigations within this ecoregion are needed for a better understanding of the GHG mitigation potential that is achievable using pasture-based systems.

3.7. Conclusions

The process-based model DNDC was used to quantify and evaluate the effects that different agronomic practices, grazing management policies, and climate projections could have on the GHG emissions arising from a pasture-based native beef cattle farm in a Mediterranean agro-pastoral system. The adoption of conservation tillage, such as minimum and no-tillage practices, was shown to be effective in mitigating GHG emissions: once implemented, they could enhance the amount of C sequestered in the soil and increase the yield of forage crops. Although the modelled increases from organic fertilization adoption induced greater soil N_2O emissions, these were totally offset by the consequently greater SOC sink rates associated with this agronomic practice. Long-term modelling using the RCP4.5 and RCP8.5 scenarios improved our understanding of the effects that climate change scenarios could have on both N_2O emissions and crop yields. The results from the 70-year modelling indicated that N_2O emissions could increase with both climate change pathways, while increases in forage yields were found only within the RCP8.5 scenario. On the one hand, the adoption of no-tillage practices coupled with a higher rate of organic fertilization showed a high beef carbon footprint reduction potential, but on the other hand, the modelled switch from a continuous to a rotational grazing system did not lead to significant GHG emissions differences per unit of product. Agricultural carbon footprint studies that use process-based modelling have been useful in the evaluation of the effectiveness of mitigation strategies that can be implemented in these systems (because they model crop growth, SOC dynamics, and soil GHG emissions). However, testing the prediction abilities of these models using site-specific field observations needs to be explored in future work.

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Supplementary materials

The following section contains: Table S3.1: Model input data for the baseline ryegrass-clover mix cultivation; Table S3.2: Model input data for the baseline perennial grass grazed; Table S3.3: Model soil input data; Table S3.4: Average herd data (2016-2018) used for the enteric methane estimation; Table S3.5: Life cycle inventory (LCI) data.

Table S3.1 Model input data for the baseline ryegrass-clover mix cultivation

Crop	Parameters	Baseline data
Ryegrass-clover mix	Crop type	Annual grass
	Fraction of leaves + stems left in field after harvest	0.1
	Max. aboveground biomass (kg C ha^{-1} yr^{-1})	3,600
	Thermal degree days for maturity	1,350
	Water demand (g water/g DM)	115
	N fixation index (crop N/N from soil)	1.5
	Optimum temperature (°C)	21
	Tilling method	Deep ploughing (30cm)
	Tilling date (month-day)	9-15
	Manure amendment applied	Compost
	Manure amendment applying date (month-day)	3-15
	Compost solid C/N ratio	14
	Organic C (kg C/ha)	700
	Organic N (kg N/ha)	50
	Compost application method	Surface spread
	Number of cuts	1
	Cutting date (month-day)	5-15
	Cut part	Grain-leaf-stem
	Cut fraction	0.9
	Length of the cultivation	1 year

DM = Dry matter

Table S3.2 Model input data for the baseline perennial grass grazed

Crop	Parameters	Data
Perennial grass pasture	Crop type	Perennial grass
	Max. aboveground biomass (kg C ha^{-1} yr^{-1})	1,224
	Thermal degree days for maturity	1,000
	Water demand (g water/g DM)	200
	N fixation index (crop N/N from soil)	1.5
	Optimum temperature (°C)	21
	Number of grazing applications	1
	Grazing starting date (month-day)	1-12
	Grazing ending date (month-day)	12-31
	Grazing hours per day	8
	Grazing intensity (heads ha^{-1})	1.3
	Additional feed (kg C head^{-1} day^{-1})	3.2
	Feed C/N	20
	Excreta handle	Deposit in field

Table S3.3 Model soil input data

Dedicated area	Parameters	Data
Ryegrass-clover mix	Top soil texture	Sandy-loam
	Bulk density (g cm^{-3})	1.3879
	Soil pH	4.9
	Field capacity (wfps)	0.32
	Wilting point (wfps)	0.15
	Clay fraction	0.09
	Hydro-conductivity (m hr^{-1})	0.1248
	Porosity (0-1)	0.435
	SOC at surface soil (0-10cm) (kg C/kg Soil)	0.0085
	Initial nitrate concentration at surface soil (mg N kg^{-1})	0.5
	Initial ammonium concentration at surface soil (mg N kg^{-1})	0.05
Perennial grass pasture	Topsoil texture	Clay-loam
	Bulk density (g cm^{-3})	1.1554
	Soil pH	8.2
	Field capacity (wfps)	0.57
	Wilting point (wfps)	0.27
	Clay fraction	0.41
	Hydro-conductivity (m hr^{-1})	0.015
	Porosity (0-1)	0.476
	SOC at surface soil (0-10cm) (kg C/kg Soil)	0.0214
	Initial nitrate concentration at surface soil (mg N kg^{-1})	0.5
	Initial ammonium concentration at surface soil (mg N kg^{-1})	0.05

Table S3.4 Average herd data (2016-2018) used for the enteric methane estimation

Parameters	Data
Lactating cows (heads yr^{-1})	146
Heifers and steers on pasture (heads yr^{-1})	142
Heifers and steers on fattening (heads yr^{-1})	12
Lactating cows (NEm) (MJ day^{-1})	41.7
Heifers and steers on pasture (NEm) (MJ day^{-1})	26.1
Heifers and steers on fattening (NEm) (MJ day^{-1})	36.6
Herds (NEa) (MJ day^{-1})	15
Lactating cows (NEl) (MJ day^{-1})	8.5
Pregnant cows (NEp) (MJ day^{-1})	2.9
Heifers and steers on pasture (NEg) (MJ day^{-1})	8.7
Heifers and steers on fattening (NEg) (MJ day^{-1})	18.2
Digestible energy (DE) expressed as % of gross energy for the fattening animals	75
Digestible energy (DE) expressed as % of gross energy for the rest of the herd	65
Ratio of net energy available in a diet for maintenance to digestible energy consumed (REM)	0.514
Ratio of net energy available for growth in a diet to digestible energy consumed (REG)	0.308

NEm = Net energy required for maintenance; NEa = Net energy required for activity; NEl = Net energy required for lactation; NEp = Net energy required for pregnancy; NEg = Net energy required for growth

Table S3.5 Life cycle inventory (LCI) data

Input	Types		Amount year^{-1}
Auxiliary products	Organic fertilizer		312 t
	Packaging org. Fertilizer (LDPE)		624 kg
	Fuel		23,907 kg
	Ryegrass-clover seeds		9,600 kg
	Packaging of ryegrass-clover seeds (paper)		38 kg
	Extra farm feed		30,100 kg
	Packaging of extra farm feed (paper)		181 kg
Input	**Products**	**Types of transport**	**Distance (one way)**
Transports	Organic fertilizer	Lorry 3.5-7.5t	424 km
	Fuel	Lorry 7.5-16t	75 km
	Ryegrass-clover seeds	Lorry 3.5-7.5t	212 km
	Extra farm feed	Lorry 3.5-7.5t	321 km
	Waste	Lorry 3.5-7.5t	50 km
Input	**Types**	**n**	**Area**
Agricultural buildings	Barns	2	300 mq
	Shed	1	150 mq
Agricultural machinery	Tractor	5	

LDPE = Low density polyethylene

Chapter 4

Applying the LCA approach to assess complex systems

Guideline to Quantify the Life-Cycle Carbon Footprint of a National Park: Application on an Italian Case Study

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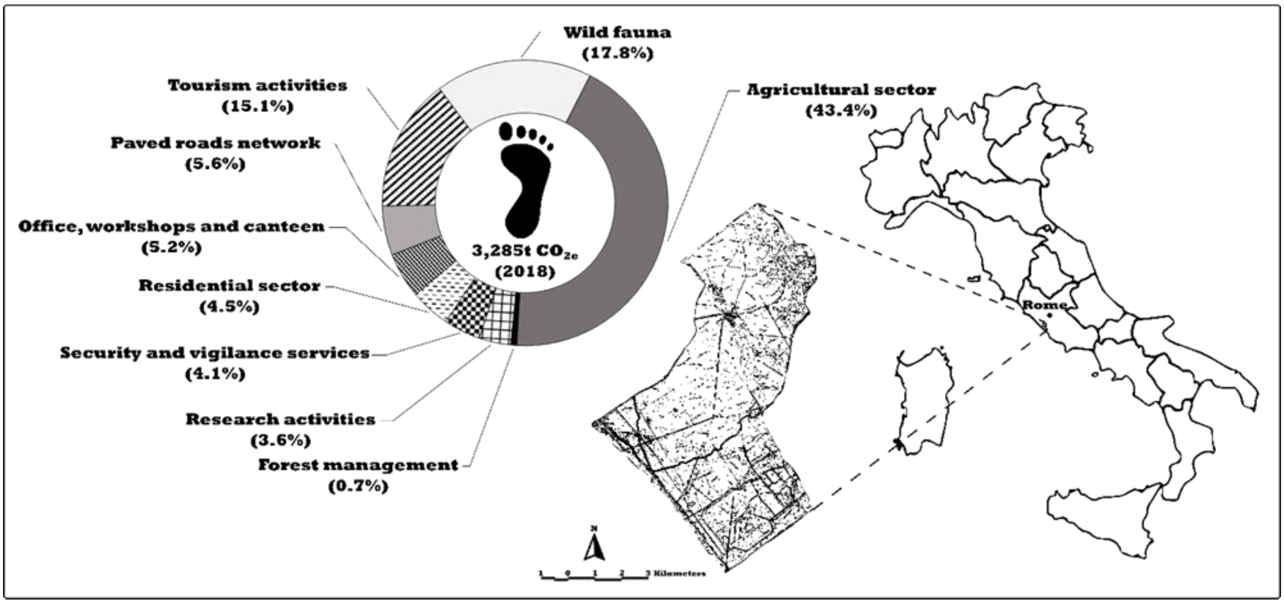
The results presented in this chapter are completely based on a paper that will be submitted to the journal: Science of the Total Environment

4.1. *Graphical abstract*



4.2. *Highlights*

- Type III ecolabels based on LCA studies provide detailed environmental information
- Sector-specific LCA guidelines guarantee reliable and comparable type III ecolabels
- Without a specific LCA guideline, National parks cannot obtain type III ecolabels
- The suitability of a proposed LCA guideline was tested on an Italian National park
- This paper showed the first cradle-to-grave carbon footprint of a National park

4.3. *Abstract*

The effects of climate change are increasing the public awareness on greenhouse gas (GHG) emissions related to human activities. The need for verified and credible information on GHG emissions is spreading and, when looking at actions to establish credible green marketing claims, eco-labelling is a possible tool to investigate. Although some National parks have started to promote their environmental services, currently there is not a specific guideline to follow in order to obtain a type III environmental declaration based on a cradle-to-grave carbon footprint (CFP) assessment. The methodological approaches and guideline proposed in this paper are demonstrated to be both feasible and suitable in providing a granular picture of the main GHG emission sources and hotspots of an Italian National park. To the best of our knowledge, this study could be considered the first cradle-to-grave CFP of a National park, and the proposed guideline could be the starting point for a widely accepted standard procedure to be followed in order to obtain a type III environmental

declaration.

Keywords: LCA; GHGs; C-sinks; eco-labelling; natural park

4.4. Introduction

Human activities such as those related to industries, transports, energy and agriculture, have led to the release of anthropogenic greenhouse gases (GHGs) into the atmosphere. Fortunately, as society prospers, there is an increasing awareness of the environmental impact of these activities.

Carbon Footprint of a Product (CFP) is a term used to describe the measurement of GHG emissions generated by a product or an organization. Wiedmann and Minx, (2008) define the CFP as a measure of the total amount of CO_2 emissions that is directly and indirectly caused over the life stages of a product or activity. However, as most of the anthropogenic activities emit other GHG than CO_2 (e.g., CH_4, N_2O, HFCs, etc.), the term carbon dioxide equivalent (CO_{2e}) is commonly used in CFP assessments. Specifically, the term equivalent means that the global warming factor of every GHG is calculated using CO_2 as means of comparison (Tjandra et al., 2016). CFPs assessment may have a wide range of application in the development of products, environmental policies and in marketing. The application that, among other, can be highlighted are: decision making, research and development, identification of areas of improvement, environmental labelling and ecological product statement (Calderón et al., 2010).

The need for verified and credible information on GHG emissions is increasing, with pressure coming from a wide range of interest groups (e.g., governmental and non-governmental organizations) aimed at reducing greenwashing (Torelli et al., 2019). In this regard, when looking at actions to establish credible green marketing claims, eco-labelling is a tool worth investigating (Taufique et al., 2019). The type III environmental certifications (i.e., eco-labelling) are declarations that provide information to the consumers through a logotype, or other type of communication tools (e.g., annual reports), on the life cycle of a product or service provided by a company or organization which is committed to achieve environmental improvements.

In 2013, the European Commission (EC) published a recommendation on the use of a common methodology to measure and communicate (e.g., eco-labelling) the environmental performance of products and organizations (EC, 2013). The basis of this common methodology is the life cycle assessment (LCA). The LCA addresses the environmental aspects and potential environmental impacts throughout a product or service' life cycle, from raw material acquisition through production, use, end-of-life treatment, recycling, and final disposal (i.e., from-cradle-to-grave) (ISO, 2006).

The initiative from the EC aimed at setting specific guidelines for LCA studies, which are called Product Environmental Footprint Category Rules (PEFCR) when related to products, and Organizational Environmental Footprint Sector Rules (OEFSR) when involving organizations. Such definite guidelines for measuring environmental performance throughout the life cycle of a specific-category product or organization, should then facilitate the comparability between LCA studies and provide principles for communicating the environmental performance, such as transparency, reliability, completeness, and clarity (EC, 2013).

To the best of our knowledge, although some National parks (e.g., Gran Paradiso National Park and Gargano National Park) have started implementing Eco-Management and Audit Scheme (EMAS) (EC, 2009) to promote their environmental commitment, currently there is not a specific guideline to follow (i.e., OEFSR) in order to obtain a type III environmental declaration based on a cradle-to-grave CFP. Therefore, we can observe that National parks are increasingly taking into consideration environmental assessment to promote their services, and only one study involving a CFP of National parks (Villalba et al., 2013) was found in literature. The work presented in this paper aimed to (i) develop and define a standard guideline to follow in order to assess life-cycle (i.e., cradle-to-grave) carbon footprint of National parks, (ii) test the applicability of the guideline proposed with a practical case study and, (iii) identify the sectors responsible for the largest GHG emissions of the case study assessed.

Along the text of this paper, the term “shall” has been used to indicate what is mandatory.

4.5. Functional unit

The primary purpose of a functional unit (FU) is to provide a reference to which the inputs and outputs of the system, a natural park in this case, are related. Therefore, the chosen FU shall be measurable and consistent with the goal and scope of the CFP study.

A natural park supplies different functionalities (e.g., tourist attraction, flora and fauna protection, preservation of the natural habitat, etc.) and it is not easy to indicate one that can embed all of them. The most common function of a natural park is to preserve the natural habitat. Therefore, it is suggested to adopt as FU one representative hectare of the park, which includes all the type of lands (e.g., agricultural soil, grasslands, savannahs, etc.) and anthropogenic activities (e.g., tourism, buildings, transports, etc.) occurring within it.

The results of the GHG quantification shall be provided in kg or metric tons (t) of carbon dioxide equivalent (CO_{2e}) produced annually per FU. Particularly, the adoption of this FU will allow to compare different National parks CFPs, even though characterized by different size.

4.6. System boundary

The system boundary (SB) is the basis used to delimitate the processes that shall be included within the assessment. A proper SB shall be consistent with the goal of the CFP, and all the criteria (e.g., cut-off criteria) used in its establishment shall be identified and explained. In this regard, the level of detail by which the SB processes will be investigated shall be clarified and, any accounting omissions (e.g., life cycle stages, processes, inputs, sectors, etc.) shall be accompanied by the implications that led to their exclusions.

Within the SB of a National park there are several sectors/activities that could take place, such as: nature-based tourism (e.g., camping, hiking, fishing, birdwatching, etc.), tourist facilities (e.g., restaurant, gift shops, hotel, etc.), construction and maintenance of infrastructure (e.g., buildings, roads, etc.), residential sector, fauna and flora preservation, and farming activities.

CFP studies carried out in accordance with the guideline proposed in this study shall include all the GHG emissions and removals occurring within the defined SB which have the potential to make a significant contribution to the final CFP value. With regard to the GHG removals (i.e., soil and forest carbon sinks) occurring within the defined SB, these shall be accounted and reported separately from the GHG active emissions.

4.7. Quantification of the GHG emissions

The quantification of the CFP outlined in this guideline follows the approach proposed by the World Resources Institute (WRI) (GHG protocol hereinafter) (https://ghgprotocol.org/product-standard) in which, to simplify the delineation of direct and indirect GHG emission sources, and to improve the transparency of the assessment, three "scopes" (scope 1, scope 2 and scope 3) are defined for the GHG accounting and reporting purposes.

4.7.1 Scope 1 emissions

Within the scope 1 are embedded all the GHG emissions physically occurring inside the border of the National park, and from sources that are owned or controlled by the park itself. In the following sections is presented a not exhaustive list of the main GHG emissions sources falling within this scope, which shall be included in the CFP analysis of National parks.

i. GHG emissions from agricultural soils

Within this sector shall be accounted all the direct and indirect N_2O emissions, as well as the CH_4 ones, coming from the soil because of its management (e.g., organic and inorganic fertilization, tillage, crop residues, etc.). The biogenic CO_2 produced by soil respiration shall not be considered.

ii. GHG emissions from animal breeding

Within this sector the direct and indirect N_2O emissions and the CH_4 coming from manure deposited during grazing, as well as those occurring from manure management (e.g., composting, stockpiling, etc.) shall be assessed. Furthermore, enteric CH_4 from both ruminant and monogastric shall be estimated. The biogenic CO_2 produced by animals' respiration shall not be considered.

iii. GHG emissions from wild fauna

Wild fauna plays an important role into National parks, and the population size of the main species living within the boundaries of the parks are generally monitored. Therefore, at least for the wild animals for which it is known the composition of the population, the direct and indirect N_2O emissions and the CH_4 coming from manure excreta, as well as the CH_4 emissions arising from enteric fermentation shall be accounted. The biogenic CO_2 produced by wild animals' respiration shall not be considered.

iv. GHG from fossil fuels combustion

The GHG emissions generated by the combustion of the fossil fuel (e.g., agricultural activities, heating systems, cooking activities, etc.) occurring inside the physical border of the National park shall be accounted. The biogenic CO_2 produced by the combustion of woody biomass (e.g., pruning, crop residues, wildfires, etc.), if accounted, shall be reported separately.

v. In-boundary transports

An estimation of the GHG emissions arising from all the transports occurring inside the physical border of the National park (e.g., shuttle bus, cars, caravans, trucks, etc.) shall be provided.

vi. Refrigerant gas leaks

An estimation of the refrigerant gasses' leaks coming from the cooling and refrigerant devices (e.g., air conditioners, fridges, etc.) that are auxiliary to the activities connected to the National park (e.g., offices, museums, restaurants, etc.) shall be provided.

vii. GHG removals

All the GHG removals occurred during the reporting time (i.e., one year) inside the physical boundary of the National park, shall be estimated and reported separately. Within this category were included soil organic carbon (SOC) sequestration dynamics, and the C-sinks related to the forest wood biomass growth.

4.7.2 Scope 2 emissions

Within the scope 2 emissions were included all the GHG emissions which, although emitted outside the physical boundary of the National park, were generated to produce the electricity consumed by the activities occurring inside it. For all the cases where the electricity it is generated inside the boundary of the National park (e.g., wind power plant, solar plant, etc.), then those emissions fall within the scope 1. Finally, in order to highlight the areas where energy efficiency could be improved, whenever possible, the electricity involved in each park' building shall be differentiated per consumption sources (e.g., lighting, cooling systems, etc.).

4.7.3 Scope 3 emissions

Within the scope 3 emissions were considered all those GHG emissions which are consequence of the activities related to the National park (e.g., purchased goods, commuting of workers, tourist transports, etc.) but that occur from sources not directly owned or controlled by the park itself. In the following sections is presented a not exhaustive list of the main scope 3 emissions sources that shall be considered in the National park CFP.

i. Purchased goods

Within this category were included the GHG emissions coming from the production, and end-of-life of the main goods (i.e., durable and non-durable) purchased by the National park during the reporting time. In accounting the GHG emissions coming from durable goods (e.g., machineries, electronic devices, etc.), their lifespan shall be considered. As regard to the GHG emissions generated by the life cycle of the buildings, these shall be accounted for all the buildings of recent construction (i.e., less than 50 years) placed within the boundary of the National park.

ii. In-boundary meals

An esteem of the GHG emissions associated to the meals consumed inside the physical boundary of the National park (e.g., tourists, employees, workers, etc.) shall be provided. Specifically, the GHG emissions associated to food productions shall consider its whole life cycle (i.e., production, processing, use, and end-of-life).

iii. Fossil fuel

Regarding the fossil fuel used for all the activities directly owned and controlled by the National park (for which the GHG emissions coming from its combustion were already accounted into scope 1), the GHG generated by its extraction and refining shall be then considered within this scope 3.

iv. Out-boundary transports

In addition to the GHG emissions arising from the out-boundary transports associated to the goods, meals and fuel purchased by the National park (see above sections), those generated by the commuting of park' employees and workers, as well as those arising from business-travels, shall be accounted. In this regard, all type of transports involved shall be considered (e.g., cars, buses, trains, airplane, etc.). Furthermore, as for the employees and workers, also for the visiting tourists an estimation of the GHG emissions generated for reaching the park shall be provided.

v. Paved roads network

The GHG emissions generated by the life cycle (i.e., production and maintenance) of the paved roads network inside the National park shall be provided.

vi. Waste (end-of-life)

The GHG emissions arising by the disposal and treatment of waste generated by the park activities shall be accounted. Specifically, it shall be considered the energy consumption and the direct GHG emissions associated to the type of disposal (e.g., landfill, incineration, recycling, composting, etc.) and to the amount produced during the reporting time. The end-of-life of durable goods (e.g., machineries, electronic devices, etc.) shall also be estimated by considering their lifespan.

4.8. Assessing uncertainty

According to the GHG protocol and to this guideline, National parks are required to report a qualitative description of uncertainty sources and methodological choices made in the inventory. These include information regarding: (i) the use and end-of-life profiles for cradle-to-grave inventories, (ii) allocation methods, (iii) the source of global warming potential (GWP) used, and (iv) any calculation models used to quantify emissions and removals.

Quantitative uncertainty assessment is not required. However, such an assessment it is recommended since it can provide a more robust result that can identify specific areas of high uncertainty that could be improved.

4.9. Case study

To examine the applicability of the guideline proposed in this paper, a case study was conducted on Castelporziano Natural Reserve (41°42'50''N - 12°24'03''E), which extends from the south-southwest of Rome towards the Tyrrhenian Sea, and covers 5,980 ha of land (Recanatesi, 2015). This area (Reserve hereinafter) was established as a State nature reserve in 1999, and it hosts one of the three Presidential estate of the Italian Republic (https://palazzo.quirinale.it/).

4.8.1 System description

The largest part of the Reserve is covered with natural or semi-natural vegetation, and the area classified as woodland reaches 4.511 ha (i.e., 75.7 %) of the total. The Reserve can be considered a unique environment in the Mediterranean area since it includes uncontaminated beaches, recent and old stabilized sand dunes, ample back dune wetlands, Mediterranean scrubland, and thickets featuring typical evergreen and aromatic species. Recent investigations show that, within the Reserve, about 90% of the forest areas have maintained their destination use without changes since 1950 (Pignatti et al., 2015).

Beside the great range of vegetation, the Reserve hosts native wild boars, fallow deer (*Dama dama*) and deer (*Cervus elaphus*). Small fauna (e.g., foxes, badgers, porcupines, etc.) is also present. Large predators are absent, and no sport hunting is allowed.

Into the Reserve, native Maremmana beef cattle and Maremmano horses are breed in pureness, and about 620 hectares of the Reserve are dedicated to the pasture and related cropping activities.

As regards to the touristic attractions, in addition to the several natural routes that can be enjoyed, the Reserve includes buildings dating from Roman Empire settlements, such as the Castle, which is currently hosting the Reserve' offices and the historical residence. But there is also a naturalistic museum, an archaeological museum, and a carriages hall that can be visited. Furthermore, a canteen is open during lunch time to tourists and Reserve' employees/workers. Finally, there is a mechanical workshop and a carpentry dedicated solely to the in-boundary needs.

Unless invited to the events organized during the year, tourists visiting the Reserve are not allowed to go inside using their own transportation, and a shuttlebus service is provided during the opening season (from 14th March to 21st June). Moreover, in addition to the normal opening season, during summer (from 4th June to 30th August) environmental courses for people with disabilities are also organized. Lastly, among the people authorized to enter the Reserve, there are also a few national and international researchers.

A small residential sector (i.e., 24 households) is present within the Reserve, and it is mainly composed by people who are in different way involved in the activities taking place within the natural park.

Finally, with the aim to preserve the natural area from wildfires, the Reserve is provided with a small firefighter station that patrols the area during the summer season. In addition, several policemen are all year-round employed to guarantee the safety of the Presidential Estate.

4.8.2 System boundary

Within the SB considered (Figure 4.1), were included all the GHG emissions (i.e., scope 1, scope 2 and scope 3) generated annually by all the Reserve' activities.

With regard to the scope 1 emissions, were considered all the GHG generated within the physical boundary of the Reserve, which are: (i) soil and animals' biological processes, (ii) fuel combustion, (iii) in-boundary transports, and (iv) refrigerant gas leaks.

As scope 2 emissions, were considered all the GHG emissions generated outside the physical boundary of the Reserve necessary to produce the electricity consumed within the SB.

Within the scope 3 emissions were included all the GHG arising from: (i) durable and non-durable goods purchased, (ii) ingredients used to prepare the meals consumed, (iii) out-boundary transports, and (iv) waste management.

A detailed framework of the GHG emissions accounted within each scope and sector is presented in Table 4.1.

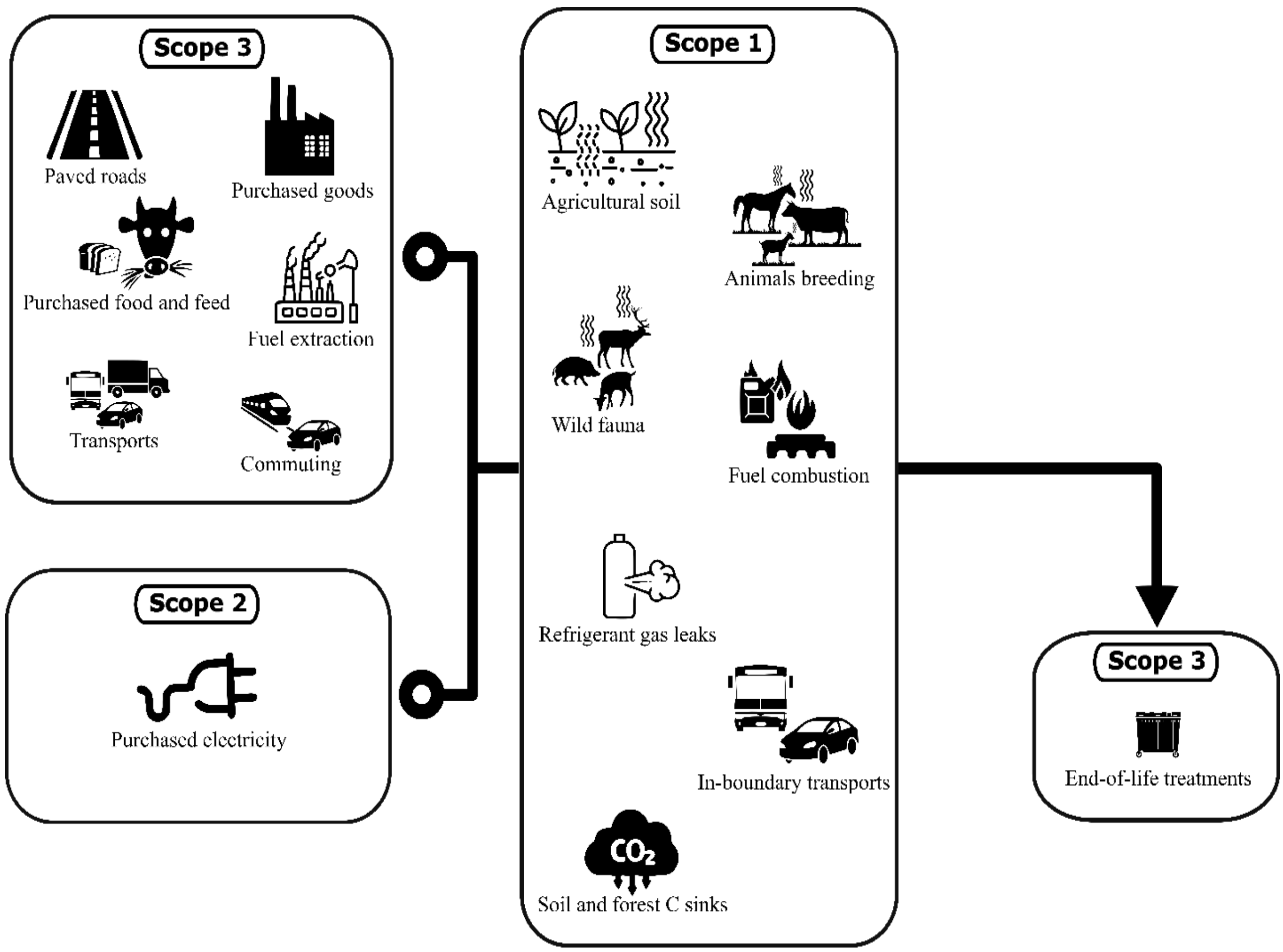


Figure 4.1 System boundaries of the scope 1, scope 2 and scope 3 emissions considered within the Reserve carbon footprint assessment.

Table 4.1 Framework of the GHG emission sources accounted within scope 1, scope 2 and scope 3

Sector	*Scope 1*	*Scope 2*	*Scope 3*
Agricultural and livestock	▪ Soil management ▪ Manure management ▪ Enteric fermentation ▪ Fuel combustion ▪ Soil organic carbon (SOC) sinks (accounted separately)	▪ None	▪ Auxiliary products (P; T; E) ▪ Purchased feed (P; T; E) ▪ Workers meals (P; T; E) ▪ Beef cattle consumption (T; M; E) ▪ Fuel extraction and refining (P; T) ▪ Agricultural machineries (P; M; E) ▪ Agricultural shelters (P; M; E)
Wild fauna	▪ Enteric fermentation ▪ Manure excreta ▪ In-boundary transports (i.e., feeding and monitoring)	▪ None	▪ Purchased feed (P; T; E)
Tourism activities	▪ In-boundary transports (i.e., shuttlebus, bus, cars and lorries) ▪ Natural gas combustion (i.e., heating and cooking) ▪ Refrigerant gas leaks (i.e., air conditioners and fridges)	▪ Electricity consumption	▪ Air conditioners (P; E) ▪ In-boundary meals (P; T; E) ▪ Out-boundary transports
Paved roads network	▪ In-situ operations (fuel combustion)	▪ None	▪ Asphalt (P; T; M; E)
Offices, workshops and canteen	▪ In-boundary transports (i.e., cars and lorries) ▪ Natural gas combustion (i.e., heating and cooking) ▪ Refrigerant gas leaks (i.e., air conditioners and fridges)	▪ Electricity consumption	▪ Electronic devices (P; E) ▪ Auxiliary products (P; T; E) ▪ In-boundary meals (P; T; E) ▪ Out-boundary transports
Residential sector	▪ In-boundary transports (i.e., cars)	▪ Electricity consumption	▪ Not considered
Security and vigilance services	▪ Natural gas combustion (i.e., heating) ▪ Refrigerant gas leaks (i.e., air conditioning) ▪ In-boundary transports (i.e., trucks and cars)	▪ Electricity consumption	▪ In-boundary meals (P; T; E) ▪ Out-boundary transports
Research activities	▪ In-boundary transports (i.e., cars)	▪ None	▪ In-boundary meals (P; T; E) ▪ Out-boundary transports
Forest management	▪ Fuel combustion (i.e., pruning activities) ▪ Forest carbon sinks (accounted separately)	▪ None	▪ Fuel extraction and refining (P; T) ▪ Machineries (P; M; E)

P= Production; T= Transports; M= Maintenance; E=End-of-life

4.8.3 Life cycle inventory

A detailed list of the life cycle inventory data related to each sector of the Reserve investigated has been reported in the supplementary materials. Specifically, the supplementary materials contain the following table: Table S.4.1. List of the emission factors involved in the Reserve' carbon footprint; Table S4.2: Life cycle inventory data of the Reserve' agricultural sector; Table S.4.3: Life cycle inventory data of the Reserve' wild fauna sector; Table S.4.4: Life cycle inventory data of the Reserve' touristic sector; Table S.4.5: Life cycle inventory data of the Reserve' office, workshops and canteen sector; Table S.4.6: Life cycle inventory data of the Reserve' residential sector; Table S.4.7: Life cycle inventory data of the Reserve' security and vigilances sector; Table S.4.8: Life cycle inventory data of the Reserve' research activities sector; Table S.4.9: Life cycle inventory data of the Reserve' forest sector.

4.8.4 Scope 1 emissions

i. Soils and animals' biological processes

Different methods were involved for the estimations of the enteric methane emitted annually by cattle, horses, and wild fauna. Specifically, a Tier 2 (IPCC, 2006) approach was adopted for cattle, a Tier 1 (IPCC, 2006) approach was used for horses, while the method proposed by Smith et al., (2015) was followed for the enteric fermentation (ruminant and hindgut) coming from wild animals (i.e., wild boars, fallow deer and deer).

As for the enteric methane, also for the GHG emissions (i.e., direct and indirect N_2O, and CH_4) from the manure deposited on pasture were used different approaches. A Tier 3 approach involving the use of a process-based model named Denitrification-Decomposition (DNDC) model (Li et al., 2000) was used for the assessment of the grazing cattle (Grossi et al., 2020). While a Tier 1 (IPCC, 2006) approach was used for the estimations of the GHG emissions coming from horses, and wild fauna. Particularly, the wild animals' N excretion rates were obtained by considering the weight of the target wild animals, and the default N excretion rates of the most similar domestic animal category provided by IPCC, (2006) and Velthof, (2014).

ii. Fuel combustion

The GHG emissions generated from the use of diesel (i.e., tillage and motor pumps) and natural gas (i.e., cooking and heating), were accounted based on the annual consumptions provided by the Reserve, and the emission factors (EFs) provided by Ecoinvent database (Wernet et al., 2016) and Bradbury et al., (2015), respectively.

Considering the annual meals that the canteen provided to the employees/workers and to the tourists, 38% of the GHG emissions arising from gas consumption were allocated to the tourist sector.

Since the annual natural gas consumption (i.e., heating) of castle and office were provided in a cumulative way, it was possible to estimate the distribution of natural gas consumption. Specifically, the estimation was made using the approach proposed by Moreci et al., (2016), and the parameters provided by De Rosa et al., (2015). Furthermore, the same approach was used for the estimation of the natural gas needed to heat the police office of the Reserve, for which primary data were not available.

The GHG generated during the construction and maintenance of the paved road networks were accounted based on the hectare of the Reserve covered by asphalt (Recanatesi, 2015) and the granulized EFs proposed by Araújo et al., (2014).

iii. In-boundary transports

By both using primary data (i.e., data provided by the Reserve), and estimations (i.e., assumptions) of the distance driven, the in-boundary transports inventory included: (i) transports (i.e., by cars) for wild fauna monitoring and census, (ii) transport of tourists (i.e., by shuttlebus and cars), (iii) transports (i.e., lorries) of meals' raw material purchased by the canteen, (iv) commuting of employees and workers (i.e., by cars and buses), (v) policemen and firefighters' patrols, (vi) researchers' activities and, (vii) residential sector.

The GHG emissions arising from the different types of transport were accounted using the EFs provided by Ecoinvent database (Wernet et al., 2016). In this regards, the average meal's weight proposed by To et al., (2019) was used to estimate the GHG arising by the transports of the meals' raw materials (i.e., by lorries).

For the estimations of the GHG emissions attributable to the residential sector it was assumed that each family (i.e., four people and one car) needs to go outside the Reserve (4 km of distance between residential sector and Reserve' gate) three times per day (e.g., school, work, grocery shopping, etc.).

Finally, the GHG emissions generated by the policemen and firefighters' patrols were accounted based on the annual distance driven declared by the related representatives.

iv. Refrigerant gas leaks

The annual GHG emissions resulting from the refrigerant gas leaked from the fridges (i.e., canteen) and air conditioners (e.g., offices, museums, workshops, etc.) were accounted based on the total number of devices, and the specific equipment' gas leaks rates (Cowan et al., 2010; EPA, 2014).

For the natural gas consumption (i.e., heating and cooking), a quota (38%) of the refrigerant gas leaks arising from the canteen were allocated to the tourist sector proportional to the annual meal consumed.

4.8.5 Scope 2 emissions

The annual GHG emissions generated by the electricity consumption from the Reserve activities (e.g., touristic attractions, offices, workshops, etc.) were obtained from the annual consumptions provided by the Reserve, and the Italian electricity mix EF obtained by the Superior Institute for Research and Environmental Protection (ISPRA, 2018).

The annual energy consumption of castle and office were estimated based on the inventory of the electronic devices of the office (e.g., lighting bulbs, air conditioners, PC, etc.), and following the approach proposed by Tjandra et al., (2016). Furthermore, the approach proposed by Tjandra et al., (2016) was involved for the estimations of annual electricity needed by the policemen' and firefighters' offices, from which the primary data were not available.

Finally, because of lack of primary data, the electricity consumed by the residential sector for heating, cooling and the domestic hot water, were obtained from average National statistics data (ISTAT, 2019).

4.8.6 Scope 3 emissions

Considering that within the 24 households (i.e., 95 people) living inside the Reserve are included the relatives of the workers/employees; that the meals consumed by the workers/employees were already estimated within the related sectors; and that the scope 3 emissions were too strictly connected to the private life of the people rather than to the Reserve activities; it was decided to exclude the scope 3 GHG contribution of the residential sector from the analysis (Table 4.1).

i. Durable and non-durable goods purchased

By considering their potential lifespans, the GHG emissions arising from the life cycle of the durable goods such: agricultural buildings and machineries (Wernet et al., 2016), paved roads (Biswas, 2013), electronic devices (Wernet et al., 2016) and air conditioners (De Kleine, 2009), were accounted.

Regarding the non-durable goods, were included the GHG arising from the production of: (i) organic fertilizers (Havukainen, 2018), (ii) concentrates (Adom et al., 2013), (iii) extra-farm feed and seeds (Wernet et al., 2016), (iv) kraft paper and Low Density Polyethylene (LDPE) used for the packaging (Wernet et al., 2016), (v) printer paper (Wernet et al., 2016), and (vi) toners (Kara, 2010).

Finally, the GHG emissions arising from the production (i.e., extraction and refining) of the fossil fuel purchased by the Reserve were accounted within this scope (Wernet et al., 2016).

ii. Ingredients used to prepare the meal consumed

The GHG emissions generated by the production of the meals consumed (i.e., employees, workers, tourists, researchers and agents) were accounted based on assumptions involving both the number of annual meals consumed by each category, and different meal types.

For example, for tourists' meals, it was assumed that half of them used the canteen service to eat proper meals (Pradhan et al., 2013), while half consumed home-made sandwiches (Espinoza-Orias and Azapagic, 2018).

Moreover, using data (i.e., food packaging) provided by Hanssen et al., (2017) and EFs provided by Wernet et al., 2016, it was possible to account for the GHG emissions arising from the production of Kraft paper and Low-Density Polyethylene (LDPE) used for the meals' packaging.

iii. Out-boundary transport

All the GHG emissions generated by the out-boundary transports related to non-durable goods (including their disposal) were estimated based on: the type of transports used, the weight carried, the distance driven, and by using the EFs provided by Wernet et al., (2016).

Furthermore, working with assumptions, it was possible to estimate the annual GHG emissions generated by the out-boundary transports related to the bus, minibus and cars involved in tourist activities. Specifically, because of the large involvement of organized excursions (e.g., school groups, elderly centres, etc.), it was assumed that all the visiting tourists reach the entrance of the Reserve by tour buses, which have transporting capacity of 30 people transported for an average distance of 500 km (both ways). With regards to the GHG emissions generated by the transport of disabled people to the summer centre, it was assumed a minibus (12 people capacity) (Shorter, 2011) driving an average distance of 70 km (both ways). Regarding the out-boundary transport emissions associated to organized events, it was assumed that each car entering the park carries 2.5 people and drives for 300 km (both ways).

The GHG emissions associated to the workers and employees commuting were accounted as well. It was assumed an average commuting distance of 30 km, and that 75% of the employees/workers use their own car, and the remaining use public transport (i.e., bus).

For the GHG emissions of transport for research activities, it was assumed that each researcher drives a car for 200 km (roundtrip).

Finally, since the distance separating the police and firefighter' headquarters from the Reserve was already accounted within the annual km provided by the related representatives, it was assumed that 85% of that distance was driven within the Reserve and the remaining 25% outside the boundary.

iv. Waste management

The GHG emissions arising from the end-of-life of durable goods such as air conditioner (De Kleine, 2009), agricultural buildings and tractors (Wernet et al., 2016), and paved roads (Biswas, 2013), were assessed considering the associated lifespans.

The end-of-life GHG contribution of toners (Kara, 2010), Kraft papers and LDPE (Turner et al., 2015) used for the packaging of meals and non-durable goods, as well as the amount of meals' leftovers (Hanssen et al., 2017) and the GHG emissions associated to its composting (Moult et al., 2018), were accounted within this section.

4.10. Impact assessment

A complete list of the EFs used in this CFP study has been reported in Table S4.1 of the supplementary material.

The annual emissions of CO_2, CH_4 and N_2O were converted in CO_{2e} using the IPCC 100-year global warming characterization factors (IPCC, 2013), while characterization factors (100-year) provided by Tian et al., (2015) and EPA, (2014) were used to convert the gas leaks of the hydrofluorocarbons (HFCs) in CO_{2e}.

The GHG sinks generated by the Reserve (reported separately from the active emissions) were quantified from the annual C-sinks related to both agricultural soils, and forest biomass growth. Specifically, the annual C-sinks were converted in CO_{2e} considering the atomic weight of C and the molecular weight of CO_2, therefore multiplying the amount of C by 3.67.

With regard to the agricultural soil, the adoption of a Tier 3 approach (i.e., DNDC model) to account for the related GHG emissions, allowed the estimation of the annual SOC dynamics (Grossi et al., 2020). Due to lack of data, the forest soil C stock changes were not accounted and assumed, according to the Tier 1 IPCC, (2006) approach, currently in equilibrium (Demertzi et al., 2016; Peñaloza et al., 2019).

Nevertheless, the annual C stored by the growth of the above ground woody biomass was included. Specifically, from the findings of Project ELITE/SIFTeC, which involved the use of Laser Imaging Detection and Ranging (LIDAR) and Geographical Information System (GIS) (Scrinzi et al., 2019), it was possible to obtain a detailed inventory of the whole forest area of the Reserve. Particularly, the live epigean biomass of the Reserve' forest (given by the weight of the significant wood volume and the weight of the twig and foliage) exceeds 800 thousand tons (in dry weight), and one million tons in fresh weight (Scrinzi et al., 2019). Therefore, by considering an average amount of 50% C content on wood dry biomass (Thomas and Martin, 2012), and annual overall forest growth rate of 1.7% (value based on expert opinion), it was possible to account for the annual C sequestered by the above ground forest biomass growth.

4.11. Uncertainty assessment

Often, the uncertainty of a specific input or output cannot be derived from the available information, since there is only one source of information that provides only a mean value. A simplified standard procedure was developed to quantify the uncertainty in these (quite numerous) cases. According to the GHG protocol and Frischknech et al., (2007), in all cases where measured single parameter uncertainties are unknown, a pedigree matrix (Weidema and Wesnaes, 1996) can be used to calculate uncertainties.

Specifically, the data sources are assessed according to five Data Quality Indicators (DQIs), which are: (i) precision, (ii) completeness, (iii) temporal representativeness, (iv) geographic representativeness, and (v) technological representativeness. Subsequently, to each DQI it is assigned a data quality rate (i.e., very good, good, fair and poor) which is then used to estimate quantitatively the overall level of uncertainty.

The approach used in this case study has included a pedigree matrix for quantifying single parameter uncertainty, while a Taylor series expansion (Hong et al., 2010) has been adopted to propagate individual parameter uncertainties and to determine the overall system uncertainty (Bravo et al., 2017). The Taylor series expansion method requires the assumption that the uncertainty distribution for each input parameter is log-normally distributed.

An open source tool (https://ghgprotocol.org/calculation-tools) developed by the WRI has been used for the quantitative uncertainty assessment of the annual GHG emission arising from the National park. Differently, the uncertainty range provided for the annual C sinks rates coming from the agricultural soil (Grossi et al., 2020) and the above-ground forest growth (Scrinzi et al., 2019), are those reported by the authors of the estimations.

4.12. Results

According to the results obtained from the CFP assessment, each hectare (i.e., the FU considered) of the total 5,980 ha composing the Reserve, emitted about 550 kg CO_{2e} (Figure 4.2) during the reporting year (2018). Therefore, by including the overall activities involved in the area, and without considering the annual agricultural soil and forest C-sinks, the whole Castelporziano Reserve generated about 3.3 Gg of CO_{2e} in 2018.

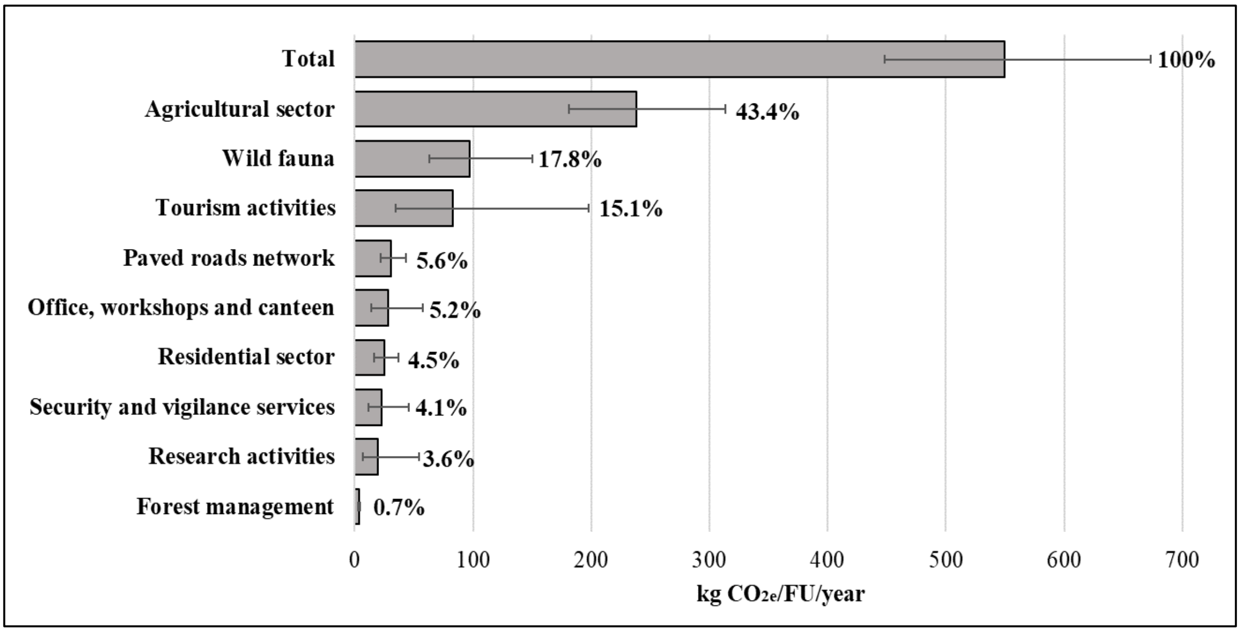


Figure 4.2 Carbon footprint of a representative hectare (FU) of the Reserve including the incidence (%) of all sectors considered during the reporting year (2018). Errors bars represent 95% CI (confidence interval)

The agricultural sector with 43.4% of share showed the largest incidence on the overall CFP (Figure 4.2). The GHG emissions generated from wild fauna (17.8%) and tourism activities (15.1%) showed similar GHG contributions.

The GHG incidence of the paved road networks (5.6%), and office, workshop and canteen sector (5.2%), where slightly higher than those arising from the residential (4.5%), vigilance services (4.1%), and research activities sectors (3.6%). While the GHG emissions generated by the activities involving forest management (i.e., pruning) showed the lowest incidence (0.7%).

Figure 4.3 shows the shares, both within the total, and within each sector, of the scope 1, scope 2 and scope 3 emissions. In this regard, the annual GHG emissions directly connected to the activities controlled by the Reserve, and occurring within it (i.e., scope 1), represented the highest incidence (63%). The GHG emissions associated to the overall electricity purchased and used (i.e., scope 2) represented 6% of the share, while the remaining 31% were totally attributable to the sources of GHG occurring outside the physical boundary of the Reserve (i.e., scope 3).

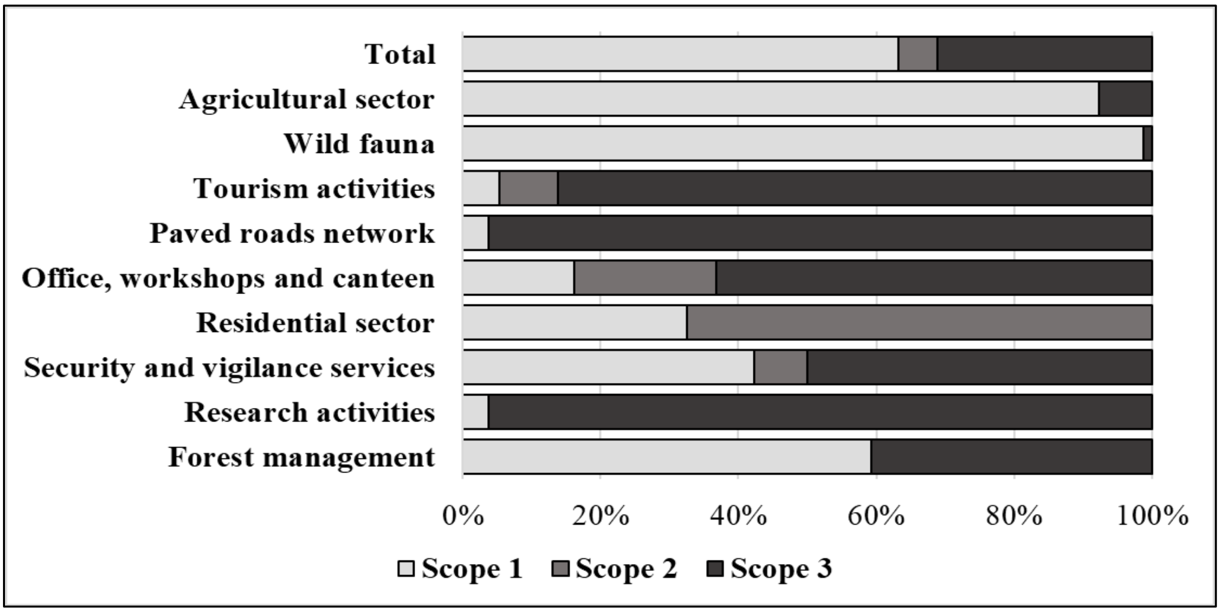


Figure 4.3 Breakdown of the scope 1, scope 2 and scope 3 emissions on the total Reserve' carbon footprint, and within each sector considered

The scope 1 emissions showed a large incidence especially on wild fauna (99%), agricultural sector (92%) and forest management (59%). The scope 2 emissions represented the larger share (67%) of the residential sector. While, research activities (96%), paved roads network (96%), tourism activities (86%), and office, workshops and canteen (63%), showed a high incidence of scope 3 emissions (Figure 4.3).

In the following sections are provided further information regarding the framework of the overall Reserve' GHG emissions and sinks presented in Table 4.2.

Table 4.2 Overall GHG emissions and sink of the Reserve, and incidence of the main emitting sources within each sector

Sector	*Scopes*	*Sub-sector*	*t CO_{2e}/year*	*% on sector*	*Total t CO_{2e}/year*
Agricultural sector	Scope 1	Enteric methane	636.84	44.6%	1427 (1084; 1877)
		Soil emissions	525.81	36.9%	
		Fuel combustion	152.75	10.7%	
	Scope 2	Extra-farm feed (P; T; E)	55.48	3.9%	
		Fuel (P; T)	21.85	1.5%	
		Auxiliary products (P; T; E)	19.02	1.3%	
		Others	14.82	1%	
Wild fauna	Scope 1	Manure emissions	387.8	66.5%	583 (379; 897)
		Enteric methane	187.2	32.1%	
		In-boundary transports	0.45	0.1%	
	Scope 2	Corn grains (P; T; E)	7.2	1.2%	
		Out-boundary transports	0.7	0.1%	
Tourism activities	Scope 1	Heating and cooking	17.0	3.4%	496 (207; 1,184)
		In-boundary transports	5.7	1.1%	
		Refrigerant gas leaks	4.3	0.9%	
	Scope 2	Electricity	42.1	8.5%	
	Scope 3	Out-boundary transports	411.3	82.9%	
		Meals (P; T; E)	15.0	3%	
		Air conditioners (P; E)	0.9	0.2%	
Paved roads network	Scope 1	In-situ operations	6.8	3.7%	184 (131; 257)
	Scope 3	Transports	30.7	16.7%	
		Raw materials extraction	69.3	37.7%	
		Mixture production	76.9	41.9%	
Office workshops and canteen	Scope 1	In-boundary transports	10.9	6.4%	169 (83; 346)
		Heating and cooking	13.4	7.9%	
		Refrigerant gas leaks	3.0	1.8%	
	Scope 2	Electricity	35.0	20.6%	
	Scope 3	Out-boundary transports	88.1	52%	
		Meals (P; T; E)	16.5	9.7%	
		Others	2.6	1.5%	
Residential sector	Scope 1	In-boundary transports	48.8	32.6%	150 (100; 223)
	Scope 2	Electricity	100.8	67.4%	
Security and vigilance	Scope 1	In-boundary transports	54.2	40%	136 (68; 271)
		Refrigerant gas leaks	2.6	1.9%	
		Heating system	0.6	0.4%	
	Scope 2	Electricity	10.4	7.7%	
	Scope 3	Meals (P; T; E)	49.5	36.5%	
		Out-boundary transports	15.9	11.8%	
		Others	2.4	1.8%	
Research activities	Scope 1	In-boundary transports	4.5	3.8%	118 (43; 325)
	Scope 3	Out-boundary transports	111.4	94.2%	
		Meals (P; E)	2.4	2%	
Forest management	Scope 1	Fuel combustion	13.2	59.3%	22 (18; 28)
	Scope 2	Fuel (P; T)	2.2	9.9%	
		Tractors (P; M; E)	6.9	30.8%	
Total annual GHG emissions generate annually by the Reserve					3,285 (2,679; 4,027)
C -sinks				Agricultural soil	-216 ± 30*
				Forest biomass growth	-25,103 ± 6,275**

P = Production; T= Transport; M = Maintenance; E = End-of-life. The values in the brackets are the lower and upper limits respectively of the 95% confidence interval (CI).
*Uncertainty range reported by the authors of the esteem (Grossi et al., 2020)
**Uncertainty range reported by the authors of the esteem (Scrinzi et al., 2019)

4.10.1 Insight on the main GHG emission sources

Without accounting for the agricultural soil C-sinks (i.e., 15% of the sector), the annual GHG emissions generated by all the activities involved with the Reserve' agricultural sector were about 1.5 Gg CO_{2e} (Table 4.2). The enteric methane (44.6%) and the N_2O soil emissions (36.9%) arising from the beef cattle breeding showed the largest incidence, followed by the fossil fuel combustion contributing for 10.7%. With regards to the scope 2 emissions, the production, transports and the end-of-life (i.e., packaging) of the extra-farm feed reached 3.9% of incidence. The GHG arising from the production, maintenance and end-of-life of agricultural buildings and machineries, as well as the meals consumed by the workers, showed an overall contribution lower than 1%.

The annual GHG emissions arising from the wild fauna sector amounted to about 580t CO_{2e} year^{-1}. Almost the entire (99%) GHG emissions generated from this sector came from the CH_4 and N_2O generated by the biological process involving manure and enteric methane of the wild fauna (Table 4.2). With regards to the scope 3 emissions, the production, transports and the end-of-life (i.e., packaging) of the corn grains used to feed the monitoring points involved in the census activities accounted for about 1%. As mentioned earlier, the SOC stock of the forest soil was assumed to be in equilibrium. Therefore, no soil C-sinks were accounted for this sector.

Of the total annual GHG emissions (i.e., about 500t CO_{2e}) coming from the touristic activities, more than 73% were generated from the out-boundary transports of the tourists (i.e., scope 3 emissions). Contribution that raises to over 82%, when including the out-boundary transports related to the annual events and the disabled people enjoying the Reserve' summer centre (Table 4.2). The GHG contribution of the overall electricity consumed (i.e., scope 2) by the main touristic attractions was the second hotspot (8.5%), with castle, archaeological, and naturalist museum sharing almost the same incidence of 2.4% (result not shown).

The annual GHG emissions generated from the life cycle of the paved roads (i.e., pre-construction, construction, maintenance and end-of-life) accounted for about 180t CO_{2e} year^{-1} (Table 4.2). The scope 3 emissions generated by the mixtures production (41.9%) and raw materials extraction (37.7%) were the main GHG hotspots. The EF adopted was provided by a study assessing the GHG emissions associated with the life cycle (20 years) of 1 km of paved road (9m width) built in Portugal (Araújo et al., 2014). Specifically, the EF was adjusted to the width of the Reserve road (5.7m width). Regarding the pavement structure, the Portuguese road was characterized by the following layers which were assumed to be similar to the Reserve' ones: 4cm of asphalt surface layer, 6cm of binder layer, 10cm of base layer, 15cm of granular base, and 15cm of granular sub-base (Araújo et al., 2014).

The overall activities related to office, workshops and canteen, accounted for about 170t CO_{2e} year^{-1} (Table 4.2). More than 50% of these emissions came from the out-boundary transports associated to the commuting of the employees, and to the business trips (i.e., scope 3 emissions). Generating about 11t CO_{2e} year^{-1}, the in-boundary transports were the main hot spot of the scope 1 emissions, of which the largest share was attributable to the employees commuting (61%), followed by workshops workers (38%) and to a less extent (1%) from canteen' workers and meals ingredients (results not shown). With regards to the scope 2 emissions, the GHG arising from the electricity consumed by offices (9%) were higher than those generated from the workshops (6.2%) and canteen (5.2%). Figure 4.4 shows the breakdown of the emissions sources responsible for the office electricity needs. Particularly, reaching 40% of incidence, the indoor lighting system was the main GHG hotspot, followed by air conditioners (35%), out-door lighting system (21%), and, to a less extent, from PC uses (5%).

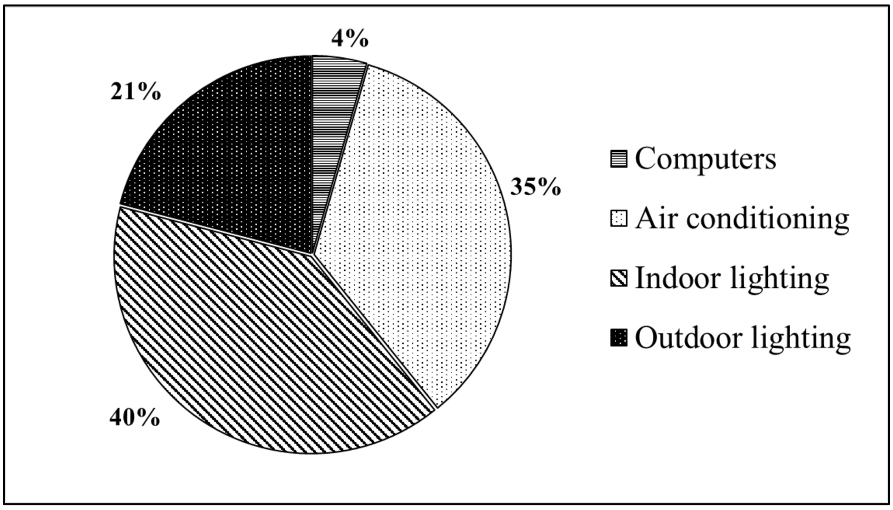


Figure 4.4 Breakdown (%) of the emissions sources responsible of the office electricity GHG contribution

The GHG emissions arising annually from the residential sector were about 150t CO_{2e}. The scope 1 emissions generated from the in-boundary transports accounted for about 33% of the total, while the remaining 67% was attributable to the domestic' electricity consumptions.

The whole annual activities associated to the security and vigilance services accounted for about 140t CO_{2e}.The scope 1 emissions generated by the in-boundary transports accounted for 40% of the sector GHG emissions (i.e., 37% police patrols round and 3% firefighter transport). The second hotspot was the GHG emissions generated by the life cycle (i.e., production and end-of-life) of the homemade meals consumed by the policemen (36.5%).

Of the about 120t CO_{2e} emitted annually by the activities related to the research activities taking place within the Reserve, the higher incidence (94.2%) was represented by the out-boundary transports of the researchers (Table 4.2).

Finally, without accounting for the above ground forest biomass C-sinks, the forest sector generated about 22t CO_{2e} year^{-1} (Table 4.2). The larger contribution was from the combustion of the fossil fuel used for the pruning activities (i.e., scope 1 emissions), while the second hot spot was the GHG emissions generated by the life cycle (i.e., production, maintenance and end-of-life) of the tractors (lifespan 30-years). The incidence of the forest sector on the overall Reserve' CFP becomes extremely significant when considering the related GHG sinks dynamics. Figure 4.5 presents the total CO_{2e} sequestered annually by each forest type within the Reserve based on data and expert opinions provided by the researchers of the project ELITE/SIFTeC (Scrinzi et al., 2019).

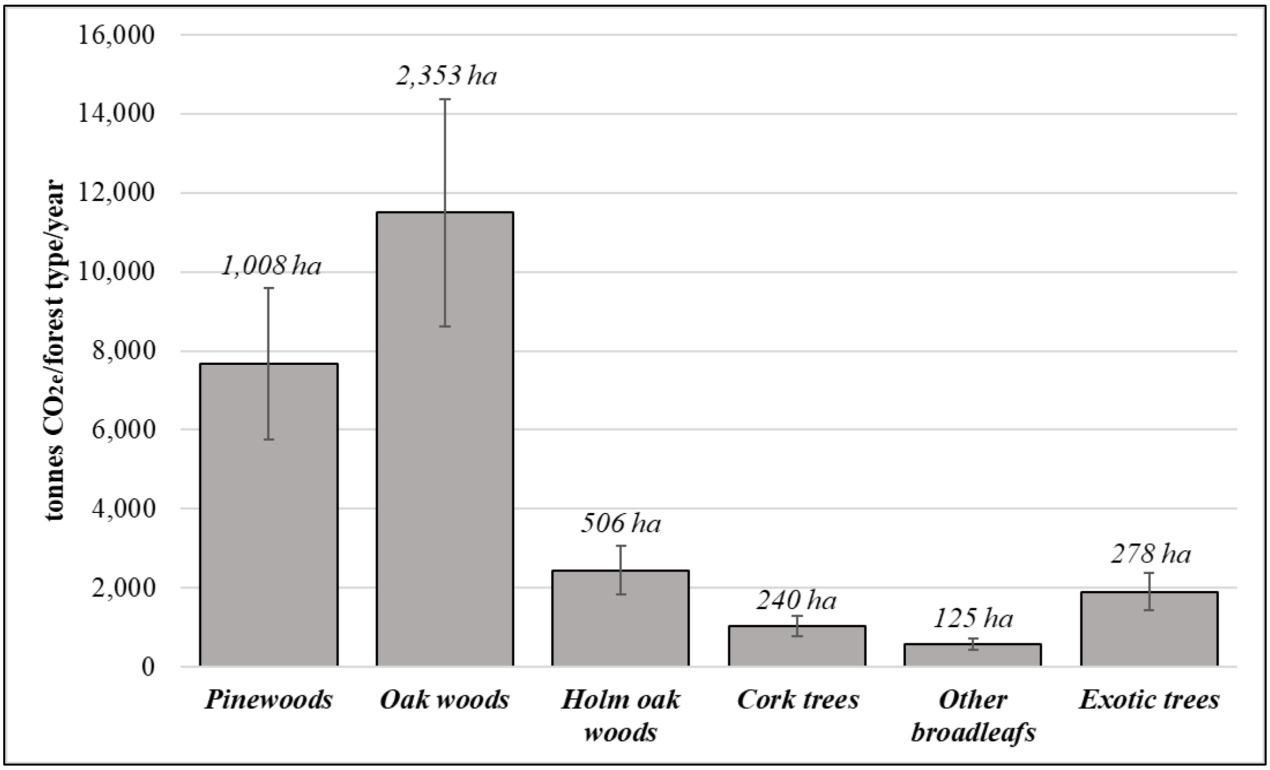


Figure 4.5 Annual GHG sinks (tCO_{2e} year^{-1}) generated by the different forest types within the Reserve. Values on top of the bar represent the extension in hectare (ha) of the related forest area. Error bars represent the standard error of the mean

Specifically, the Figure 4.5 shows how the annual tonnes of CO_{2e} sequestered by the growth of the holm oak woods and cork trees, are enough to compensate more than 90% of the GHG emitted in one year by all sectors of the Reserve. Further detail regarding this aspect (i.e., number of trees ha^{-1}, t of DM, and annual growth rates) can be found in Table S.4.9 of the supplementary materials.

4.13. Discussion

If on one hand the GHG emissions generated in 2018 from the whole Castelporziano Reserve sectors were about 3.3 Gg of CO_{2e} (i.e., about 550 kg CO_{2e} FU^{-1}), on the other hand, by including in the CFP assessment the agricultural soil (i.e., about 220t CO_{2e} $year^{-1}$), and forest C-sinks (i.e., -25 Gg CO_{2e} $year^{-1}$) (Table 4.2), the Reserve could be considered as an important CO_2 sink that, net of the GHG emissions, in 2018 has stored about 3.7t CO_{2e} FU^{-1} corresponding to a total of about 22 Gg CO_{2e} removed from the atmosphere.

Forest plays a strategic role in carbon balance (Nunes et al., 2019), and protected natural areas can be effective in both preventing conversion of land uses and implementing mitigation strategies. For instance, providing sufficient time for forest to recover, reducing the intensity of each cut (Zhou et al., 2013), replacing dying or low productivity stands, protecting young sprouts from damage after harvest, and planting tree mixes that are more resilient (Bellassen and Luyssaert, 2014), are just some examples of managements that could help enhancing forest C storages.

Although characterized by different size and incidence, the sectors (e.g., residential, agriculture, public transportations, offices, etc.) included in the CFP of the Reserve can be treated similarly to other systems different from National parks. Due to their analogies, the methodological approaches and the guideline proposed in this study could be suitable also for an estimation of the GHG sources/sinks which are normally associated to cities and/or districts.

When looking to the possible mitigation strategies that could be implemented, the scope 1 and scope 2 emissions were the ones in which the Reserve should focus more, thanks to the larger control exercised on them. As a scope 1 emissions for example, the adoption of less soil invasive tillage practices could increase the current annual soil C-sink rates, which in turn could decrease the overall incidence of this sector on the total. In fact, a switch from the current Reserve' soil tillage practices (i.e., 30 cm ploughing) to no-tillage ones, showed a significant potential reduction (26%) of the GHG emissions arising from the beef cattle rearing (Grossi et al., 2020), which in turn has the potential to reduce the overall Reserve CFP of about 5%.

With regards to scope 2 emissions, a greater use of energy-saving light bulbs (e.g., in the office, museums, etc.), switching off the air-conditioning in the office rooms during lunch breaks, or the switch to a totally renewable energy supply, are just some examples that could be effective in reducing the overall contribution of this scope. However, in order to reliably quantify the effectiveness of these sector specific GHG mitigation strategies, attention shall be given to the inventory data collection.

In this context, an effective data lifecycle management based on the digitalization of the key input and output data, could help natural parks in both keeping track of the information that might make significant difference in term of environmental performance, and in evaluating the effect of minor sector specific mitigation strategies that otherwise could remain undetected.

In presence of detailed and granular data (e.g., out-boundary distance driven, type of meals, number and type of lighting bulbs, etc.) it becomes then possible to quantify the benefits of equally detailed and granular mitigation strategies (e.g., a more efficient commuting, pattern diet shifts, greater use of energy-saving light bulbs, etc.). This is especially important when assessing those activities resulting in a significant contribution within each sector.

The out-boundary transports (i.e., scope 3) represented about 19% of the overall annual Reserve' GHG emissions (result not shown). Particularly, it contributed for 94.2% of the research sector, 82.9% of the tourism activities, and 52% of the office, workshops and canteen sector. As a general rule, within the sectors where transports are the biggest source of GHG emission, exploring flexible way of working, and engaging people (e.g., tourists, workers and employees) in reducing travel and commuting, could represent a good mitigation opportunity. Actually, this source of emission is a complex task to reduce and can only be accomplished with the agreement and participation of the stakeholders. For example, the organizations can encourage the use of public transport by offering free shuttle bus from nearby stations to their offices, or a discount on the entrance ticket to the tourist that reach the park by sustainable transports (e.g., public transport, electric vehicle, bicycle, etc.).

Finally, to successfully implement a green marketing strategy that engages the final consumers (tourists in this case) and make easier to understand the park' progresses towards the environmental targets, the organizations need to effectively communicate and report their current achievements and future GHG reduction commitments. According to Villalba et al., (2013), a different FU (i.e., GHG emissions/visitor-day) could potentially reflect better the annual CFP, and the efficiency of the National parks in servicing the tourists. However, it is also true that, because of its large year-to-year variability, the application of this FU could fail in representing the claims on the effectiveness of specific mitigation strategies implemented during the year. Therefore, although other FUs can be developed and integrated to effectively communicate (e.g., convert the annual GHG emissions in km driven by a car) the result of the CFP assessment, the authors agreed that the FU proposed in this guideline was the most effective in both communicating the environmental goals achieved, and in comparing CFP of different National parks.

4.14. Conclusion

By providing a granular picture of the main GHG emission sources and hotspots of the Castelporziano Reserve, the methodological approach and guideline proposed in this paper showed to be both feasible and suitable in achieving the proposed and planned objectives. Indeed, to the best of our knowledge, the one presented in this study could be considered the first cradle-to-grave CFP of a National park. Starting from the CFP of 2018, and by providing annual CFP reports, the Reserve could now start tracking its GHG emissions trend, and in doing so, it could effectively inform (i.e., providing the rate of GHG reduction) all the stakeholders of the results obtained by introducing new specific mitigation policies. Last but not least, the guideline proposed in this paper could be the starting point for developing a widely accepted standard procedure (i.e., OEFSR) to be followed in order to obtain type III environmental declarations (i.e., eco-labelling) for National parks.

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Supplementary materials

The following section contains: Table S4.1: List of the emission factors involved in the carbon footprint of the Reserve; Table S4.2: Life cycle inventory data of the Reserve' agricultural sector; Table S.4.3: Life cycle inventory data of the Reserve' wild fauna sector; Table S.4.4: Life cycle inventory data of the Reserve' touristic sector; Table S.4.5: Life cycle inventory data of the Reserve' office, workshops and canteen sector; Table S.4.6: Life cycle inventory data of the Reserve' residential sector; Table S.4.7: Life cycle inventory data of the Reserve' security and vigilances sector; Table S.4.8: Life cycle inventory data of the Reserve' research activities sector; Table S.4.9: Life cycle inventory data of the Reserve' forest sector.

Table S4.1 List of the emission factors involved in the Reserve' carbon footprint

Input	*Unit*	*(kgCO$_{2e}$/unit)*	*Data source*
Diesel production	1 kg	0.51	(Wernet et al., 2016)
Diesel combustion	1 kg	3.17	(Wernet et al., 2016)
Ryegrass-clover seeds	1 kg	1.62	(Wernet et al., 2016)
Compost (4% N content)	1 kg	0.03	(Havukainen, 2018)
Concentrate feed	1 kg	0.6	(Adom et al., 2013)
Kraft paper unbleached	1 kg	0.84	(Wernet et al., 2016)
Paper to recycling plant	1 kg	1.576	(Turner et al., 2015)
Tractors (lifespan 30 yrs)	1 kg	5.73	(Wernet et al., 2016)
Barn & shed (lifespan 50 yrs)	1 mq	168.9	(Wernet et al., 2016)
Corn grains	1 kg	0.533	(Wernet et al., 2016)
Natural gas combustion	1 m^3	1.8	(Bradbury et al., 2015)
Refrigerant gas R32	1 kg	675	(Tian et al., 2015)
Refrigerant gas R404a	1 kg	3,922	(EPA, 2014)
ITA electricity mix	1 kWh	0.284	http://www.isprambiente.gov.it/
Sandwiches	1 unit	0.856	(Espinoza-Orias and Azapagic, 2018)
Canteen meals production	1 meal	1.89	(Pradhan et al., 2013)
Agents and workers' meals	1 meal	1.62	(Pradhan et al., 2013)
Event meals production	1 meal	2.27	(Pradhan et al., 2013)
LDPE production	1 kg	2.1	(Wernet et al., 2016)
LDPE to recycling plant	1 kg	0.029	(Turner et al., 2015)
Composting	1 kg	0.044	(Moult et al., 2018)
Air conditioner	1 unit	282.5	(De Kleine, 2009)
PC monitor 17"	1 unit	303	(Wernet et al., 2016)
PC desktop	1 unit	210	(Wernet et al., 2016)
Printer	1 unit	63.3	(Wernet et al., 2016)
Printer paper	1 kg	0.773	(Wernet et al., 2016)
Toner	1 unit	1.21	(Kara, 2010)
Transports - car	1 km	0.232	(Wernet et al., 2016)
Transport - regular bus	1 pkm	0.0911	(Wernet et al., 2016
Transport - minibus	1 km	0.89	(Shorter, 2011)
Transports (lorry <3.5t)	1 tkm	1.9	(Wernet et al., 2016)
Transports (lorry 3.5-7.5t)	1 tkm	0.52	(Wernet et al., 2016)
Transports (lorry 7.5-16t)	1 tkm	0.22	(Wernet et al., 2016)
Paved roads (lifespan 20 yrs)	1 km	116,660	(Araújo et al., 2014)

LDPE = Low density polyethylene; pkm = Passenger-kilometre; tkm = Tonne-kilometre

Table S4.2 Life cycle inventory data of the Reserve' agricultural sector

Data	*Unit*	*Amount*
[1]Cattle reared	LUs	286
Horses reared	LUs	39
[2]Horses enteric methane	kg CH_4/LU/year	18
[2]Horses manure methane	kg CH_4/LU/year	2.34
[2]Horses Nitrogen excreta	kg N/LU/year	52.2
Ryegrass-clover seeds purchased	kg/year	10,913
[3]Ryegrass-clover seeds packaging - Kraft paper	kg/year	43
Distance from seed storehouse	km	212
Beef - concentrate feed	kg/year	30,100
[3]Beef concentrate feed packaging - Kraft paper	kg/year	181
Horses - concentrate feed	kg/year	40,792
[3]Horse concentrate feed packaging - Kraft paper	kg/year	245
Distance Reserve-to-feed' storehouse	km	321
Gasoline for agricultural machineries	kg/year	23,907
Gasoline for motor pumps	kg/year	17,600
[3]Distance Reserve-to-recycling plant	km	50
[3]Distance Reserve-to-fuel pumps	km	75
[3]Transport involved in fuel	Type	lorry (7.5-16t)
[3]Transport involved for all others raw materials	Type	lorry (3.5-7.5t)
Tractors dedicated to agricultural activities	n	5
[3]Average weight of tractor	kg	12,000
[3]Lifespan of tractor	years	30
Agricultural buildings - sheds	mq	150
Agricultural buildings - barns	mq	300

[1]Further data available in Grossi et al., (2020); [2]IPCC, (2006); [3]Estimate; LUs = Livestock units

Table S4.3 Life cycle inventory data of the Reserve' wild fauna sector

Data	*Unit*	*Amount*
Fallow deer	n	1,020
Deer	n	40
Wild boar	n	3,354
[1]Goat (EF)	kg CH_4/head/year	5
[1]Deer (EF)	kg CH_4/head/year	20
[1]Swine (EF)	kg CH_4/head/year	1.5
[2]Fallow deer (M_w)	kg of LW/head	40
[2]Deer (M_w)	kg of LW/head	60
[2]Wild boar (M_w)	kg of LW/head	40
[1]Goat (M_d)	kg of LW/head	40
[1]Deer (M_d)	kg of LW/head	120
[1]Swine (M_d)	kg of LW/head	300
Fallow deer (E_{fa})	kg CH_4/head/year	5
Deer (E_{fa})	kg CH_4/head/year	11.9
Wild boar (E_{fa})	kg CH_4/head/year	0.3
[3]Fallow deer	kg N/head/year	10
[1]Deer	kg N/head/year	13.7
[1]Wild boar	kg N/head/year	8
[1]Fallow deer and deer - EF_{3PRP}	kg N_2O-N/kg N	0.01
[1]Boar - EF_{3PRP}	kg N_2O-N/kg N	0.02
[1]$Frac_{LEACH}$	kg N leached or runoff/kg N	0.3
[1]$Frac_{GASM}$	kg N volatized/kg N	0.2
[1]EF_4	kg N_2O-N/(kg N volatilised)	0.01
[1]EF_5	kg N_2O-N/(kg N leached)	0.0075
[1]Goat (fallow deer)	kg CH_4/head/year	0.17
[1]Deer	kg CH_4/head/year	0.22
[1]Swine (wild boar)	kg CH_4/head/year	0.5
Monitoring/check points	n	87
[2]Average distance between check points	km	0.7
Length of the foraging activities	days/year	32
Corn grains provided	kg/day	400
[2]Capacity of the corn grains paper bag	kg grains/pack	50
[1]Weight of the paper bag	kg paper/pack	0.15
[2]Distance between park and storehouse	km	50
[2]Transport involved in purchasing corn	type	lorry (3.5-7.5t)
[2]Distance park to recycling plant	km	50
[2]Transport involving waste management	type	lorry (3.5-7.5t)
[2]Staff members for foraging activities	n	1
Staff members for census activities	n	12
[2]Distance staff' houses-to-Reserve (both way)	km	40
[2]Transport involved	Type	car
[2]Staff member per car	members/car	1
[2]Tot. out-boundary distance driven	km	3,040

[1]IPCC, (2006); [2]Estimate; [3]Velthof, (2014); EF = Emission factor; M_w = Body mass of target animal; M_d = Standardized IPCC body mass for domestic animal; E_{fa} = Emission factor adjusted for wild animal; EF_{PRP} = Emission factor for urine and dung deposited on pasture; $Frac_{LEACH}$ = Leached fraction; $Frac_{GASM}$ = Volatilized fraction; LW = Live Weight

Table S4.4 Life cycle inventory data of the Reserve' touristic sector

Data	***Unit***	***Amount***
Tourists visiting the Reserve	people/year	7,983
Disabled enjoying the summer center	people/year	1,734
Public events organized in the Reserve	events/year	26
Participants per events	people/event	50
[1]In-boundary distance driven by the shuttlebus	km/day	50
[1]Cars entering the Reserve per event	cars/event	20
[1]In-boundary distance driven by cars (both way)	km/car	10
[2]Weight of the average meal	kg/meal	0.54
[1]Type of transport involved in meals' ingredients	type	lorry <3.5t
Distance between park gate and canteen (both way)	km	8
[1]Natural gas canteen - cooking	mc/year	1,081
[1]Natural gas canteen - heating	mc/year	1,167
Natural gas (castle + offices)	mc/year	10,980
[3]Rome HDD for 21°C	dimensionless	2,161
[4]HD of the office area	kWh/mq/year	36.4
[1]Natural gas needed to heat the office	m^3gas/mq/year	3.66
Building area occupied by the offices	mq	1,040
Area of the castle	mq	700
[1]Tot natural gas attributed to the office	mc/year	3,804
[1]Tot natural gas attributed to the castle	mc/year	7,176
Area occupied by the archeologic museum	mq	600
Area occupied by the castle (no offices included)	mq	700
Area occupied by the carriage's hall	mq	200
Area occupied by the naturalistic museum	mq	450
[1]Tot. number of air conditioning involved	n	33
[5]C - [6]x - t	kg - % - year	1.6 - 10 - 1
$RFRG_{lks}$	kg R32/year	5.2
Electricity used by the archeologic museum	kWh/year	40,093
Electricity used by the naturalistic museum	kWh/year	38,987
Electricity used by the carriage's hall	kWh/year	1,352
[1]Electricity used by the castle (no office included)	kWh/year	46,738
[1]Electricity used by the canteen	kWh/year	19,574
[1]Tot. meals consumed by tourists visiting the park	meals/year	9,283
[7]Meals paper waste	kg/meal	0.005
[7]Meals waste LDPE	kg/meal	0.005
[7]Meals leftovers	kg/meal	0.077
[8]Sandwiches waste: Paper; LDPE	kg/sandwich	0.041; 0.017
[8]Sandwiches leftover	kg/sandwich	0.043
[1]Distance between park and recycling plant	km	50
[1]Transport involved in waste management	type	lorry (3.5-7.5t)
[1]Tour buses (30p) needed for transports	buses/year	266
[1]Tot. Distance driven by the minibuses	km/year	4,550
[1]Distance driven by the meals' raw materials	km/meal	70
[1]Transport involved for meal' raw material purchased	type	lorry <3.5t

[1]Estimate; [2]To et al., (2019) [3]De Rosa et al (2016); [4]Moreci et al., (2016); [5]Product datasheet; [6]Cowan et al., (2010); [7]Hanssen et al., (2017); [8]Espinoza-Orias and Azapagic, (2018); HDD = Heating degree days; HD = Heating demand; C = refrigerant capacity of the equipment; x =leaks rate in percent of capacity; t = years used for the reporting period; $RFRG_{lks}$ = Refrigerant leaks; LDPE = Low density polyethylene

Table S4.5 Life cycle inventory data of the Reserve' office, workshops and canteen sector

Data	***Unit***	***Amount***
Employees of: Offices; Carpentry; Garage; Canteen	n	19; 5; 7; 3
Working days	days/year	250
[1]Rate of employees using personal car	(0-1)	0.75
[1]Rate of employees using public transportation	(0-1)	0.25
[1]In-boundary commuting (both way)	km/employ/working day	8
[1]Tot. meals consumed by employees	meals/year	8,500
[2]Weight of the average meal	kg/meal	0.54
[1]Transport involved in meals' ingredients	type	lorry <3.5t
Distance park gate to canteen (both way)	km	8
Natural gas consumed by the carpentry	mc/year	3.7
Natural gas consumed by the garage	mc/year	2.7
[1]Natural gas consumed by the canteen - heating	mc/year	1,876
[1]Natural gas consumed by the canteen - cooking	mc/year	1,737
Air conditioners within: office; canteen	n	17; 1
[3]C air conditioners	kg	1.6
[4]x air conditioner	%	10
t air conditioner	year	1
Office - air conditioners $RFRG_{lks}$	kg R32/year	2.72
Canteen - air conditioners $RFRG_{lks}$	kg R32/year	0.16
Fridge within the canteen	n	1
[3]C fridge cell	kg	10
[5]x fridge cell	%	5
t fridge cell	year	1
Canteen - fridge cell $RFRG_{lks}$	kg R404a/year	0.5
[1]Electricity used by the offices	kWh/year	54,275
Electricity used by the carpentry	kWh/year	14,024
Electricity used by the garage	kWh/year	23,456
[1]Electricity used by the canteen	kWh/year	31,443
Office: PC desktops; Printers	n	18; 19
Office - Air conditioners	n	17
Reams consumed	reams/year	245
Weight of a ream	kg/ream	4.68
[3]Page printed per toner	pages/toner	2,500
[1]Toners needed	n/year	49
[1]Lifespan PC desktop, Monitor and Printers	year	10
Canteen PC desktops	n	1
Meals paper waste	kg/year	42.5
Meals waste LDPE	kg/year	42.5
Meals leftover	kg/year	365.5
[1]Distance between park and waste plant	km	50
[1]Transport involved in waste management	type	lorry (3.5-7.5t)
Car owned by the Reserve	n	7
Average km driven by each car - business trips	km/car/year	7,000

[1]Estimate; [2]To et al., (2019); [3]Product data sheet; [4]Cowan et al., (2010); [5]EPA, (2014); C = refrigerant capacity of the equipment; x = leaks rate in percent of capacity; t = years used for the reporting period; RFRGlks = Refrigerant leaks; LDPE = Low density polyethylene

Table S4.6 Life cycle inventory data of the Reserve' residential sector

Data	*Unit*	*Amount*
Distance from houses-to-Reserve' gates (both way)	km	8
[1]Transport involved	type	car
[1]Daily trips	trips/day/car	3
[1]Resident families	n	24
[1]Tot. in-boundary distance driven	km/year	210,240
[1]Average are of a house	mq/house	117
[2]Energy required for heating	kWh/mq	67.1
[2]Energy required for cooling	kWh/mq	45.8
[2]Energy required for domestic hot water	kWh/mq	14.8
[1]Tot. number of houses	n	24
Tot. energy required - heating	kWh/year	186,454
Tot. energy required - cooling	kWh/year	127,267
Tot. energy required - domestic hot water	kWh/year	41,126
Tot. energy required by the sector	kWh/year	354,846

[1]Estimate; [2]ISTAT, (2019)

Table S4.7 Life cycle inventory data of the Reserve' security and vigilances sector

Data	***Unit***	***Amount***
Police patrols involved	n/year	14
Mean distance driven by each police patrol	km/patrol/day	50
Firefighter - (truck <3.5t)	n	3
Firefighter - cars	n	2
Distance driven by firefighter trucks	km/truck/year	1,333
Distance driven by firefighter cars	km/car/day	6,250
Air conditioners within the police station	n	23
Air conditioners within the firefighter station	n	1
[1]C air conditioners	kg	1.6
[2]x air conditioner	%	10
t air conditioner	year	1
Police station - air conditioners $RFRG_{lks}$	kg R32/year	3.68
Firefighter station - air conditioners $RFRG_{lks}$	kg R32/year	0.16
[3]HD of the office area	kWh/mq/year	68.9
Tot. m^2 occupied by police station	mq	86
Police station - air conditioners	n	23
Police station - PC desktops	n	21
Police station - printers	n	4
[4]Toner needed	n/year	26
Reams of paper used by police station	reams/year	130
Working days - police station	days/year	365
Working days - firefighters	days/year	120
Tot. mq occupied by firefighter office	mq	24
Firefighter - air conditioners	n	1
Firefighter - PC desktops	n	1
[2]Lifespan PC desktop, Monitor and Printers	year	10
Tot. number of policemen	policeman/working day	85
Tot. number of firefighters	firefighters/working day	5
[4]Tot. meals - policeman	meals/year	31,025
[4]Tot meals - firefighters	meals/year	600
Meals paper waste	kg/year	158
Meals waste LDPE	kg/year	158
Meals leftover	kg/year	2,435
[4]Distance from park-to-recycling plant	km	50
[4]Transport involved in waste management	type	Lorry (3.5-7.5t)

[1]Product datasheet; [2]Cowan et al., (2010); [3]Moreci et al., (2016); [4]Estimate; C = refrigerant capacity of the equipment; x =leaks rate in percent of capacity; t = years used for the reporting period; RFRGlks = Refrigerant leaks; LDPE = Low density polyethylene

Table S4.8 Life cycle inventory data of the Reserve' research activities sector

Data	***Unit***	***Amount***
[1]Distance research area-to-Reserve' gates (both way)	km	8
[1]Transport involved	type	car
Researchers' entrance	n/year	2,400
Tot. in-boundary distance driven	km/year	19,200
[1]Sandwiches consumed by researchers	sandwiches/year	2,400
Sandwiches paper waste	kg/year	40.8
Sandwiches waste LDPE	kg/year	98.4
Sandwiches leftover	kg/year	103.2
[1]Distance from park-to-recycling plant	km	50
[1]Transport involved in waste management	type	Lorry (3.5-7.5t)

[1]Estimate

Table S4.9 Life cycle inventory data of the Reserve' forest sector

Data	***Unit***	***Amount***
Fuel consumption for pruning activities - chain saw	kg/year	680
Fuel consumption tractors	kg/year	3,493
Tractors dedicated to pruning activities	n	3
[1]Average weight of tractor	kg	12,000
[1]Lifespan of tractor	years	30

Forest type	***Ha***	***Trees/ha***	***[2]t DM/total area***	***[3]Annual growth rate***	***t C fixed/year***
Pinewoods	1,008	597	220,161	2.0%	2,092
Oak woods	2,353	1,183	430,944	1.5%	3,135
Holm oak woods	506	1,406	88,658	1.5%	665
Cork trees	240	1,086	37,101	1.5%	278
Other broadleaf	125	1,124	15,382	2.0%	154
Exotic tree	278	1,184	42,599	2.5%	517
Total	4,511	-	834,845	1.7%	6,840

[1]Value based on esteem; [2]ELITE/SIFTeC project Scrinzi et al., (2019); [3]Value based on expert opinion; DM = Dry matter

Chapter 5

Summary and Conclusion

The CFP (from cradle-to-grave) of the organic beef produced by the local supply chain saw the breeding and fattening phase as the main source of emissions (86%), followed by home consumption (9%), retail (4%), and slaughtering activities (1%). Despite the short average distance (10 km) involved, transporting meat from shop-to-home represented 20% of the GHG arising from the consumption stage, and 80% of those arising from the transports involved along the whole life cycle. This aspect seems to contradict the idea that, because avoiding intermediate transports, buying food directly from the producer is more environmentally sustainable. Indeed, by considering the findings of this study, the choice of local products or "zero-miles products" is not enough to guarantee an environmentally sustainable food consumption, and other processes/activities involved in the supply chain should be carefully considered.

A better understanding of SOC dynamics is needed when assessing the CFP of livestock products and the effectiveness of possible agriculture mitigation strategies. In this regard, by considering the interactions between (i) climate, (ii) soil, and (iii) tillage practices, process-based models have been shown to be useful tools in simulating the long-term effects that these interactions have on crop yields, SOC dynamics, and GHG emissions (Doltra et al., 2019).

Among the currently available process-based models, e.g., Daycent (Parton et al., 1998), Roth-C (Coleman et al., 1997) and Ceres (Gabrielle et al., 2006), the DNDC (Li et al., 1992) has been one of the most validated worldwide (Guo et al., 2012). Several works showed that the DNDC is capable of simulate the basic patterns and magnitudes of GHG emissions, crop yield, or C sequestration under various agro-ecosystems (Zhang and Niu, 2016; Singh and Benbi, 2020; Chen et al., 2020).

In this thesis, the different farming management scenario modelled with the DNDC model showed that the adoption of conservation tillage, such as minimum and no-tillage practices, could enhance both the amount of C sequestered in the soil and increase the yield of forage crops. Specifically, the modelled switch from Ct to Nt has resulted in beef CFP reduction of 35%.

Although the use of organic fertilizers (i.e., pelleted digestate manure) showed to be effective in increasing the soil C stocks and thus in reducing the overall GHG contribution of the system, increasing soil C stocks is not necessarily simple or even possible at all locations. Indeed, different fields can present different C sinks rates in relation to soil properties, climate and management. In this context, when assessing the net C sink rates from the application of organic amendments, it is important to consider its alternative fates. A net C sink rate will occur only if the C contained in the amendments follows a lower degradation path (i.e., its return in atmosphere) than its alternatives. For example, land with low C stocks showed a higher carbon storage potential than land with high C content (Sykes et al., 2020), and thus it should be prioritized.

The adoption of the guideline proposed in this thesis has provided a granular picture of the main GHG emission sources and hotspots of the Castelporziano Reserve. Specifically, by including the overall activities involved in the area, the Reserve generated about 3.3 Gg of CO_{2e} in 2018. However, when the agricultural soil (i.e., about 210t CO_{2e} year^{-1}), and forest (i.e., about 25 Gg CO_{2e} year^{-1}) C-sinks were included in the CFP assessment, the Reserve turns into a significant CO_2 sink site that, net of the GHG emissions, in 2018 has stored 3.7t CO_{2e}/FU corresponding to about 22 Gg of CO_{2e} removed from the atmosphere.

The LCA-based guideline developed in this thesis could be the starting point for developing a widely accepted standard procedure (i.e., OEFSR) to be followed in order to obtain type III environmental declarations (i.e., eco-labelling) for National parks.

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Chapter 6

List of the PhD Activities Done During the Course

6.1. List of publications

Grossi, G., Vitali, A., Lacetera, N., Danieli, P.P., Bernabucci, U., Nardone, A. 2020. Carbon Footprint of Mediterranean Pasture-Based Native Beef: Effects of Agronomic Practices and Pasture Management under Different Climate Change Scenarios. Animals 10, 1-17. https://doi.org/10.3390/ani10030415

Grossi, G., Goglio, P., Vitali, A., Williams, A.G. 2019. Livestock and climate change: impact of livestock on climate and mitigation strategies, Anim. Front. 9:1, 69-76. https://doi.org/10.1093/af/vfy034

Vitali, A., ***Grossi, G***., Martino, G., Bernabucci, U., Nardone, A., Lacetera, N. 2018. Carbon footprint of organic beef meat from farm to fork: a case study of short supply chain. J. Sci. Food. Agric. 98, 14. 5518-5524. https://doi.org/10.1002/jsfa.9098

Chiriacò, M.V., ***Grossi, G***., Castaldi, S., Valentini, R. 2017. The contribution to climate change of the organic versus conventional wheat farming: A case study on the carbon footprint of wholemeal bread production in Italy. Journal of Cleaner Production 153, 309-319. http://dx.doi.org/10.1016/j.jclepro.2017.03.111

6.2. List of poster communications and oral presentations

Grossi, G., Vitali, A., Bernabucci, U., Danieli P.P., Nardone, A., Lacetera, N. 2018. Comparing direct N_2O soil emissions and indirect N-fluxes from a Mediterranean agro-pastoral system using DNDC model and IPCC approach. Volume of abstracts. Claudia Heidecke, Hayden Montgomery, Hartmut Stalb, Lini Wollenberg (Eds.). Thünen Working Paper 103. p 113. http://dx.doi.org/10.3220/WP1535709029000 [Poster presentation]

Grossi, G., Vitali, A., Lacetera, N., Nardone, A., Bernabucci, U. 2017. Comparison between cow milk and soymilk combining nutritional values and greenhouse gas data. ASPA 22nd Congress Book of Abstracts, Italian Journal of Animal Science. 16: sup 1, p 177. https://doi.org/10.1080/1828051X.2017.1330232 [Poster presentation]

Grossi, G., Chiriacò, M., Castaldi, S., Valentini, R. 2016. Carbon footprint of snail meat: A case study from an Italian organic outdoor rearing. X Conference of the Italian LCA Network 2016. Life Cycle Thinking, sustainability and circular economy. Edited by di Arianna Dominici Loprieno, Simona Scalbi, Serena Righi. ENEA. ISBN 978-88-8286-333-3. p 211-220. [Oral presentation]

6.3. List of conferences participations

- ✓ XVI Annual Conference “AISSA”. Climate change effects on agriculture, forest and rural area in Italy. Tuscia University, Italy. 14-15/02/2019.

- ✓ International Conference on Agricultural GHG emissions and Food Security - Connecting research to policy and practice. Berlin, Germany. 10-13/09/2018.

- ✓ Annual Meeting of the multi-stakeholder initiative Livestock Environmental Assessment and Performance (LEAP) Partnership. FAO Headquarter - Rome, Italy. 21/09/17

- ✓ 22nd Conference - Animal Science and Production Association (ASPA). Perugia, Italy. 13-16/06/2017

6.4. List of workshops participations

- ✓ Three-Country GASL Multi-Stakeholder Meeting on determining priorities and options in climate-resilient and low-carbon ruminants' production development. Bishkek - Kyrgyzstan, 10-11/02/2020. http://www.fao.org/europe/events/detail-events/en/c/1259817/

- ✓ Identifying low carbon and climate resilient pathways for the ruminant sector in the selected countries of Central Asia. Bishkek - Kyrgyzstan, 4/10/2019. http://www.fao.org/europe/events/detail-events/en/c/1207982/

- ✓ Identifying low carbon and climate resilient pathways for the ruminant sector in the selected countries of Central Asia. Tashkent - Uzbekistan, 02/10/2019. http://www.fao.org/europe/events/detail-events/en/c/1207976/

- ✓ Identifying low carbon and climate resilient pathways for the ruminant sector in the selected countries of Central Asia. Dushanbe - Tajikistan, 30/09/2019. http://www.fao.org/europe/events/detail-events/en/c/1207966/

6.5. List of seminars participations

- ✓ European Networking Meeting. Demonstration action to mitigate the carbon footprint of beef production in France, Ireland, Italy and Spain. Life Beef Carbon. Verona, Italy 01/02/2018.

- ✓ Climate change: the route from Kyoto to Paris. And now? Tuscia University, Italy 12/04/17

- ✓ Technological overview of Biogas production from bio-waste. Tuscia University, Italy. 22/02/17

- ✓ Technologies to reclaim contaminated soils: overview of the recent regulatory framework. Tuscia University, Italy. 15/02/17

6.6. List of seminars held

- ✓ Impact of livestock on climate. Tuscia University, Italy. 12; 18 and 19/12/19.
- ✓ Environmental product declarations: Eco-labelling of agri-food products. Tuscia University, Italy. 20/03/2019.
- ✓ Impact of livestock on climate. Tuscia University, Italy. 7; 8; 14 and 15/11/18.
- ✓ Environmental product declarations: Eco-labelling of agri-food products. Tuscia University, Italy. 11; 18/03/2018.
- ✓ Impact of livestock on climate. Tuscia University, Italy. 22; 29; 20 and 21/12/17.
- ✓ Application of the Life Cycle Assessment (LCA) methodology for the Carbon Footprint of Food. Faculty of Bioscience and Agro-Food and Environmental Technology. University of Teramo, Italy. 18/05/17.

6.7. Tutorship activities

- ✓ Co-relator of the M.Sc thesis in Agricultural Science and technology (LM-69) entitled: Verifica dell'effetto del management aziendale sulla capacità di mitigare i gas climalteranti nell'allevamento del bovino da latte. Academic year 2018/19. Candidate: Luca Alessi.

6.8. Participations in research projects

- ✓ Participation in the project: Identifying low carbon and climate resilient pathways for the ruminant sector in the selected countries of Central Asia. Tuscia University & Food and Agriculture Organization of the United Nations (FAO). http://www.fao.org/fileadmin/user_upload/reu/europe/documents/events2020/GLEAM/CN_en.pdf

6.9. Abroad internships

- ✓ School of Water, Energy and Environment (SWEE). Cranfield University, UK. Supervisors: Dr Pietro Goglio and Dr Adrian Williams. From 4/04/18 to 28/09/18.

6.10. List of courses participations

- ✓ Course: R programming for statistics and data science. Tuscia University. (25 hours)
- ✓ Course: English course for PhD students. (50 hours)