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Formulated diets based on the carbon footprint of the ingredients

Formulazione di diete sulla base dell'impronta di carbonio degli ingredienti

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Index

Abstract

With the pressing issue of the GHGs and CO_2 emissions and the related climate change, in the livestock sector the environmental impact of dairy farms has become an urgent and debated problem in the public and within the industry itself. The purpose of this study is to investigate the environmental impact that dairy cows' rations have upstream, before the consumption by the animals. The study was performed comparing 10 rations, 5 hay-based for the Parmigiano Reggiano consortium area and 5 silage-based, in terms of economic and environmental (Carbon Footprint) costs, comparing their versions optimized for nutrient supply (actual diet used in the farm), economic and environmental costs. The results show how the difference between the economic and environmental costs can be considered significant and when estimated on a 100-cows herd the impact became of importance. In fact, concerning the silage-based rations the difference per ration between the current diet (optimized for the nutrient supply) and the one optimized for sustainability reaches the amount of 22,265 euros/year and a similar value of CO_2 (22 tons CO_2). Differences are similar when it comes to the hay-based diets, that are 12,045 euros/year and 22 tons of CO_2. Results also show that the optimization from both an economical and environmental perspective are in practice equivalent in terms of final cost of the ration, probably due to the direct and linear relationship that can be found between the economic cost and environmental impact. For the same reason the rations' environmental cost is decreasing moving from the more nutrient diet to the most ecological ones. In conclusion the optimization for the environmental sustainability is strongly related also with the reduction of the cost of the diet, but in general lead to a lower economic cost together with a lower carbon footprint. The hay-based diets tested resulted more expensive from an economical point of view but more environmentally sustainable.

1. Contribution of livestock to climate change

Nowadays, the issue of greenhouse gas emissions and the related global warming has become of primary importance. The last IPCC report (2022) harshly warns that mean global temperature must not exceed 1.5°C of positive anomaly and says it's imperative that all human activities must work together due to reach zero emissions by 2050, depending on each country.

It is estimated that agriculture sector represents about 20% of total anthropogenic emissions, with an increasing trend (IPCC, 2019) while livestock sector alone contributes for 18% (FAO, 2006); specifically, in the UE livestock sector amounts for 17% of total emissions (EEA , 2019) with an increase of about 6% between 2007 and 2018 (FAO, 2019)

In Italy livestock sector contributes for 79% of all agricultural emissions. "Dairy cow" stands out as the most GHG emitter between each animal category amounting for 36.9% (ISPRA, 2020)(Fig.1).

Emissions are this high because of its large interface with the environment: "Three concerns have emerged. First, the production of animal protein, particularly when fed on dedicated crops, is typically less efficient than the production of equivalent amounts of plant protein. Second, extensive livestock are often kept in remote environments where deforestation and land degradation reflect weakness in institutions and policies. Lastly, intensive livestock production tends to cluster in locations with cost advantages (often close to cities or ports) where insufficient land is available for the recycling of waste from livestock leading to nutrient overloads and pollution" (FAO, 2013).

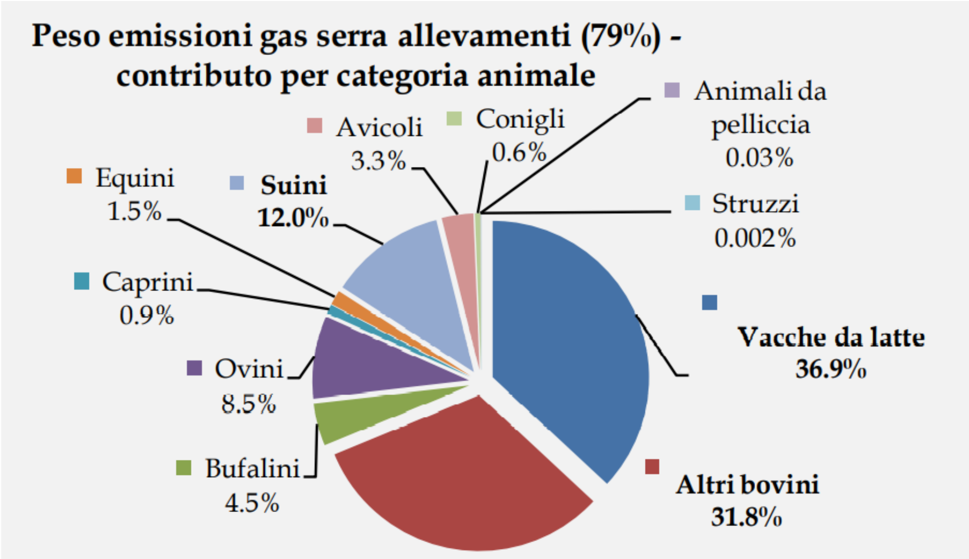


Figure 1: weight of GHG emissions from livestock (79%) in Italy: animal categories ISPRA, 2020.

1.1 Main sources of emissions

GHG emissions can be defined as direct or indirect emissions. The direct ones are related to animal production (methane from enteric fermentation and manure, nitrous oxide from fertilizers spreading on soils) and to energetic sector (FAO, 2013).

The indirect ones are related to land use, land use change and forestry (LULUCF).

Emissions from production, processing and transport of feed account for about 45 percent of sector emissions. The fertilization of feed crops and deposition of manure on pastures generate substantial amounts of N_2O emissions, representing together about half of feed emissions (FAO, 2013).

About one-quarter of feed emissions are related to land use change (less than 10% of total) (*ibidem*)

Enteric fermentation is the second largest source of emissions, contributing about 40% to total emissions. Cattle emits most of the enteric CH_4 (77%), followed by buffalos (13%) and small ruminants (10%) (*ibidem*).

Methane and N_20 emissions from manure storage and processing (application and deposition excluded) represent about 10% of the sector's emissions. Emissions associated with energy consumption (directly or indirectly related to fossil fuel) are mostly related to feed production, and fertilizer manufacturing, in particular. (FAO, 2013) (Fig.2).

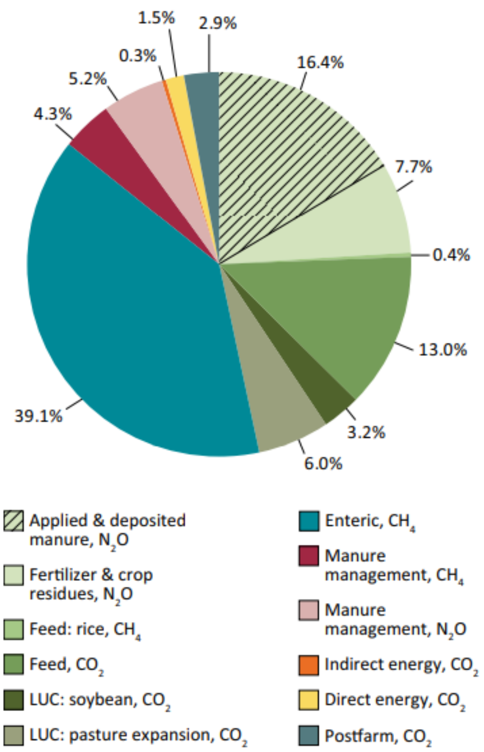


Figure 2: Global emissions from livestock supply chains by category of emission, GLEAM, 2013.

• Feed, N2 O including:
- Fertilizer & crop residues, N2 O – emissions from fertilizer applied to feed crops and from the decomposition of crop residues;
- Applied & deposited manure, N2 O – emissions from manure applied to feed crops and pasture or directly deposited on pastures by animals.
• Feed, CO2 – emissions from the production, processing and transport of feed;
•LUC: soybean, CO2 – emissions from the expansion of cropland for feed production;
• LUC: pasture expansion, CO2 – emissions from the expansion of pasture;
•Feed: rice, CH4 – emissions from rice cultivation for feed purposes;
• Enteric, CH4 – emissions from enteric fermentation;
• Manure management, CH4 – emissions from manure storage and processing (application and deposition excluded);
• Manure management, N2 O - emissions from manure storage and processing (application and deposition excluded);
• Direct energy, CO2 –emissions from energy use on animal production unit (heating, ventilation, etc.);
• Indirect energy, CO2 – emissions related to the construction of the animal production buildings and equipment;
• Postfarm, CO2 – emissions related to the processing and transportation of livestock product between the production and retail point.

1.1.1 Carbon Dioxide

Livestock account for 9% of global anthropogenic emissions of CO_2 (FAO, 2006). It includes mostly N fertilizer production, processing and transport, fossil fuels, tillage and liming on cultivated soils, deforestation for pasture and feed crop land.

Changes in land use have an impact in carbon emissions and many of the land use changes involve livestock, for example occupying land as pasture or arable land for feed crops.

Deforestation is another main issue, since a huge amount of carbon is released in the atmosphere from it. It is particularly important in South America, the continent suffering the largest net loss of forests (FAO, 2006). The conversion of forest into pasture releases about 2.4 billion tonnes of CO_2 per year (*ibidem*), particularly when the converted area is not logged but simply burned.

However, LULUCF sector emissions in particular are extremely difficult to quantify, and the values reported for this sector are known to be of low reliability. Herzog (2009) estimated a 12,2% of global GHG emissions in 2005 related with LULUCF, while IFOAM (2016) estimated 6-17% in total global GHG emission from conversion of forest land to agricultural land or pastures.

1.1.2 Methane

Livestock account for about 80% of agricultural methane emissions and about 35-40% of the total anthropogenic methane emissions (3.1 gigatonnes CO_2-eq of CH_4) (IPCC, 2007). Methane is released from enteric fermentation or from manure management (storage and processing).

Among domesticated livestock, ruminant animals (cattle, buffaloes, sheep, goats and camels) produce significant amounts of methane as part of their normal digestive process. In the rumen, microbial fermentation convers fibrous feed into products that can be digested and utilized by the animal; this enteric fermentation, produces methane as a by-product, which is exhaled by the animal (US-EPA, 2006).

There are significant spatial variations in methane emissions from enteric fermentation:
In Brazil, in 1994, 93% of agricultural emissions was methane from enteric fermentation, 72% of the country's total emissions of methane; over 80% of this originated from beef cattle (FAO, 2013).

In the USA methane from enteric fermentation totalled 5.5 million tonnes in 2002. This was 71% of all agricultural emissions and 19% of the country's total emissions (US-EPA, 2006).

This variation reflects the fact that levels of methane emission are determined by the production system and regional characteristics. They are affected by energy intake and several other animal and diet factors (quantity and quality of feed, animal body weight, age and amount of exercise). Those factors vary among animal species and among individuals of the same species (FAO, 2006).

The anaerobic decomposition of organic material in livestock manure also releases methane. This occurs mostly when manure is managed in liquid form, such as in lagoons or holding tanks. Manure deposited on fields and pastures, or otherwise handled in a dry form, does not produce significant amounts of methane (*ibidem*).

Methane emissions from livestock manure are influenced by several factors that affect the growth of the bacteria responsible for methane formation, including ambient temperature, moisture and storage time (*ibidem*).

Globally, methane emissions from anaerobic decomposition of manure have been estimated to total just over 10 million tonnes, about 4% of global anthropogenic methane emissions (US-EPA, 2005).

1.1.3 Nitrous Oxide

Livestock activities contribute substantially to the emission of nitrous oxide, the most potent of the three major greenhouse gases; they account for 65% of global anthropogenic emissions, and 75-80% of agricultural emissions, both crop and livestock production (FAO, 2006).

Current trends suggest that this level will increase over the coming decades (FAO, 2006). Nitrous oxide emissions amount to 1.25 +/- 1 % of the nitrogen applied. This estimate is the average for all fertilizer types, as proposed by Bouwman (1995) and adopted by IPCC (1997). Emission rates also vary from one fertilizer type to another.

Livestock production can be considered responsible for a global N_2O emission from mineral fertilizer of 0.2 million tonne N_2O-N per year (FAO, 2006).

Nitrous oxide is very persistent in the atmosphere, where it last for up to 150 years (FAO, 2013). In addition to its role in global warming, N_2O is also involved in the depletion of the ozone layer (Bolin, et al., 1981).

1.1.4 Ammonia

Galloway et al. (2004) estimated that global anthropogenic emission of ammonia reached 47 million tonnes N in 2003. Some 94% of this is produced by the agricultural sector; livestock contributes for 68% of the agricultural share, mainly from deposited and applied manure (FAO, 2006).

The estimated global NH_3 volatilization loss, from synthetic N fertilizer use in the mid-1990s, totalled about 11 million tonnes N per year. Of this, 0.27 million tonnes emanated from fertilized grasslands, 8.7 million tonnes from rainfed crops and 2.3 million tonnes from wetland rice (FAO/IFA, 2001); most of this occurs in the developing countries (8.6 million tonnes N) nearly half of which in China (FAO, 2006).

In these countries about 50% of the nitrogen fertilizer used is in the form of urea (FAO/IFA, 2001) and emissions losses from urea may be 25% in tropical regions and 15% in temperate climates, due to warmer climate in tropical regions (FAO, 2006).

As it is known, a large share of the world's crop production is fed to animals and mineral fertilizer is applied to much of the corresponding cropland.

FAO (2006) estimated that 20 to 25 % of mineral fertilizer use (about 20 million tonnes N) can be ascribed to feed production for the livestock sector; on this basis, livestock production can be considered responsible for a global NH_3 volatilization from mineral fertilizer of 3.1 million tonnes NH_3-N (tonnes of nitrogen in ammonia form) per year.

1.2 Emissions by species

Cattle are the main contributor to GHG emissions with about 4.6 gigatonnes CO_2-eq, representing 65 percent of sector emissions. Beef cattle (producing meat and non-edible outputs) and dairy cattle (producing both meat and milk, in addition to non-edible outputs) generate similar amounts of GHG emissions. Pigs, poultry, buffaloes and small ruminants have much lower emission levels, resulting a quarter of the previous categories (ranging 7-10% of total emissions) (Fig.3) (FAO, 2013).

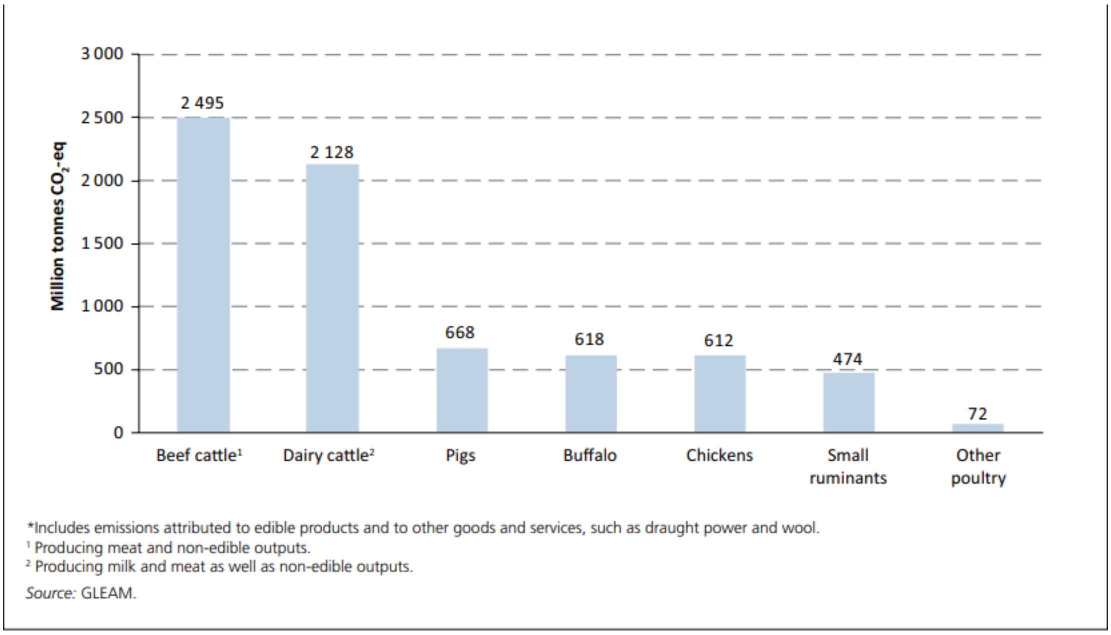


Figure 3: global estimates of emissions by species, FAO (2013)

2. How climate change influences crop yields and livestock productivity

2.1 Crops

Climate and weather changes are influencing crop yields and livestock productivity in Europe, impacting differently across Europe regions (Fig.4). This leads to both positive and negative effects: potential positive effects related to increased temperatures are expected mostly in northern Europe, because of the increases in the length of growing seasons that can improve the suitability for growing crops in those areas. On the other hand, a reduction in crop productivity is projected in large parts of southern Europe, due to faster crop development rates and subsequent negative effects on grain filling (EEA , 2019). Climate change can also directly and directly impact agricultural production: direct impacts relate to changes of cultivation areas, soil loss, water availability and direct effects of increased levels of CO_2 on growth. Indirect effects are the increases of pests, diseases, invasive species and extreme weather events, such as hailstorms and intense heat and frosts (*ibidem*).

Increase in temperature may cause an acceleration in phenological development, with a reduced time for biomass assimilation and subsequently a lower crop yield. In some areas, such as northern European countries, the warmer climate conditions may allow the cultivation of new crops/varieties (Ciscar, Fisher-Vanden, & Lobell, 2018). Warmer temperatures determine an earlier start to active crop growth, faster plant development and a potential extension of the crop-growing season, especially for perennial crops (Olesen, 2016). Shorter crop growing cycles have negative effects on grain filling and consequently on crop productivity because of the reduced time for biomass accumulation and yield formation (Ciscar, Fisher-Vanden, & Lobell, 2018). Moreover, warming and water deficits can influence quality and digestibility of many crops, such as

Panicum maximum, because of the increase in leaf lignin (Habermann, Dias de Oliveira, Contin, Delvecchio, & Viciedo, 2019). In fact, as the plant matures, phenolic acids and lignin are deposited limiting polysaccharide digestibility by the animal (Jung & Allen, 1995).

On the other hand, harvesting forage at an earlier stage of maturity increases its soluble carbohydrate content and reduces lignification of plant cell walls thereby increasing its digestibility (Van Soest, 1994) and decreasing enteric CH_4 production per unit of digestible DM (Tyrell, Thomson, Waldo, Goering, & Haaland, 1992).

Increased temperatures and CO_2 concentrations may increase herbaceous growth and favour legumes over grasses in mixed pastures (He, et al., 2019). Under elevated CO_2 conditions, forage quality is expected to decline, with losses of concentrations of iron, zinc, and protein in plant by up to 8% by 2050 (Smith & Myers, 2018). These impacts will result in greater nutritional stress in grazing animals as well as reduced meat and milk production.

As it is said above, climate and weather can remarkably affect the growth and composition of crops, so adaptation strategies are necessary to cope these problems: "The decision to utilize particular forages in support of dairy production should be based on a number of key factors, such as available land use, type of manure management, soil type and topography, climate, and availability of purchased forages and feeds" (Harrison & al, 1994).

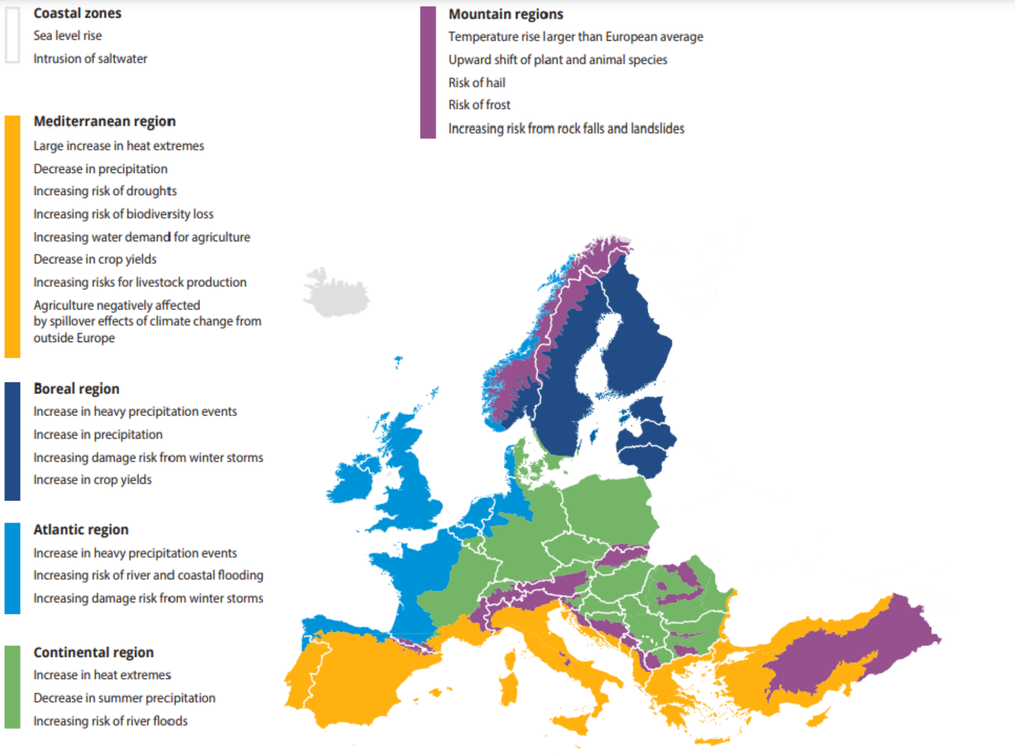


Figure 4: Main climate change impacts on the agricultural sector for the main biogeographical regions in Europe. EEA report, 2019.

2.2 Livestock

2.2.1 Dry Matter Intake (DMI), milk yield and milk quality

High temperatures can directly affect livestock, too. Most of dairy animals have thermoneutral zone in the range 10-30°C (Nardone, Ronchi, Lacetera, & Bernabucci, 2006) so higher temperatures enhance heat gain beyond that lost from the body and induce Heat Stress (HS).

However, heat stress is caused by a combination of environmental factors: temperature, relative humidity, solar radiation, air movement, and precipitation (Bohmanova, Misztal, & Cole, 2007).

Increasing air temperature, temperature-humidity index (THI) and rising rectal temperature above critical thresholds are related to decreased dry matter intake (DMI) and milk yield and to reduced efficiency of milk yield (West, 2003).

This happen because heat also has effect on appetite centre of the hypothalamus, that causes decrease of feed intake (Nardone, Ronchi, Lacetera, & Bernabucci, 2006). In fact, feed intake declines rapidly at air temperatures above 30°C, reaching -40% at 40°C (Rhoads, Baumgard, Suagee, & Sanders, 2013). West (2003) also reported a reduction in DMI by 0.85kg with every 1° C rise in air temperature above a cow's TNZ, accounting for approximately 36% of the decrease in milk production. To compensate this decrease of DMI, it is necessary to formulate diets with increased nutrient density and maintenance of the normal rumen function, avoiding nutrient excesses, during hot climate (West, 2003).

Ravagnolo et al. (2000) suggested that cow DMI and milk yield were most affected by climatic variables, more than cow body temperature, suggesting that maximum temperature and minimum relative humidity were the most critical variables to quantify heat stress. Milk yield declined by 0,2kg per unit increase in THI, when THI exceeded 72.

Authors concluded that THI can be used to estimate the effect of heat stress on production.
Based on the last formulated index (Yousef, 1985) THI can be described as:

$$THI = (Tdb + 0.36 \times Tdp) + 41.2$$

Where *Tdb* is dry bulb temperature (°C) and *Tdp* is dew point temperature (°C)

For this reason, total average milk production/cow is significantly higher in spring period (42.74 ± 4.98 L) compared to summer (39.60 ± 5.091 L) (Joksimovic Todorovic, Hristov Davidovic, & Stankovic, 2011).

Hot environment affects also milk quality: Kadzere et al. (2002) reported that milk fat, solids-not-fat (SNF) and milk protein percentage decreased by 39.7, 18.9 and 16.9%, respectively. Analysis of protein fractions also showed a reduction in percentage of casein, lactalbumin, immunoglobulin G (IgG) and IgA. Lactose content varies slightly (4.45 ± 0.54% in spring vs 4.03 ± 0.24 % during summer), instead (Joksimovic Todorovic, Hristov Davidovic, & Stankovic, 2011).

2.2.2 Physiologic effects

Increased temperatures can also alter the physiological mechanisms of rumen with growth at risk of metabolic disorders, such as altered acid-base balance or oxidative stress.

In fact, during heat stress panting increases the loss of CO_2 via pulmonary ventilation, reducing the blood concentration of carbonic acid, resulting in a respiratory alkalosis. (Benjamin, 1981). To maintain blood concentration of carbonic acid, and consequently compensate for higher blood pH, animals need to excrete bicarbonate in the urine. Chronic hyperthermia also causes prolonged inappetence which further aggravates the supply of total carbonic acid in the rumen, resulting into subclinical and acute rumen acidosis (Kadzere, Murphy, Silanikove, & Maltz, 2002).

During Heat Stress, dairy animals face up also an increase of reactive oxygen species (ROS), which have negative impacts on normal physiology and body metabolism (Das et al., 2016). To cope these effects, significantly higher levels of stress indices such as catalase, superoxide dismutase (SOD), glutathione (GSH), reductase, and malondialdehyde was observed in dairy cattle during summer compared to spring seasons (Yatoo, Dimri, & Sharma, 2014).

Moreover, heat stress suppresses immune and endocrine system, enhancing susceptibility of the animal to disease (Das, et al., 2016). Primary indicators of immunity response include white blood cells (WBCs), red blood cells (RBCs), haemoglobin (Hb) and packed cell volume (PCV); they get altered on thermal stress: WBC count increases by 21-26% (Abdel-Samee, 1987) and RBC count decreases by 12-20% (Habeeb, 1987) in thermally stressed cattle. Higher PCV values result as an adaptive mechanism to provide water necessary for evaporative cooling process.

Also, cortisol increases in heat stressed animals which causes down-regulation or suppression of L-selectin expression on the neutrophils surface (Burton & Ronald, 2013). This suppression results in a weak neutrophils function and, consequently, in outcome of diseases following exposure to infective organisms.

In addition, hormonal alterations, like declined triiodothyronine or thyroxine concentration occur with heat stress probably reflecting the cows attempt to reduce metabolic heat production (West, 2003).

One of the most common health problems related to heat stress is subclinical or clinical ketosis (Lacetera & al, 1996). Sanders et al. (2009) also observed that, during heat stress, incidence of lameness is increased, maybe due to increase in standing time: this cause also thin soles, white line disease, ulcers, and sole punctures. Heat stressed dairy cattle also face up higher incidence of mastitis: this could be due to high temperatures facilitating survival and multiplication of pathogens in the mammary gland (Das, et al., 2016).

2.2.3 Effects on reproductive system

Heat stress reduces length and intensity of estrus, while increases incidence of anestrous and silent heat in farm animals (Singh, Chaudari, Singh, Singh, & Maurya, 2013). It increases ACTH and cortisol secretion, and block estradiol-induced sexual behaviour (Hein & Allrich, 1992). Low estradiol secretion suppresses signs of estrus, ovulation, transport of gametes and ultimately reduced fertilization (Wolfenson, Roth, & Meidan, 2000).

Heat stress also reduces oocyte development and increases prolactin level, resulting in acyclicity and infertility (Singh, Chaudari, Singh, Singh, & Maurya, 2013). However, FSH secretion is elevated under HS condition probably due to reduced inhibition of negative feedback from smaller follicles.

Conception rates drop from about 40-60% in cooler months to 10-20% or lower in summer (Cavestany, El-Whishy, & Foot, 1985).

Embryonic growth and survival are also affected during heat stress in dairy cattle. It causes embryonic death by interfering with protein synthesis, oxidative cell damage, reducing interferon-tau production for signalling pregnancy recognition, and expression of stress-related genes associated with apoptosis (Das, et al., 2016). Moreover, exposure of post-implantation embryos and foetus to HS also leads to various teratologies (Wolfenson, Roth, & Meidan, 2000).

2.2.4 Infectious and vector-borne diseases

Climate change will also have effects on distribution and incidence of infectious diseases of livestock: "Growing infectious disease burdens in domesticated animals may have wide-ranging impacts on the vulnerability of rural livestock producers in the future, particularly related to human health and projected increases in zoonoses" (Bett, et al., 2017). In fact, climate change may cause shifts in disease distribution and prevalence with the breakdown of endemic stability: this is the consequence of both distribution and abundance of disease-causing vectors, increased with changes in rainfall and temperatures (Thornton, van de Steeg, Notenbaert, & Herrero, 2009) through places where they have never been reported.

3. Carbon Footprint

Since a clear definition is missing for Carbon Footprint, it is open to different interpretations. Generally, Carbon Footprint (CF) is defined as the main parameter used to determine the environmental impact of products, services, organizations, events or individuals; it allows to evaluate the effect of anthropogenic activities on climate change, calculating GHG emissions released in the atmosphere from these activities during all life cycle of the examined system (LCA).

It has become a widely used term in the public debate of climate change during these years: it was originally developed by the publication "ecological footprinting" by Rees (1992) and was than defined by Wackernagel (1994) who provided more methods of calculating footprints.

Wiedmann and Minx (2008) defined carbon footprint as "a measure of the exclusive total amount of carbon dioxide emissions that is directly and indirectly caused by an activity or is accumulated over the life stages of a product", even though there are more gases that produce GHG emission, but "many of those are either not based on carbon or are difficult to quantify because of data availability".

3.1 Carbon Footprint calculation

Carbon footprint is the sum of different contributes of greenhouse gases included in one emission associated with human activities.

The calculation is expressed in kilograms (or tons) of CO_2 equivalent, that is the impact of a certain quantity of gas compared to the same quantity of CO_2.

3.1.1. Greenhouse gases involved in the calculation

Which greenhouse gases should be included in the CF calculation it has been established by the Kyoto Protocol (1997), in occasion of the United Nations Framework Convention on Climate Change.

Main gases are:

- Carbon dioxide (CO_2)
- Methane (CH_4)
- Nitrous oxide (N_20)

To which are added:

- Hydrofluorocarbons (HFC)
- Perfluorocarbons (PFC)
- Sulfur hexafluoride (SF_6)

3.1.2 Global Warming Potential (GWP)

Greenhouse gases warm the earth by absorbing energy and decreasing the rate at which the energy escapes the atmosphere. These gases differ in their ability to absorb energy, because they have various radiative efficiencies. They also differ in their atmospheric residence times. Each gas has a specific global warming potential (GWP), which allows comparisons of the amount of energy the emissions of 1 ton of a gas will absorb over a given time period, usually a 100-year averaging time (GWP100), compared with the emissions of 1 ton of CO_2 (Vallero, 2019).

The GWP has been also defined as the ratio of the time-integrated radiative forcing from the instantaneous release of 1 kg of a trace substance relative to that of 1kg of a reference gas (IPPC,1990):

$$GWP(x) = \frac{\int_0^{TH} a_x \bullet [x(t)]\, dt}{\int_0^{TH} a_r \bullet [r(t)]\, dt}$$

Where:

- TH is the time horizon over which the calculation is considered
- a_x is the radiative efficiency due to a unit increase in atmospheric abundance of the substance in question (i.e., $Wm^{-2}\ kg^{-1}$)
- [x(t)] is the time-dependent decay in abundance of the instantaneous release of the substance, and the corresponding quantities for the reference gas are in the denominator

Common name	Chemical formula	AR5
Carbon dioxide	CO_2	1
Methane	CH_4	28
Nitrous oxide	N_20	265

The table is adapted from the IPCC Fifth Assessment Report, 2014 (AR5) GWP values for 100-year time horizon.

3.2 Calculating the carbon footprint of dairy cattle rations

In this study, CF is used to establish the environmental impact of dairy feed, in order to formulate environmentally sustainable rations for dairy cattle.

Bearing in mind that several aspects could determine the reduction of livestock's environmental impact, it is reasonable to think that it must include the reduction of dairy feed emissions.

In fact, as it has already been showed, this represents a substantial percentage of total agricultural impact.

In this study, CF is defined as the emission per unit (kilograms) of DM of feed produced, expressed as kilograms CO_2eq per kilogram of DM. However, many papers consider CF based on different unit, such as area unit (ha), or economic unit. For this reason, they were discarded from this study.

4. Guidelines for the formulation of dairy cow rations

Formulating rations for cattle is essential to provide the nutrients that are required by the animals to stay healthy and optimize production; also, the ration should combine the nutrient needs, trying to find what feeds are best to select in order to obtain maximum profit. (Erickson, Kenneth, & Kalscheur, 2020).

In this study, rations are formulated starting by the carbon footprint of forages and feeds in general, due to obtain them environmentally sustainable.

Diet formulation for the high producing dairy cow requires knowledge of the nutrients that are needed by the mammary gland to produce milk. These nutrients include water, proteins (amino acids), carbohydrates, fats, minerals and vitamins, understanding that their physical characteristics and their combined interactions are essential to successful dairy cattle feeding (Fig.5).

This section entirely refers to "Nutrition and feeding of dairy cattle" by Erickson & Kenneth, 2020.

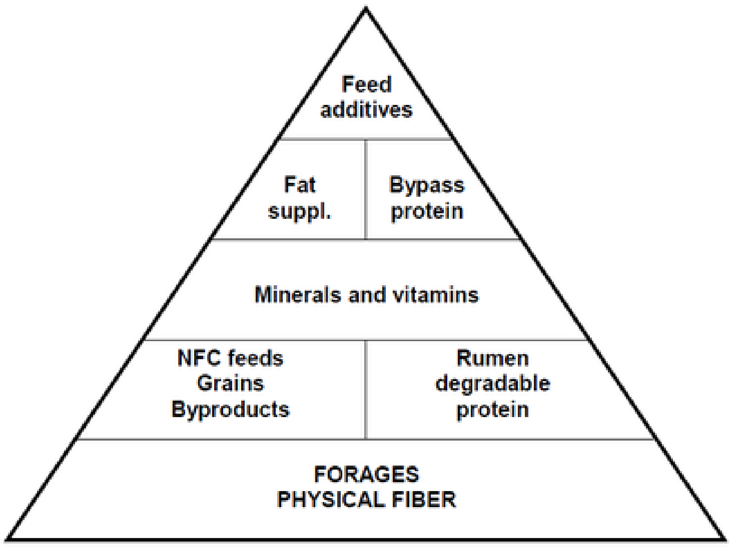


Figure 5 The ruminant feed pyramid, referred to: [Formulating dairy cow rations (umn.edu)]

4.1 Water

Water is the main component of milk and also of the total body weight in the dairy cow (respectively 87% and 56-81%).

Water is also essential for rumen microbial development in the preruminant calf and critical in the conversion of the calf from non-ruminant to ruminant. Appuhamy et al. (2016) derived two equations to estimate free water intake for lactating cows: first equation utilizes dry feed intake, second utilizes milk yield.

Eq.1

L/d = -91.1 + 2.93 X DMI + 0.61 X DM% + 0.62 X NaK (combined concentration, mEq/kg DM) + *2.49 X crude protein% + 0.76 X mean ambient temperature* (°C)

Eq.2

L/d = -60.2 + 1.43 X milk yield + 0.64 X NaK (mEq/kg) + 0.83 X DM% + 0.54 X mean ambient temperature + 0.08 X days in milk

4.2 Protein and amino acids

Protein is typically measured in feedstuffs as crude protein (CP) which is defined as the %N in a feed multiplied by 6.25 (because feed proteins contain approximately 16%N).

Crude protein is divided into two portions, rumen undegradable protein (RUP) and rumen degradable protein (RDP).

The RUP fraction will bypass the rumen and pass to the small intestine for digestion similarly to that of non-ruminants. Proteins are subject to proteolysis and digestion to amino acids which can be absorbed by enterocytes in the small intestine.

The RDP fraction is degraded to amino acids, dipeptides, and ammonia by the microbes present in the rumen.

It is suggested that %RDP should be close to 10% while %RUP can be 5.5% to 6.0% dietary DM.

All animals do not have a protein requirement, but amino acid requirement, because there are ten essential amino acids used for enzymes production, milk proteins, immunoglobulins, muscle and various organ and tissues in the body. Some feeds, such as corn, are deficient in the essential amino acid lysine. Other, such as soybean feedstuffs, are deficient in methionine.

4.3 Carbohydrates

Carbohydrates represent the largest component in the diet of dairy cattle (70% in the diet of lactating dairy cattle).

The two most common carbohydrates used in feeding cattle are cellulose (beta 1,4 glucose units) and starch (alfa 1,4 and 1,6 glucose units). Sources of carbohydrates include forages, roughages, grains and sugars. Forages including hay, hay-crop silage, grain-based silage, are primarily digested by cellulolytic bacteria which result in the production of acetic and butyric acid.

4.3.1 Carbohydrate types

Carbohydrates are divided into two fractions: structural carbohydrates and related compounds, called neutral detergent fibre (NDF) such as cellulose, hemi-cellulose and lignin (despite lignin is not a carbohydrate but it is part of NDF) and non-structural carbohydrates, such as starch and sugars, called non-fibre carbohydrates (NFC).

The recommended concentration of NDF to feed is about 27-28% of the diet DM for lactating cows.

Primary sources of NDF are hays, silage, pasture and roughages. Lignin content increases as the plants mature and it is negatively correlated with digestibility. On the other hand, NFC can be estimated by difference using the following equation:
NFC = 100 – (% CP + (% NDF - % neutral detergent insoluble crude protein) + % ash + % ether extract (lipids and waxes)

Typically, NFC should provide about 35% of diet DM in a lactating cow.

4.3.2. Rumen fermentation

Microorganisms, which reside in the forestomach of ruminants, ferment carbohydrates to produce end products called volatile fatty acids (VFA)

These VFA are used as energy sources by the cattle; the primary VFA for cattle are acetic acid, propionic acid, and butyric acid.

Acetic acid and butyric acid are used for milk fat synthesis in the mammary gland of the lactating cow, while propionic acid is primarily used for glucose. Glucose is the primary precursor of the disaccharide lactose which is the major osmol-regulator of milk.

4.3.3. Feed processing

Processing of feed like forages through rollers at the time of harvest will help to expose the starch of the seed and the hemicellulose of the stalks. This process will aid the fermentation of the silage in the silo, but also enhance the digestibility of the internal contents of the plants (starch and hemicellulose). Processing starch is typically done mechanically through hammer mills or grinders to expose the starch to the rumen microbiota. Steam flaking of starch sources results in the gelatinization of starch making it more digestible in the rumen.

4.3.4. Recommendations

It is suggested that most cows be fed with diets containing greater than 50% of the diet as forages, however, this can vary significantly depending on the inclusion of fibrous by-products.

Heifers and dry cows are fed diets with a much greater proportion of forages than lactating cows due to the lesser nutrient requirements of cattle in these life-phases.
Finally, higher quality forages (lesser NDF) will result in decreasing the need for purchased feeds and enhance the farm's profits.

4.4. Fat

Fat can be divided into two types, glycerol and non-glycerol: non-glycerol type fats have little to no nutritive value and include waxes and sterols; glycerol-type fats include triglycerides, phospholipids and glycolipids and are of nutritive value.

Unsaturated fats have double bonds (most plant fats), whereas saturated fats are fully hydrogenated (most terrestrial animal fats).

4.4.1 Recommendations

Almost all feed, with exception of water and minerals, contain fat. Recommendations to feed typically indicate not to feed more than 8% of fat in total dry matter. A typical TMR (Total Mixed Ration) with no supplemental fat will contain about 3-4%. Adding 5 pounds of common oilseeds will result in 5.4% fat diet, which can reach 7.35% to high producers near peak, adding an additional pound of prilled fat.

4.5 Minerals

Minerals are inorganic compounds required for many different bodily functions from structure, and nerve impulses to osmotic balance. Some minerals also serve as catalysts for reactions or are necessary for enzyme function.

Minerals are divided into two categories:

a) Macrominerals: including Ca, P, Mg, K, Cl, Na, S, required in gram quantities.
b) Microminerals: required in mg or ug quantities.

In dairy cattle, mineral nutrition is essential for the success of the lactation.

4.5.1. Macrominerals: Calcium

Because of the large amount of milk that cows produce at parturition, there is a large draw on Ca. The calcium requirement for lactating cows is variable, with a minimum of 0.61% of the diet, but can be increased to 1% especially when feeding additional fat in the diet.

4.5.2 Other minerals

In table 1 are presented the requirements for the main macrominerals for a dairy cow ration.

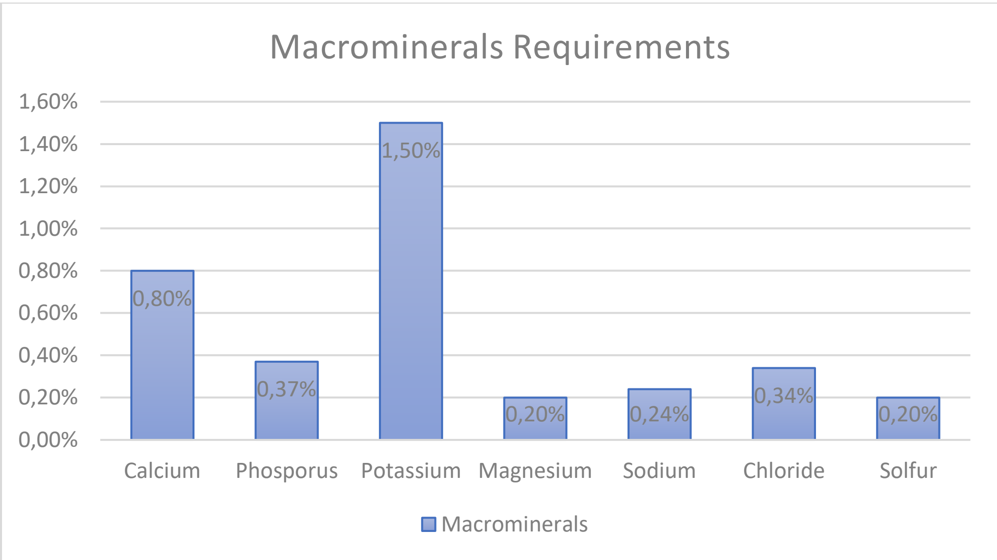


Table 1: Microminerals requirements for dairy cows. They are expressed in percentage of DM of dairy feed.

reffered to: Nutrition and feeding of dairy cattle, Peter S. Erickson, Kenneth F. Kalscheur, 2020.

4.5.3 Microminerals requirements

In this paragraph are presented the requirements for the main microminerals:

- Copper: 0.15mg/kg of milk
- Iodine: 0.6mg/100 kg of body weight during maintenance, this increases to 1.5mg/100 kg of body weight during lactation due to thyroxine production
- Iron: max 24mg/kg of diet DM
- Manganese: 40mg/kg of diet DM
- Molybdenum: 10mg/kg of diet DM
- Zinc: 22.8mg/kg of diet DM
- Selenium: 0.3mg/kg diet supplemental selenium

4.6 Vitamins

Vitamins are organic compounds that can be divided into two categories: water-soluble and lipid soluble.

Water-soluble vitamins are synthesized within the rumen, lipid-soluble are lipid-based and they are: vitamins A, D, E, K.

4.6.1 Vitamin requirements

Here are presented the vitamin requirements for a dairy cow ration:

- Vitamin A (retinol): 110.25 IU
- Vitamin D. 30.87 IU
- Vitamin E: 1.000 IU/ day for dry cows, 500 IU/ day for lactating cows

4.7 Feed additives

Feed additives are typically added to dairy cattle diets to improve performance such as growth, milk yield, milk component yield, feed efficiency, and health. They can also affect methane production (Weiske,2005), resulting an option for lowering emissions.

Common feed additives are Ionophores, end-products of bacterial fermentation, which reduce the numbers of Gram-negative bacteria resulting in reduced incidence of ketosis and improved feed efficiency. Ionophores such as monensin, lasalocid, salinomycin, nigercin and gramicidin can decrease methane production in two ways:

- Firstly, they increase feed conversion efficiency by:
  - increasing the ratio of acetate to propionate and decreasing energy lost during feed fermentation
  - decreasing breakdown of feed protein and bacterial protein synthesis, which makes high roughage feeding more efficient.

  This increases productivity (weight gain per unit of feed intake) by adjusting several fermentation pathways, which reduce methane output per unit of product.
- Secondly, because of their effect on rumen fermentation, they directly reduce the amount of methane produced per unit of food intake (Weiske, 2005).

Also, probiotics are thought to enhance nutrient digestibility through increasing bacterial species. They are developed primarily to improve animal productivity by directly influencing rumen fermentation (Clark & Ipharraguerre, 2001)

Other additives could be special enzyme which can improve production when added to the diets of livestock, such as phytase, protease/deaminase, amylase, cellulase and hemicellulose (xylanase) (Weiske, 2005).

5. Key parameters affecting the carbon footprint of feed crops

For this study, key parameters were analyzed to determine how much each crop impacts the environment.

This was done in order to formulate rations for dairy cows based on ecologically sustainable forages and feeds tailored to each production region.

In fact, each region differs primarily in climate and soil composition, leading to different decisions in choosing which crops are most suitable in a specific area, ultimately generating lower emissions through more conscious use of fertilizers and pesticides while simultaneously the possibility of improving production and profits on the farm.

5.1 Climate and geographic regions

In order to pick the most suitable plant species for dairy feed cultivation in a specific region, it is crucial to know the climate of that region.

In fact, climate has since long been recognized as the major driver of global vegetation distribution (Von Humboldt & Bonpland, 1805) and climate variables are considered the primary driver to explain species ranges at larger spatial extent.

5.1.1 Köppen-Geiger classification

This study analyzed 12 papers developed in 8 different world crop-regions:

Adom et al. (2012) from the USA, Ghazouani et al. (2018) from Tunisia, Hauggard-Nielsen et al. (2016) and Mogensens et al. (2014) from Denmark, Gollnow et al. (2014) from Australia, Gan et al (2011), (2012) and Wiens et al. (2014) from Canada, Bacenetti et al. (2018) from Italy, Zhang et al. (2017) from China, Jat et al. (2019) from India.

Since these regions are substantially different from one another from a climatic point of view, the Köppen Classification was referenced to identify in the best way possible each region's climate.

This classification aims to empirically map climate distributions around the world: it distinguished five main classes and 30 sub-types and it is based on threshold values and seasonality of monthly air temperature and precipitation. The first version of this system was developed in the late 19th century and then adjusted by Beck et al. (2018), who present the new global maps of the Köppen-Geiger climate classification at 1-km resolution for the present day (1980-2016) (Fig. 6, a) and for projected future conditions (2071-2100) under climate change (Fig.6, b).

The five main climate groups are denominated by a capital letter: A (tropical), B (arid), C (temperate), D (continental), and E (polar) matched with another letter which indicates the seasonal precipitation type, creating a binary code, while the third letter indicates the level of heat.

However, the main issue with this classification is that, for some climatic areas – for example, the temperate area – it does not mark the potential great differences that can be found within the same area. Nevertheless, this classification is still very valuable to describe in a general way the climate of a certain area.

5.1.2 Climatic regions of the studies

Adom et al. (2012) distinguished 5 regions in the US, based on a combinations of productions practices and climatic condition.

Region 1 correspond to the north-eastern states, which the most remarkable are Maine, Pennsylvania, New York. This region is characterized by a Dfb climate, that it is a cold climate with humid winter (*Winterfeucht kalte klimate*). Average temperature of the warmest month is below 22°C and at least 4 months have an average temperature above 10°C.

Region 2 corresponds to south-east states, such as Kentucky, Tennessee, North and South Carolina, Georgia, Florida, up to Louisiana. The most common climate of this region is Cfa, that is temperate with humid summer (*Sommertrocken temperierte klimate*): average temperature of the warmest month is above 22°C.

Region 3 corresponds to the states overlooking the great lakes, up to Missouri, that are characterized by a Dfa climate, that is a cold climate with humid winter. Unlike region 1, this region has an average temperature of the warmest month above 22°C.

Region 4 comprises all the great central States, from North Dakota to Idaho, from Kansas to Nevada, from Texas to Arizona. It was difficult to define a single climate that encompassed the numerous microclimates that exist in this region.

Therefore, it was decided to select the climate that was most favorable to dairy feed cultivation, that is the flat area between Kansas and Texas which flaunts a Cfa climate, a temperate climate with humid summers (S*ommerfeucht temperierte Klimate*), where the hottest month has an average monthly temperature higher than 22°C.

The Rocky Mountains area was excluded, because it is characterized by a semiarid climate (BS), which is unfavorable to dairy feed cultivation.

Region 5 includes the East Coast states: California, Oregon and Washington, which are characterized by temperate climate with dry summers (*Sommertrocken temperierte Klimate*), with at least one winter month having at least three times as much precipitations as the driest summer month, i.e., less than 30mm on average (Cs).

Ghazouani et al. (2018) conducted the study in Sousse, on the east coast of Tunisia. This area is characterized by a virtually desert climate, with an average annual temperature of 19.5°C and average annual rainfall of only 339mm (BWh).

The study by Henrik Hauggard-Nielsen et al. (2015) took place in Denmark, specifically in Flekkebjerg in the Sjaelland region. This area is characterized by a Dfb climate, that is cold and wet winter climate (Winterfeucht kalte Klimate) with average temperature of the warmest month below 22°C and at least 4 months averaging over 10°C. For this region, 9.0°C and 646mm are reported as annual averages. Another study, by Mogensen et al. (2014) calculates carbon footprint of crops in Denmark.

Gollnow et al. (2013) performed their study in Australia, but the geographical area of dairy feed production is not specified.

According to Chauhan et Rachaputi (2014) the most important agricultural production areas are located on the eastern belt, from Queensland to Victoria crossing New South Wales, which are characterized by a Cf climate, i.e., with temperate climates with humid summers (*Sommerfeucht temperierte Klimate*).

Studies by Gan et al (2011; 2012) refer to the Canadian prairies, located between the provinces of Alberta, Saskatchewan and Manitoba. This region is characterized by a Df climate, that is, a cold climate with wet winters (*Winterfeucht kalte Klimate*). Also the study by Wiens et al. (2014) refers to Manitoba region.

Bacenetti et al. (2018) refer to the Po plain area located in Norther Italy, Lombardy Region in particular, which is characterized by a temperate climate (Cf) with humid summer.

Zhang et al. (2017) carried out their study in China. They refer to the whole China, comprehending different areas all over the country: North China Plains, which are characterized by a Dwa-type climate, that is a cold climate with dry winter (*Wintertrocken kalte Klimate*). This is one of the most intensive agricultural regions in China, accounting for 23.2% of the chinese cropland area. 12.2°C and 480mm are reported as annual temperature and precipitation average, respectively (Yang & al, 2018). Other areas are: South China, lower basin of the Yangtze River, irrigated area and arid area in Northwest China, and Northeast China.

Lastly, study in India from Jat et al. (2019) refers to New Delhi region, which climate is hot semi-arid (Bsh).

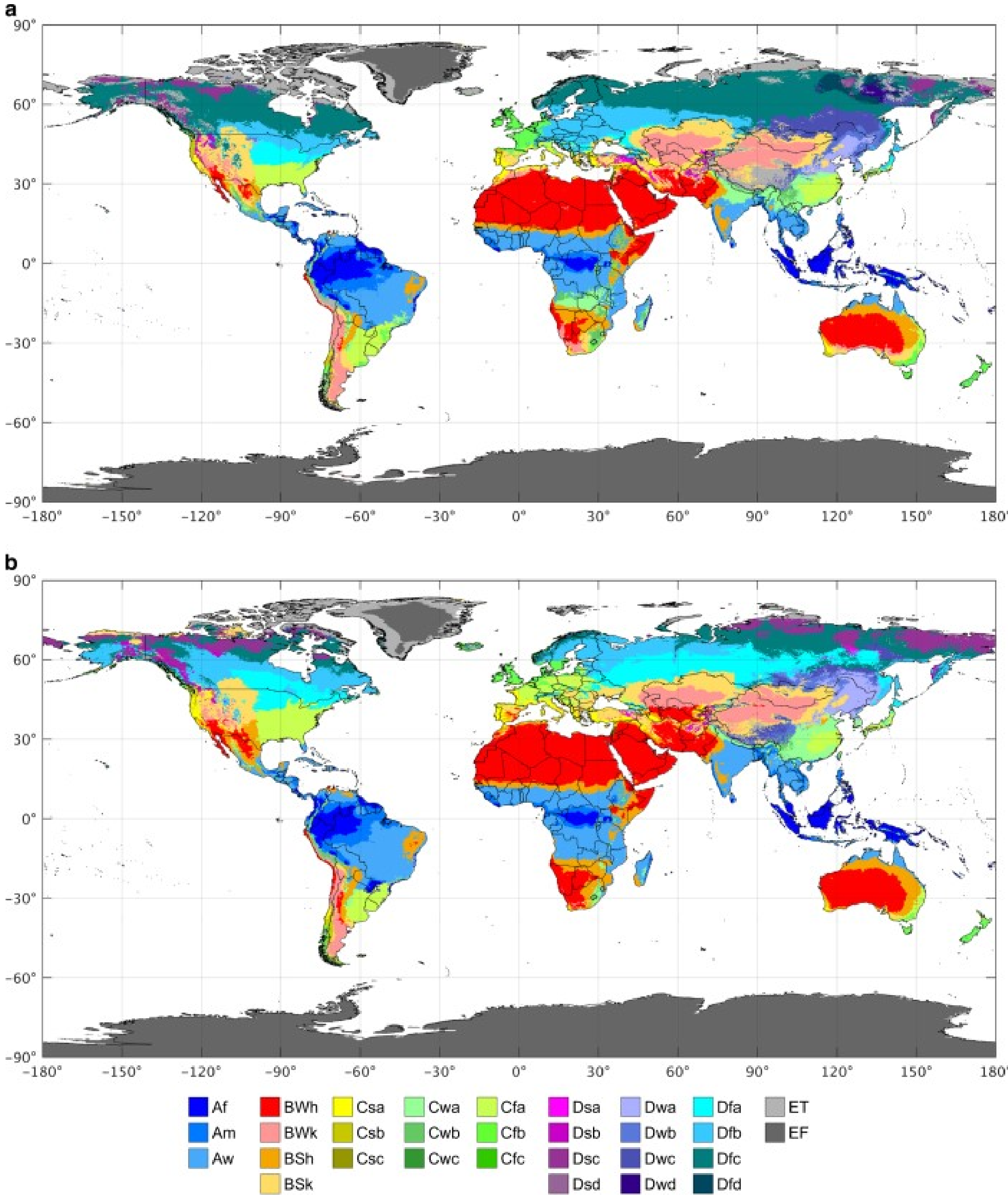


Figura 6: Kopper-Geiger classification, referred to Beck et al. (2018). a) refers to present (1980-2016) b) refers to projected future condition (2070-2100) under climate change.

5.1.3 Soil Classification

Another factor to consider in dairy feed production is the soil composition.

Soil analysis is useful to know how much a soil can already supply and what is the nutrient demand of the crops. Routine soil analysis include soil acidity (pH), lime requirement, available calcium, available magnesium, available phosphate, total nitrogen and organic matter (Weiske, 2005). Also an analysis of soil N is useful to more effectively target fertilizer and manure application on field and it can reduce over-fertilization of crops and fertilizers production, reducing GHG emissions (Weiske, 2005).

According to the Soil Taxonomy System (USDA, United States Department of Agriculture, Soil Taxonomy - A Basic System of soil classification for main and interpreting soil surveys, 1999) there are 12 types of soils (Fig.7).

Only 5 papers consider soil classification in their study: Gan et al. (2011; 2012) in Canada, Hauggard Nielsen et al. (2015) in Denmark, Jat et al. (2019) and Pandey et al. (2014) in India.

In the Canadian Prairies (Gan et al., 2011), there are 3 different types of soil: brown soil, classified as Aridic Hapleboroll, dark brown soil, classified as Typic Boroll, and black soil, classified as Typic Haplustoll. In another study of Gan et al. (2012), two localities in the region of Saskatchewan were reported: Indian Head, characterized by a Typical Haplustoll soil, and Swift Current, characterized by an Aridic Hapluboroll soil.

Hauggard-Nielsen et al. (2015) conduct a study in Flakkebjerg, Denmark. The soil of this region is classified as Alfisol (Typic Agrudalf).

The experimental site in New Delhi (India) by Jat et al. (2019) was a flat and well-drained sandy loam soil (Typic Haplustept), while in Varanasi the site was an inceptisol with sandy loam texture. Analysis of New Delhi experiment soil reveals that it had 4.63 g/kg of organic C and a pH of 7.8.

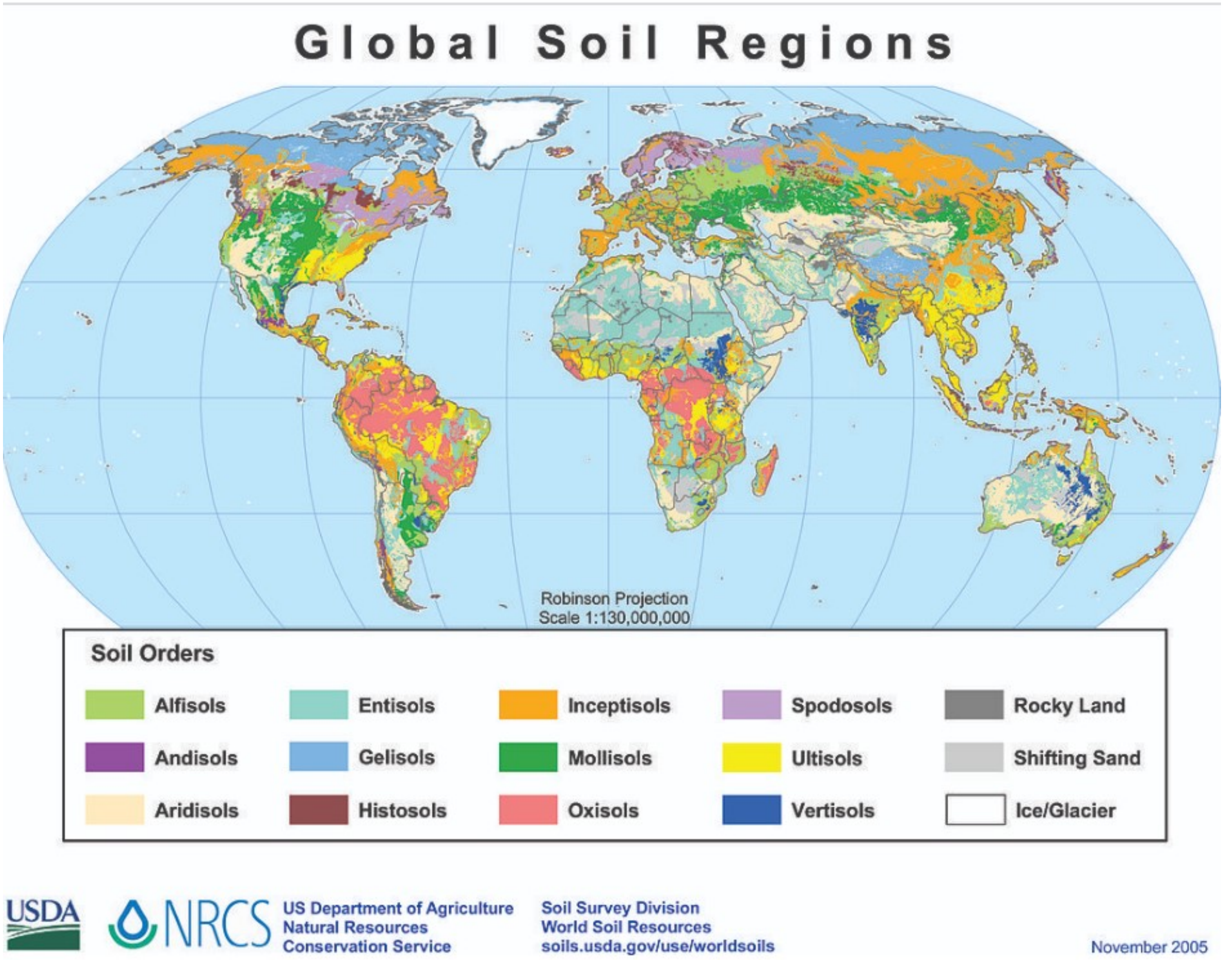


Figura 7 reffered to Natural Resources Conservation Service Soils, United States Department of Agriculture

5.2 Emission factors in crop production

In almost the totality of papers reviewed for this study Life Cycle Assessment (LCA) is used to determine the integrated assessment of environmental impacts along the life cycle of crops.

LCA is an analytical and systematic methodology that assesses the environmental footprint of a product or service, throughout its life cycle.

The most common system used is the "cradle-to-farm gate" system, which refers to the carbon impact of a product from the moment it is produced to the moment it enters the farm.

An example of system boundary is shown in the figure below. It defines the processes and input/output components that could be taken into account in a life cycle study for dairy feed crops.

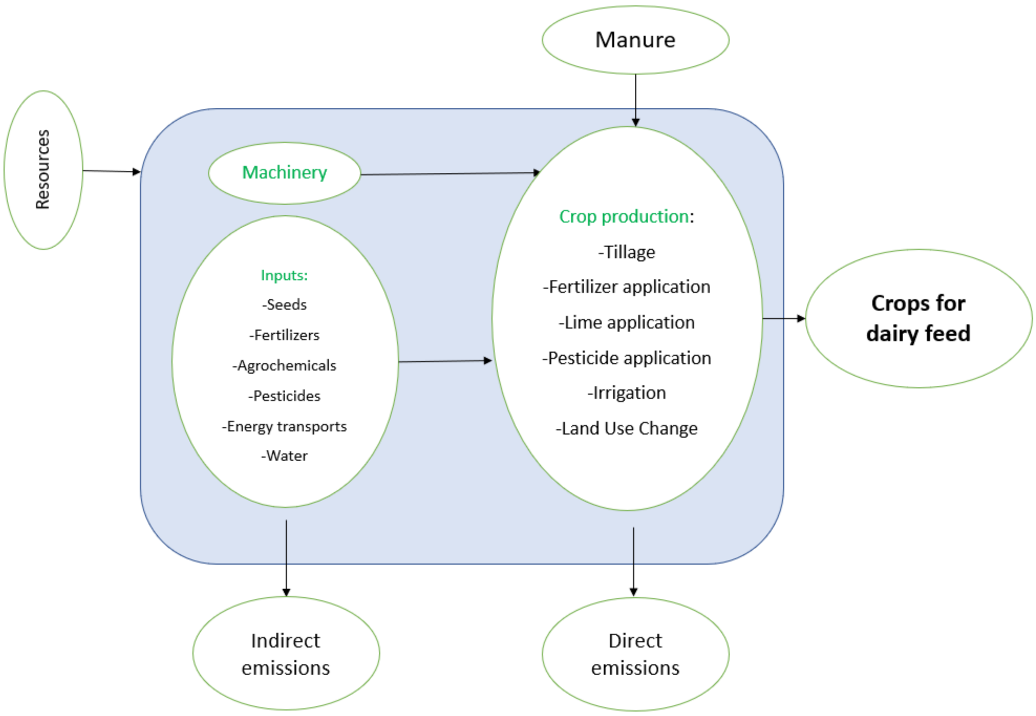


Figure8: Example of sytem boundaries for emission factors in crop production

5.2.1 Tillage

Tillage is a fundamental practice in agriculture management. It is defined as a method of working the soil either physically, chemically, mechanically or biologically to create suitable conditions for seedling germination, establishment and growth (FAO, 2017). It prepares the soil for plating or seeding by ploughing, cultivating or otherwise turning it. It also controls weeds and mixes organic matter, fertilizer and manure with the soil.

Generally, there are two types of tillage systems, conventional and conservative tillage system:

- Conventional tillage refers to use of a mouldboard or animal drawn plough to incorporate residue into the soil by extensive tillage. This system is mainly practiced in many developing regions and is carried out by manual labour using native tools or cutlass. In mechanized system, mechanical soil manipulation is done by ploughing through one or more harrowing (FAO, 2017).
- Conservation tillage system, in contrast, are primarily based on reducing soil disturbance by restricting any land preparation activities to a shallow depth and eliminating soil inversion, while conserving and managing crop residues (*ibidem*). Conservation tillage aims to leave at least 30% of the previous crop residues remaining on the soil.

Cultivation of soils through ploughing is the most energy demanding process in the production of arable crops. The diesel fuel used contributes directly to CO_2 emissions and tillage also has a major influence on soil C emissions since it is thought to be the principal agronomic activity to reduce soil organic carbon (SOC) stocks.

5.2.2 Irrigation

Irrigation makes agriculture possible in areas previously unsuitable for intensive crop production. About 20% of total arable cropland is under irrigation, producing about 40% of the global harvest (Sauer, et al., 2010), even though irrigation is a very carbon intensive practice, particularly when pumping is required. The energy required for pumping depends on the crop water requirement, total head, flow rate and system efficiency (FAO, 2017).

CO2 emissions from irrigation were calculated based on the energy needed for pumping and water application. Energy for abstraction of water is calculated by Rothausen and Conway (2011) by apply a basic theoretical physical relationship, which prescribes that the energy required to lift 1 m^3 of water up 1 m at 100% efficiency is 0.00027 kWh.

5.2.3 Fertilizers, manure and lime

Fertilizers are the main factors to produce GHG emissions. They are widely used across the world to improve soil fertility adding macro and microelements for an optimal crop development (FAO, 2017).

The most common fertilizers used in agriculture are nitrogen, potassium, phosphate and sulphur fertilizer. Nitrogen fertilizer derived for about 97% from synthetically produced ammonia via the Haber-Bosch process (FAO, 2006).

As it is previously shown, NH_3 volatilization from synthetic N fertilizer is globally responsible for 11 million tonnes N per year (FAO, 2006) and synthetic fertilizer in general (manufacturing and application) account for 13% of total agricultural emission of GHGs (FAO, 2014).

Indirect nitrous oxide emissions are calculated from the nitrogen lost by leaching and volatilization. Nitrogen lost through volatilization of ammonia was assumed to be 10% of the mineral and organic fertilizers applied (IPCC, 2006).

The remaining plant matter after harvesting such as straw and roots is a nitrogen source for nitrification and denitrification too, contributing directly and indirectly to N_20 production (Gan et al, 2011).

Manure deposited on land results in substantial ammonia volatilization too: even though wide variations in the quality of forages consumed by ruminants make N emissions from manure on pastures difficult to quantify, FAO/IFA (2001) estimate the N loss via NH_3 volatilization from animal manure to be 23% worldwide.

Considering the substantial N loss from volatilization during storage, the total ammonia volatilization from manure can be estimated at about 40% (FAO, 2006).

Agricultural lime is commonly used in the management of croplands and grasslands to decrease soil acidity. Lime is often applied in the form of crushed limestone ($CaCO_3$) or crushed dolomite ($CaMg(CO_3)_2$). Adding carbonates to soils in the form of lime or dolomite leads to CO_2 emissions as the carbonate limes dissolve and release bicarbonate ($2HCO_3$), which evolves into CO_2 and water (H_20). Direct emissions from lime application can be calculated using the Emission factor of IPCC (2006) for limestone of 0.396kg CO_2/kg limestone (FAO, 2017).

5.2.4 Pesticides

A pesticide is any substance used to kill, repel, or control certain forms of plant or animal life that are considered to be pests. Pesticides include herbicides for destroying weeds and other unwanted vegetation, insecticides for controlling a wide variety of insects, fungicides used to prevent the growth of molds and mildew, disinfectants for preventing the spread of bacteria, and compounds used to control mice and rats (www.niehs.nih.gov). Modern agriculture relies on the use of pesticides as tools for plant protection agent to maintain high yields. The two most important classes are organochlorine and organophosphorus compounds (Golfinopoulos, 2003): some organochlorine pesticides are very resistant and remain active long in the ecosystem, while organophosphorus dissipate rapidly in soils as a result of mineralization (FAO, 2006).

Pesticides are almost entirely produced from crude petroleum or natural gas products (West and Marland, 2002). Emissions from pesticides are therefore related to the energy input both from the material used as feedstock and the direct energy inputs (FAO, 2017).

In the United States the volume of herbicide used for corn and soybean amounted to 74600 tonnes, about 70% of the total herbicide used in agriculture in 2005 (FAO, 2006). However, the use of pesticides is declining in developed countries, as a result of technological improvements, the introduction of genetically modified crops and the improved toxicity of pesticides (FAO, 2006). In EU there also are directives and regulations that make EU system the most stringent in term of controlling the use of pesticides.

5.2.5 Fuel

In the livestock sector, emissions associated with energy consumption (directly or indirectly related to fossil fuel) are mostly related to feed production and fertilizer manufacturing. In particular, fossil fuel use in manufacturing fertilizer may emit about 41 million tonnes of CO_2 per year (FAO, 2006), while on-farm fossil fuel use may emit about 90 million tonnes CO_2 per year (FAO, 2006), which include machinery for crop management, harvesting, processing and transport of feed. Harvesting emissions are generated by: crop handling by the harvest machine, loading of the harvested crop into trailers or trucks, and transport by trailers or trucks in the field (FAO, 2017). Energy is also consumed on animal production site for ventilation, illumination, milking and cooling (FAO, 2019). Diesel consumption occurs in transport of fertilizers, pesticides and seeds, and major emissions occur during tillage process. Its consumption is dependent upon the size of machinery, tillage depth, frequency and type of tillage (Jaiswal & Agrawal, 2020)

Fortunately, there are some cases where feed production does not account for the biggest share of fossil energy use, because nowadays many dairy farms use electricity as their main form of energy. In the absence of estimates representative of all world regions it remains impossible to provide a reliable quantification of the global CO_2 emissions that can be attributed to farm fossil fuel used by the livestock sector. A rough indication of the fossil fuel-use related emissions can be obtained by supposing that the expected lower energy needs for feed production at lower latitudes, and the elsewhere, lower level of mechanization (FAO, 2006).

Improvement of manure management can help reducing emissions too, by a wider use of anaerobic digestion, increasing biogas production and consequently replacing fossil fuels. For this reason, green energies based on vegetal biomass are taking off: worldwide, fuel ethanol production increased from 20 billion litres in 2000 to 40 billion litres in 2005 (FAO, 2006). In 2005, in Europe, the total area used for biofuel crop production was around 1.8 million hectares (EU, 2006).

5.2.6 Land Use Change

Land use change is a highly complex process, that results from the interaction of diverse drivers which may be direct or indirect. It can involve numerous transitions, such as clearing, grazing, cultivation, abandonment and secondary forest re-growth (FAO, 2013). In this assessment, land use change is considered as the transformation of forest to arable land for feed crops.

As it is previously shown, LUC is responsible for about 9.2% of total GHG emissions from livestock supply chains and around 12.2% of global GHG emissions (Herzog, 2009).

As livestock is the world's largest user of land resources for feed production, LUC may contribute significantly to the GHG emission of animal feed: according to the product-based approach, LUC is associated with the feeds grown in the regions where deforestation takes place, whereas in the land-based approach, LUC is a factor assigned to all feeds based on the assumption that all use of land for crop production increases pressure on land use, thus causing LUC somewhere in the world (Mogensen, Kristensen, Nguyen, Trydeman Knudsen, & Hermansen, 2014).
However, very few LCA have included soil C sequestration in the overall GHG estimations, mainly due to methodological limitations. For this reason, carbon sequestration is excluded from CF calculation for feed crops in this study.

6. Experimental contribution: Formulating diets based on the carbon footprint of the ingredients

6.1 Introduction

Usually, the formulation of diets for dairy cows requires that they would be in line with the hedonistic principle according to which people try to maximize their profits and minimize their costs.

This, however, does not always coincide with the best health status of the animal, and moreover, under the influence of the economic problem, there is a risk of negatively affecting the environment. Fortunately, however, the best economy coincides with the highest efficiency of ration utilization by the cattle, which reduces excretions and thus pollution from livestock farms.

In this study, the issue that aims to be addressed is the impact that ration is having on the environment in the pre-weaning stage, that is, before the animal uses it.

The hypothesis is that inexpensive and low-impact foods at the digestive and metabolic stage may have caused an environmental impact upstream, during their production, transportation and processing processes, so that the ration itself, before it is used by the animal, may already be more or less impactful, regardless of cost.

Therefore, the purpose is to compare rations currently in use by livestock farms, in terms of economic cost and environmental cost, with their versions optimized for economic and environmental costs themselves, through the use of carbon footprint.

6.2 Materials and methods

6.2.1 Diets formulas and characteristics

For this study, 10 rations for dairy cows were analysed and compared: 5 hay-based currently used in the Parmigiano Reggiano consortium area, and 5 silage-based rations used outside the consortium. The farms are all located in northern Italy, between the regions of Emilia-Romagna, Piedmont and Lombardy.

The rations are in line with the ideal parameters for dairy cows, as described in Chapter 4.

The 5 hay-based rations have the following characteristics:

- Ration 1 = 43% hay, 29% grain meals, 28% cakes and supplements
  DMI: 25,08 kg
- Ration 2 = 60% hay, 31% grain meals, 9 % corn flakes and supplements
  DMI: 19,3 kg
- Ration 3 = 60% hay, 32% grain meals, 8% corn flakes, molasses and soy hulls
  DMI: 20,36 kg
- Ration 4 = 62% hay, 27% grain meals, 11% corn flakes, straw and supplements
  DMI: 24,91 kg
- Ration 5 = 39% hay, 26% grain meals, 35% corn and soy flakes and supplements
  DMI: 27,43 kg

The 5 silage-based rations have the following characteristics:

- Ration 1 = 71% silage, 12% grain meals, 17% protein concentrate and supplements
  DMI: 21,54 kg

- Ration 2 = 52% silage, 25% grain meals, 23% flaxseeds, hay and supplements
  DMI: 20,64 kg
- Ration 3 = 50% silage, 16% grain meals, 34% hay, seeds and supplements
  DMI: 21,8 kg
- Ration 4 = 75% silage, 19% grain meals, 6% hay and supplements
  DMI: 19,31 kg
- Ration 5 = 83% silage, 11% grain meals, 6% hay, distiller and supplements
  DMI: 22,97 kg

6.2.2 Creation of the Feed inventory

A mixed study review of papers published in Science Direct (www.sciencedirect.com; last access on 8th June 2022) ISI Web of science (www.webofknoledge.com; last access on 8th June 2022), Springer Link (www.link.springer.com; last access 8th june 2022), Taylor and Francis online (www.tandfonline.com; last access 8th June 2022) Nature (www.nature.com; last access 8th June 2022) was performed covering a time-span of 8 years (2011-2019).

Studies were selected if they reported the CF calculation of the main crops and dairy feed stuffs. Studies that examined CF calculation of milk production, without calculating also dairy feed CF, were discarded.

Studies that take account only for area unit (ha) or economic allocation, but not for mass allocation (kgCO_2eq of DM of dairy feed) for the calculation of CF were discarded.

Studies reporting CF of various cropping systems, without calculating each crop of the examined systems, were discarded too. In this study, crops were assumed to grow in monoculture due to insufficient data for determining typical crop rotation practices at a global scale.

For this reason, few papers (12) from 7 different countries fulfilled these criteria and were included in the present review.

6.2.2.1 Alfalfa

Alfalfa showed a lower carbon footprint compared to other crops, due to its lower need for inorganic fertilizer application. In fact, it has the unique ability to fix atmospheric N_2 (Russelle, et al., 2001), increases soil organic matter (Peoples, Herridge, & Ladha, 1995), and offers the possibility of differing harvest schedules, stimulating the productivity of the subsequent crop (Tabacco, Comino, & Borreani, 2018). Moreover, alfalfa is one of the most used crops for hay, especially in Italy, as it is a high-protein-content feed (Bacenetti, Lovarelli, Tedesco, Pretolani, & Ferrante, 2018).

Only few papers considered Alfalfa and only 2 (Hauggaard-Nielsen et al., 2015; Bacenetti et al., 2018) define Alfalfa cultivar as *Medicago sativa.* No taxonomy data were reported by other authors.

Adom et al. (2012) distinguished Alfalfa in hay and silage and classified the harvesting area in 5 different dairy production regions of the USA. Average Alfalfa hay CF (kgco2eq/kg DM) was 0.178 with a maximum of 0.27 (Region2) and a minimum of 0.14 (Region 3 and 4). Average Alfalfa silage CF was 0.188 with a maximum of 0.28 (Region 2) and a minimum of 0.15 (Region 3 and 4). The major contributors towards the regional footprints for both alfalfa hay and silage were identified as crop nitrogen residue, phosphate, lime, diesel fuel and electricity requirements. In all regions, these factors contributed between 80% and 90% toward the overall regional footprint. On the other side, the impacts related due to the application of potash, boron, crop protection chemicals, and use of gasoline were minimal ranging between 4% and 14%

toward the carbon footprint for both alfalfa hay and silage. Contributions to carbon (GHG) footprint due to the application of inorganic fertilizer for both alfalfa hay and silage was less than 10% in all dairy production regions, as this species doesn't require high fertilization.

Hauggaard-Nielsen et al. (2015) considered Alfalfa in a three-season field experiment in Flakkebjerg (Denmark), as a pure stand in the second season or in perennial grass-legume intercrops. Alfalfa was considered as a pure stand in order to determine the single crop CF. Considering the capacity of Alfalfa to perform BNF in this study no N fertilization was performed contributing to generate the lowest carbon footprint (0.055). However, when the SOC factor is excluded from the calculation, the final result is 0.142, in line with the other observed values.

Ghazouani et al. (2018) considered Alfalfa in a life cycle analysis of raw milk production in Sousse, Tunisia. CF resulted in this study 0.21 but individual input and output factors were not specified, so it is not possible to speculate about this result. The only possible hypothesis is that the result is strongly influenced by the severe climate of this area, characterized by high temperatures and low mean rainfall. That could influence the crop yield due to lack of water. Otherwise, the result could be considered low in relation to other results, which can be explained by the fact that most of the farmers in this region do not use fertilizers and heavy machinery for tillage (Ghazouani et al., 2018).

In Italy, a study by Bacenetti et al. (2018) compared two production practices for alfalfa: without and with irrigation. The results showed that irrigated fields produced lower GHG emissions resulting in a lower CF for alfalfa hay (0.08) compared to non-irrigated fields (0.085). This can be explained by the fact that crop yield with irrigation is increased. For both scenarios, the mechanization of harvest is the main environmental hotspot, due to fuel consumption and related combustion emissions.

6.2.2.2 Corn

Corn is one of the main crops produced for dairy feed. It has a large production all over the globe, especially in the US which is the predominant feed energy source for livestock industry (USDA, 2011).

Corn is one of the most cultivated crops also in Europe, because of the high yield and its ease to be insiled. It is a good source of ruminally fermentable carbohydrates, due to its high starch content, but is low in protein (Brito & Broderick, 2006). More than half of corn production is used as feed (FAO, 2006).

Adom et al. (2012) concluded that in the US GHG emissions for corn grain were about two times greater than for the corn silage, resulting in a higher CF for corn grain. It is explained by the fact that more inorganic fertilizer is needed for corn grain production, and it also emits more greenhouse gases by drying, an inevitable process for corn grain. Average corn grain CF for the 5 regions described in the paper is 0.39 kg Co2eq/kg DM, with a maximum of 0.44 for regions 2 and 4 and a minimum of 0.36 for region 1, while average Corn silage CF is 0.20, with a maximum of 0.26 for region 2 and a minimum of 0.16 for region 1. Inorganic fertilizers, manure, phosphates, lime, fuel, drying and N_2O emissions due to residues contributed approximately 80-90% of corn grain CF and 73-90% of corn silage CF, towards the regional CF. In some regions, like region 4, there is also a high level of natural gas contribution, due to the high energy requirements.

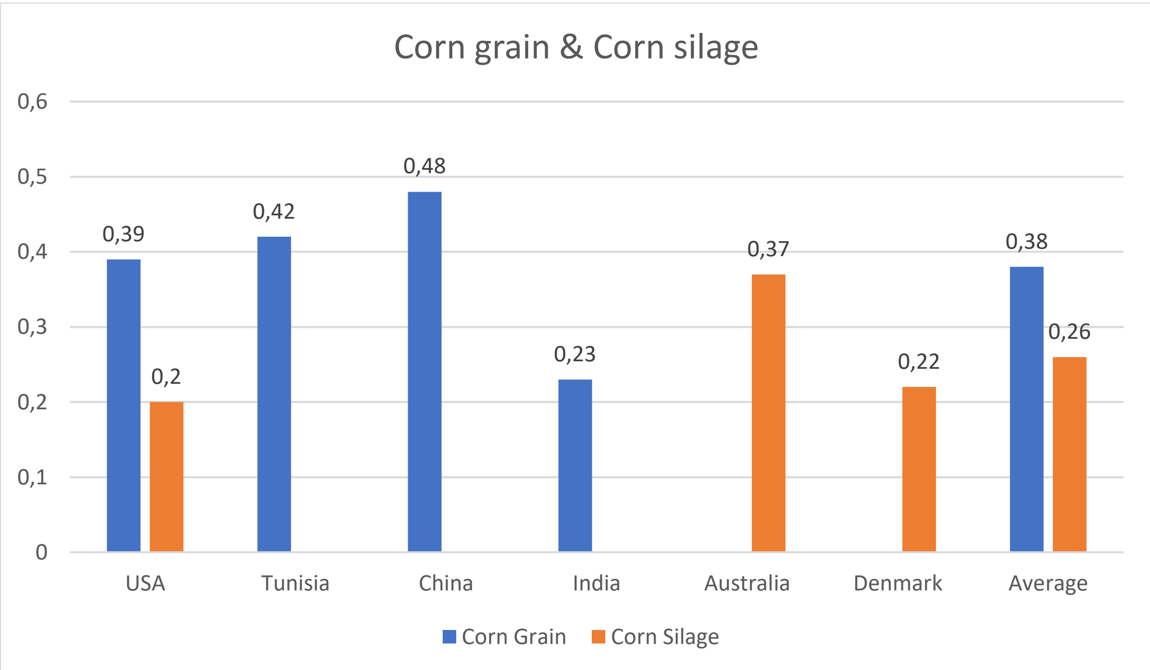
Also, Ghouzani et al. (2018) concludes a high CF for corn grain in Sousse, Tunisia, with a value of 0.42 kg CO2eq/kg DM, even though individual inputs are not specified.

Corn silage production in Australia results in a CF of 0.37 (Gallnow et al., 2014), turning out to be the highest value for corn silage. In Denmark, a study by Mogensen et al. (2014) estimate the CF of different feedstuffs for dairy cattle using life cycle assessment (LCA). Corn silage CF results in a value of 0.224. This value does not include the share of carbon loss from the soil during the cultivation process. In fact, corn is not a nitrogen- or carbon-fixing species, so the net SOC implicates an addition of +0.083 on the CF, bringing the CF value for corn silage to be 0.307. The study also includes the indirect LUC, leading to a final CF of 0.435. However, in the papers analysed for this study, the CF of crops rarely includes this type of factor as well, which is why it was decided to standardize the values by excluding them from the calculation.

In China, Zhang et al. (2017) performed a study on the carbon footprint of grain production. Corn grain turns out to have a value of 0.48: emissions came from nitrogen fertilizer (39%), fuel consumption by agricultural machinery (20%), electricity consumption for irrigation (18%) and straw burning (18%).

Jat et al. (2019) defined a CF for corn grain in India of a range between 0.21-0.24, for this reason it has been chosen an average value of 0.225 (0.23).

Table 2: Corn grain and silage CF (kgCO_2eq/kg DM)



6.2.2.3 Grass hay and Grass silage

Grass silage and grass hay are common options for dairy feed. 4 Papers take into account Grass hay or grass silage: 2 consider both, 2 consider only grass silage.

In the US grass showed a higher carbon footprint than other forage crops and nearly as high as the corn grain. This is explained by the fact that grass typically requires less maintenance and inputs, but produces lower yields compared to other crops. Also, there is higher variability in yields because of the climate influence in terms of grass composition and mass. (Adom et al., 2012)

Inorganic fertilizers were the major contributors ranging 34% to 90% toward the footprint of grasses. Lime contributions were significant in regions 1 and 3, because it reflects the acidic nature of soil in these regions. They range between 13% and 19% (Adom et al., 2012).

Average Grass silage CF was 0,33, with a maximum of 0,48 for region 2 and a minimum of 0,28 for region 4.

Average Grass hay CF was 0,32, with a maximum of 0,47 for region 2 and a minimum of 0,27 for region 4.

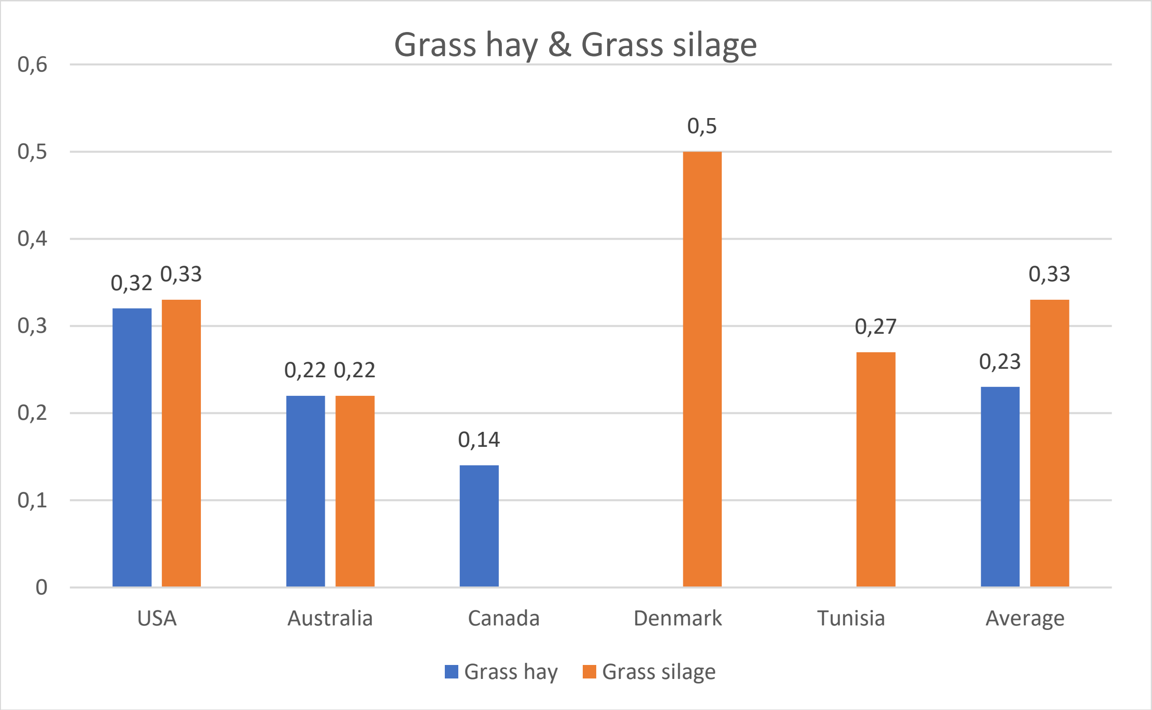
Ghouzani et al. (2018) derived a CF for grass silage of 0,27 in Tunisia, while Gollnow et al. (2014) assess a value of 0.22 for both grass silage and grass hay CF in Australia, resulting the lower result in the study for this crop.

In Denmark, Mogensen et al. (2014) estimate a CF for grass silage of 0.503, even though it turns out to be 0.671 when SOC and LUC are considered, resulting the highest value for grass silage in this study.

A study presented by Wiens et al. (2014) and carried out in Manitoba (Canada) shows that the CF of grass hay (alfalfa-grass mixture) is 0.14. Even more, if carbon sequestration is also considered, the CF of this crop turns out to be -0.21, thus able to fix more carbon in the soil, than it leaks into the atmosphere.

However, the uncertainty on the SOC data is very high (40%). The study suggests that this should be further investigated with more research. As seen for other studies, emissions from inorganic fertilizer application are found to be the majority out of the total (70 percent), followed by diesel use (18 percent) and finally fertilizer, pesticide and seed production (12 percent).

Table 3 Grass hay and Grass silage CF (kg CO_2 eq/ kg DM)



6.2.2.4 Soybean

Soybean (*Glycine max*) is the fourth most important crop in the world in terms of area harvested and production (FAO-FAOSTAT, 2018) as it is a significant protein source for humans and animals. The global soybean production increased to 336.6 million tons in 2019 from 220.8 million tons in 2005 (Zhang, et al., 2022).

Brazil is the world's leading soy producer and exporter, together with the United States. The expansion of soy in Brazil is directly and indirectly associated with the loss of forests and other natural vegetation (Escobar, et al., 2020). In fact, deforestation related to soy production in Brazil remains a major contributor to the GHG emissions. At present, this is concentrated in the so-called MATOPIBA region (consisting of the states of Maranhao, Tocantins, Piauì, and Bahia).

In the study of Escobar et al. (2020), they assess the CF of Brazilian soy for export by capturing the nationwide variation in LUC (Land Use Change) and crop management practices, domestic transport, logistics, industrial processing and international shipping across the entire export volume per year (2010-2015). Municipal CFs, between the 10th and 90th percentiles range from 0.28 to 0.75, showing a very large variability.

The largest CFs are found for municipalities across the MATOPIBA states, mainly in Maranhao and Tocantins (Cerrado biome) and Piauì. On the other hand, the lowest CFs are found in the states of Paranà, Santa Catarina, Sao Paulo and Rio Grande do Sul, where municipalities are relatively close to ports of export and large-scale deforestation occurred several decades ago. (Fig 9a)

In fact, LUC contributes most of the CF of the MATOPIBA states (72-87%) while it accounts for only 18% of the emission associated to Mato Grosso.

Domestic transport is the sub-stage that makes the second greatest contribution, after LUC, to the country-wide CF. It plays an important role in Central-Western states such as Mato Grosso (43%), Goiàs (37%), and Mato Grosso do Sul (35%), where most of the municipalities rely on road transport to export soy to international markets.

Crop production makes a substantial contribution to the CF across the MATOPIBA states where heavy doses of lime are applied to correct soil pH, as well as in the Southern states.

Piauì shows the largest CF among all the states (4.08), which is about 6 times larger than the average Brazil CF (0.68).

At the biome-level, the largest CF is quantified for the Cerrado biome (1.00) followed closely by the Amazon (0.86) (Fig.9b)

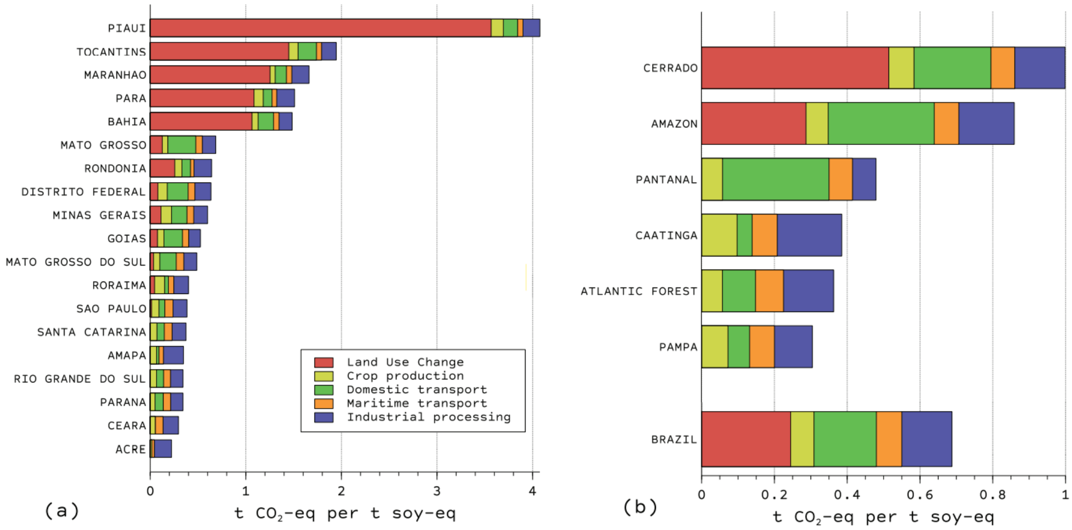


Figure 9: Carbon footprint of the soy exporting states (a); biomes and the whole country (b) in the period 2010-2015, as CO_2-eq per soy-eq (kg kg^{-1})

From an importer perspective, the five largest CFs among the twenty largest soy importers are estimated for Spain (1.23), Saudi Arabia (1.22), Japan (1.03), Portugal (0.96) and Germany (0.89). In the five largest CFs, LUC accounts for more than 60% of the emissions. Indeed, at the supra-national level, the European Union (EU) shows the largest CF (0.77), where LUC makes up more than 50% of the CF, while it accounts for 34% in North America (0.74) and 27% in China (0.67). This is because soy imported into the EU mostly originate from Northern Brazil, due to its geographical proximity to EU ports, that is the hotspot for soy-related deforestation (Cerrado biome), while in Southern Brazil deforestation occurred long time ago.

On the other hand, marine transport accounts for a relatively small share of total GHG emission genereted by the EU (5%), as compared to Eastern Asia (15%) and China (13%).

Industrial processing makes a significant contribution to the CF of all regions, especially in North America (31%), Europe (29%) and China (25%), while the share of crop production is between 9% and 16% across world regions.

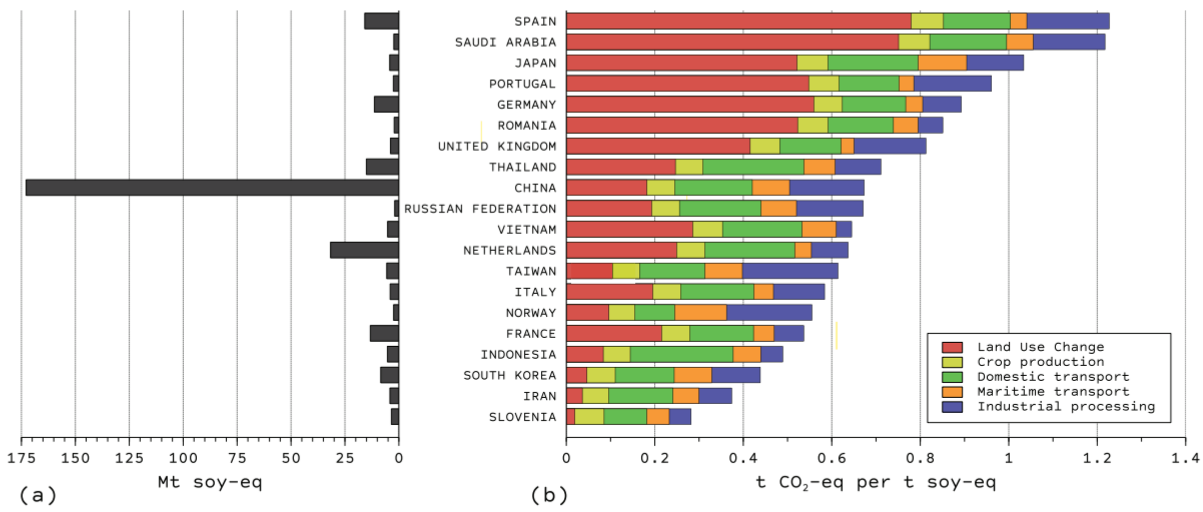


Figure 10: Total import quantities of soybean and derivates as soy-eq (a) and Carbon footprint of major soy importing countries, as CO_2-eq, per soy-eq

United States are also a soybean producer, as well as importers.

Study from Adom et al. (2012) shows different CF for soybean cultivation across the 5 regions of the United States: the highest value belongs to Region 2 (0.52), while the lowest belongs to Region 3 (0.33), generating an average CF of 0.39 for the whole country.

Since Soybean is a nitrogen-fixing crop, it doesn't need high inorganic nitrogen fertilizer application. The main contributors (70-86%) of the overall GHG emissions are: lime application, fuel and N_20 emissions from soybean residues.

A significant role is attributed to lime application, since in Region 2 and 3 the acidic nature of soils required more lime to increase soil pH for plant growth.

Emissions of N_20 from crop residues were large compared to N_20 released from the application of N fertilizers.

6.2.2.5 Wheat

Wheat has one of the highest CF values for dairy feed crops, largely due to its need of high rates of application of inorganic nitrogen fertilizer.

In fact, in Adom et al. study, Winter Wheat has an average CF of 0.43, ranging between a maximum of 0.51 of Region 3 and a minimum of 0.38 of Region 1.

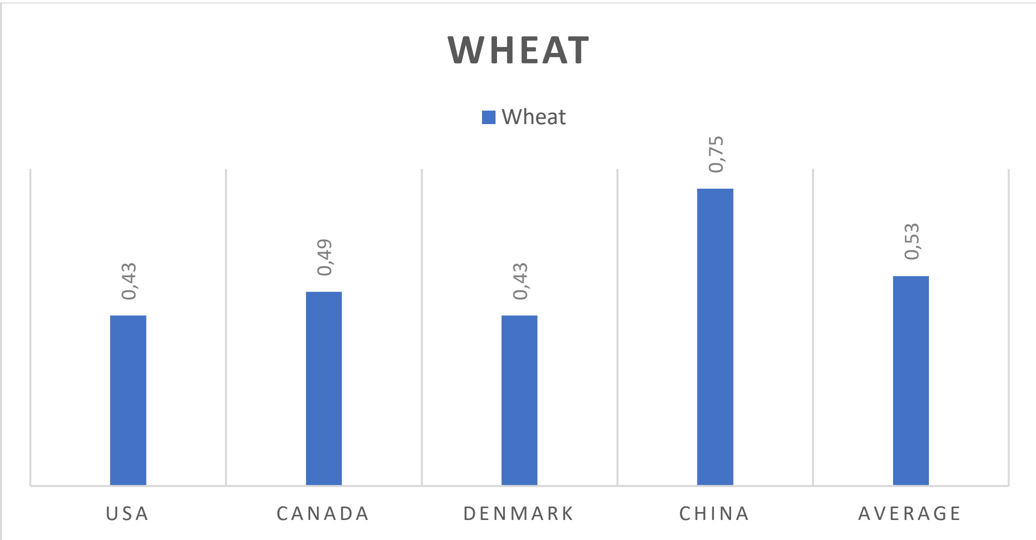
Inorganic nitrogen and phosphate fertilizers, diesel, and the impact of N_20 releases contributed 93-95% of the overall GHG emissions in each region. About 65% of inorganic N fertilizer GHGs was from field application, while 35% was due to fertilizer manufacture.

In China, Zhang et al. (2017) a carbon footprint for Wheat of 0.76. It is an average value through the different regions of the study. Emissions resulted to be 9119kg C eq/ha, of which 37% came from electricity consumption for irrigation, 28% from nitrogen fertilizers, 25% from fuel consumption by agricultural machinery and 6% from straw burning.

In the study of Mogensen et al. (2014), wheat grain CF results 0.43 in Demark. Wheat was assumed as grown without manure input and with no straw removed to have a C sequestration close to 0gC/ha/year. However, when carbon sequestration is considered, the CF rises to 0.52, and when LUC is also considered, CF results 0.74.

Gan et al. (2011) defined CF for various crops in semiarid areas of Canada. They assessed emissions from a three-site experiment, characterized by three types of soil: Brown soil, Dark Brown soil and Black soil. Spring Wheat CF harvested in Black soil results 0.56, higher than in Dark Brown (0.53) and Brown soil (0.39). This is because of the greater crop yield but the efficiency is lower. The average CF along the three sites is 0.49. Major contributors to the emissions are production, transportation, storage and application of synthetic N fertilizers, and crop residue decomposition. Production and application of N fertilizers account for about 57-65% of the total emissions, and crop residue decomposition accounts for a further 16-30%. The remaining 13-18% of the total emissions are associated with the production of phosphorus fertilizers, herbicides, fungicides, as well as miscellaneous field operations.

Table 4: Wheat CF (kgCO_2eq /kg DM)



6.2.3 Feed Inventory

The carbon footprints of the feeds used in the rations analysed in the study are shown in the table 5.

Since it was not possible to derive all the individual CFs of the feeds, especially considering the geographical reference area of the study (northern Italy), some assumptions and approximations were made regarding this parameter.

Concerning crops (category 1), the only specific CF is that of alfalfa hay (0.08), calculated in the study by Bacenetti et al. (2018), which refers to its production in the Po valley area.

On the other hand, for almost all crops, an average value among those calculated in various regions of the world was used as CF (see previous section). Some CFs, such as the Ryegrass and Barley silage ones, are specific from studies by Haggard-Nielsen et al. (2011) and Mogensen et al. (2014) in Denmark, respectively.

Ryegrass in particular was obtained by averaging CFs under high or low soil fertilization.

Some by-products (soy hulls, wheat straw), seeds (flax, cotton, sunflower) or other feeds (molasses, fat, beet pulp) are reported in category 2, while mineral ingredients and other feed stuffs, used within rations, are reported in category 3.

Table 5 feed inventory of the feeds carbon footprint used in the rations

Feed input	Emission factors (kg CO_2eq/kg DM) CF	Reference
Category 1 (Crops)		
Corn silage	0.26	Adom et al. (2012), Gollnow et al. (2013), Mogensen et al. (2014)
Corn grain	0.38	Adom et al. (2012), Ghouzani et al. (2018), Zhang et al. (2017), Jat et al. (2019)
Alfalfa hay (Ita)	0.08	Bacenetti et al. (2018)
Alfalfa silage	0.18	Adom et al. (2012)
Grass hay	0.23	Adom et al. (2012), Gollnow et al. (2013), Wiens et al. (2014)
Grass silage	0.33	Adom et al. (2012),Ghouzani et al. (2018) Gollnow et al. (2013), Mogensen et al. (2014)
Ryegrass (Den)	0.25	Hauggard-Nielsen et al. (2011)
Wheat grain	0.53	Adom et al. (2012), Gan et al. (2011), Mogensen et al. (2014), Zheng et al. (2017)
Soy meal (US)	0.54	Adom et al. (2012)
Oats	0.85	Adom et al. (2012)
Barley grain	0.35	Gan et al. (2012), Mogensen et al. (2014)
Barley silage (Den)	0.29	Mogensen et al. (2014)
Clover mix (Aus)	0.22	Christie et al. (2008)
Category 2		
Soy hulls (US)	0.5	Thoma et al. (2010)
Fat (tallow)	0.66	Adom et al. (2012)
Molasses (SE)	0.14	Flysjo (2008)
Winter wheat straw (DE)	0.17	Gollnow et al. (2014)
Cotton seeds (Aus)	0.64	Gollnow et al. (2014)
Flax seeds (Can)	0.62	Gan et al. (2011)
Sunflower seeds (Pt)	0.87	Carboncloud.com
DDGS	2.3	Adom et al. (2012)
Beet pulp (NL)	0.82	van Middelaar (2014)
Category 3		
Gypsum	0.002	Adom et al. (2012)
Lime	0.75	Adom et al. (2012)
Limestone	0.013	Adom et al. (2012)
Sodium Chloride	0.18	Adom et al. (2012)
Soda powder	0.44	Adom et al. (2012)
Supplements	1.07	Adom et al. (2012)
Propylen Glycol	4.14	winnipeg.ca

6.2.4 Assumptions and approximations

For some of the processed products, such as grain meals, cakes, and mash, the CF of the grains of origin were used because it was not possible to obtain these values from the literature and these values are not inclusive of the CF of the processing side as well. This, of course, represent a limitation in the present study.

For Corn Flakes, on the other hand, the environmental impact of steam flaking was calculated: given the assumption that the equipment consumes 26.3 kL of natural gas and 17.5kwh of electricity to process 1000kg of corn DM (Cole, et al., 2020) and that the C footprint of electrical generation was assumed to be 0.823 kg CO_2eq/kWh (Adom et al. 2012) the environmental impact to process 1 kg of corn grain DM turns out to be 0.07 kg CO_2 eq / kg DM .

Corn Flakes CF = Corn grain CF (0.38) + Steam Flaking CF (0.07) = 0.45

The assumptions made for other feed CFs are listed below (kgCO_2/kgDM):

- Ryegrass silage: 0.26 from Corn silage CF
- Protein concentrate: 0.87 from Sunflower seeds CF
- Corn mash: 0.26 from Corn silage CF
- Flax Cake: 0.53 from Soybean CF imported in Italy from Brasil (0.58), from which 0.05 of sea freight emissions is subtracted
- Corn meal: 0.38 from Corn Grain CF
- Barley meal: 0.35 from Barley Grain CF
- Soy cake: 0.54 from Soy meal
- Mineral and Vitamin supplement: 1.07 from Supplement
- Polyphyte hay: 0.23 from Grass hay
- Wheat silage: 0.33 from Grass silage
- Wrapped alfalfa: 0.18 from alfalfa silage
- Polyphyte silage: 0.33 from Grass silage

6.2.5 Feeds prices allocation

Current prices (August-September 2022) of individual feeds were obtained through the Bologna Commodity Exchange database, or through specialized operators in the industry when not available in the database.

In table 5 are reported the diet ingredients with their unit prices (€/kg), DM content (%) and unit CF ($kgCO_2/kgDM$). All values are approximated to 2 decimal places.

Ingredients	Unit price (€/kg)	DM	CF (%DM)
Corn meal 64%	0,38	85%	0,32
Flax cake 32%	0,58	90,90%	0,48
Sodium Carbonate	0,15	95,60%	0,42
Min+Vit1	2,20	96,59%	1,03
Polhyphyte hay 49.13	0,28	88,67%	0,20
Propylenic glycol	2,85	97%	4,02
Alfalfa hay 44NDF	0,32	91,30%	0,07
Alfalfa silage	0,17	46,82%	0,08
Alfalfa hay 49NDF	0,33	88,39%	0,07
Barley meal 52%	0,35	89,27%	0,31
Corn silage 32ss 33a	0,05	32%	0,08
Wheat silage	0,11	31,40%	0,10
Ryegrass hay	0,24	90,02%	0,21
Soy meal.44%	0,57	88,77%	0,48
Protein concentrate	0,37	90,07%	0,78
Cottonseeds	0,50	91,52%	0,59
Hydrogenated Fat	2,30	99%	0,65
Sodium bicarbonate	0,36	95,60%	0,42
Ryegrass silage	0,08	45%	0,15
Wrapped alfalfa	0,18	50%	0,09
Corn silage 32ss 25a	0,05	32%	0,08
Flaxseeds	1,20	92,15%	0,57
Alfalfa hay 46NDF	0,33	88,26%	0,07
Polhyphyte hay 58.10	0,27	88,98%	0,21
Polhyphyte hay 52.11	0,27	88,98%	0,21
Polhyphyte silage	0,11	33,69%	0,11
Barley meal 58.10	0,42	88,52%	0,31
Corn meal 73% starch	0,38	87,54%	0,33
Corn flakes	0,27	87,65%	0,39
Sodium chloride	0,13	99,85%	0,18
Whole corn mash	0,12	58,33%	0,22
Soymeal 47%	0,58	90,00%	0,49
Molasses	0,33	76%	0,11
DDGS	0,40	91,05%	2,09
Alfalfa hay 58NDF	0,16	89,14%	0,07
Wheat straw	0,11	86,20%	0,15
Beet pulp	0,39	91,45%	0,75
Soy hulls	0,34	90,20%	0,45
Mix soybean hulls-sunflower	0,35	88,00%	0,30
Soybean flaked	0,71	90%	0,64
Glycerol	1,70	97,30%	1,04
Wheat bran	0,15	87,31%	0,15
Sunflower seeds meal	0,37	91,08%	0,79
Calcium carbonate	0,05	99,20%	0,01
Soy cake	0,60	90,90%	0,49

Table 5: Ingredients list with their economic and environmental costs

6.2.6 Optimization of the diets at the lower cost and at the lower environmental impact

6.2.6.1. Software

The software used for diet optimization is the dynamic rationing software NDS (Nutritional Dynamic System), which is based on the CNCPS v6.5/v6.55 model, developed by RU.M.&.N. SRL. (Reggio Emilia, Italy), in collaboration with the Cornell University, Department of Animal Science. The version used in the study is the 3.9.10.01.

6.2.6.2. Optimization of the diets

The optimization process consisted of a cycle in which, starting from the ration currently in use on high-production farms in northern Italy, the following steps were taken:

a) Input costs;
b) Diet optimization for feed costs;
c) Environmental impact assessment at the minimum diet cost;
d) Inputing of the ingredient's carbon footprint;
e) Optimization for environmental impact (based on the carbon footprint inputs);
f) Evaluation of ration costs after the optimization for environmental impact.

Limits on ingredient changes were set at 10% of the amount currently in use.

6.2.7 Statistical Analysis

The statistical analysis was conducted using the software IBM SPSS V.28 (IBM Corp. Released 2020. IBM SPSS 240 Statistic for Windows, Version 28.0. Armonk, NY: IBM Corp).

A first analysis was conducted within diet typology to compare the economic and environmental cost of the actual diet and the diets optimized for the lower cost and the lower environmental impact.

A second analysis was performed including the whole data set using a mixed model where the diet typology and the method of optimization were the fixed factors and the individual farms nested within the diet typology were employed as random factor.

6.3 Results and Discussion

The comparison between the different methods of diet optimization divided by diet typology is reported in table 6 and 7. It is clear how in general the optimization for the nutrient supply is more expensive in terms of economic cost and environmental impact in both the areas considered. The difference between the different optimization methods is however not significant because of the limited number of cases considered (n=5). The difference between the mean economic costs can be considered relevant from a practical point of view especially if extended on a 100-cow herd basis. For instance, concerning the silage-based diet, the economic difference between the actual diet and the sustainable optimized diet is 0.61 euros which became 61 euros/ration and 22,265 euros on a yearly basis. From an environmental point of view the difference between the two diets is again 0.61 kg CO_2 that on a 100 animals' herd is equal to more than 22 tons CO_2 per year. When it comes to the hay-based diet, the economic difference between the actual diet and the sustainable optimized diet is 0.33 euros, which became 33 euros/ration and 12,045 euros on a yearly basis, while the environmental impact between the two diets amounts to 0.60 kg CO_2, that on a 100-cows herd is equal to more than 22 tons CO_2 per year.

Table 6: Silage-based diet evaluations

	Actual diet	Economic diet	Sustainable diet	Significance
Economical evaluation (€)	8.19±1.04	7.74±1.10	7.58±1.01	ns
Environmental evaluation (kgCO_2eq/cow)	9.61±1.46	9.12±1.36	9.00±1.47	ns

Table 7: Hay-based diets evaluations

	Actual Diet	Economic diet	Sustainable diet	Significance
Economical evaluation (Euro)	10,56 ±3,18	10,21±2,82	10,23±2,88	ns
Environmental evaluation (kgCO_2/cow)	7,4±2,32	7,1±1,95	6,8±2,11	ns

A further statistical analysis was conducted to highlight the effect of the diet typology and the optimization principle across the whole dataset. The results are reported in Table 8 and show how the hay-based diets are more expensive from an economical point of view and exert a lower environmental impact in comparison to the silage-based ones. These differences show a trend for a statistical significance ($P < 0,1$). Concerning the optimization method, the differences were in any case significant with higher values for the diets optimized for nutrient supply when the economic cost is considered ($P < 0,001$), and a gradual decrease from the diet optimized for nutrient supply to the ones optimized for the environmental impact when the optimization method is of concern. From these results it appears that the optimization from both an economical and environmental perspective are in practice equivalent in terms of final cost of the ration and this is probably related to the direct and linear relationship that can be found between the economic cost and environmental impact (CF) as represented in the Figure 10 which is derived from the data reported in the table 8. For the same reason the rations' environmental cost is decreasing moving from the more nutrient diet to the most ecological ones.

Table 8: Comparison between diet typology and type optimization

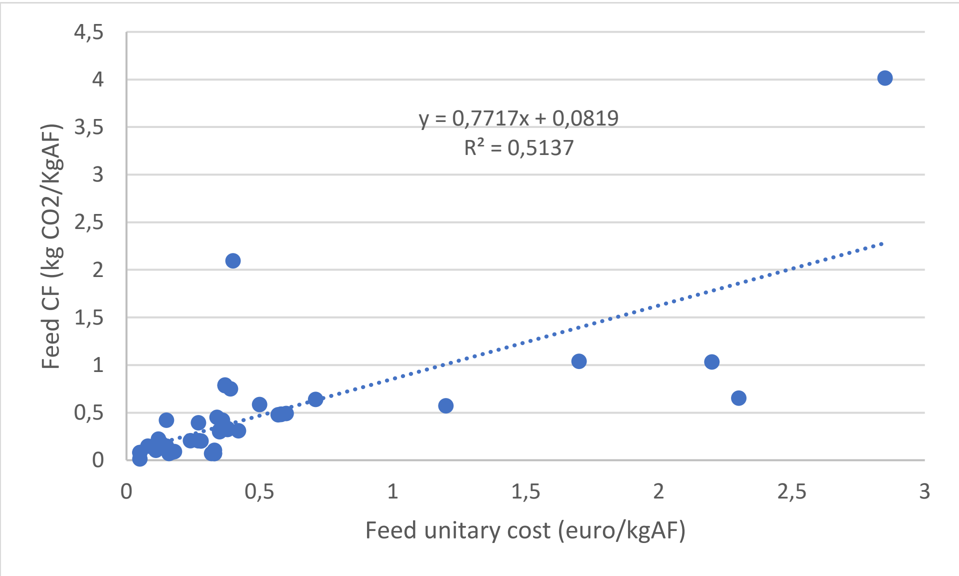
	Diet		Optimization (Opt)				P-value		
	Silage	Hay	Nutr S	Econ C	Env C	SEM	Diet	Opt	Diet*Opt
Economic evaluation (€)	7,83	10,33	9,37b	8,97a	8,91a	0,44	0,074	<0,001	0,294
Environmental evaluation (kgCO2)	9,24	7,11	8,50c	8,11b	7,91a	0,36	0,063	<0,001	0,438

Nutr S = Nutrient Supply

Econ C = Economic Costs

Env C = Environmental Costs

Figure 10: Relationship between economic and substainable costs



6.4 Conclusions

In conclusion our results show that the optimization of the diet for the nutrient supply is the most expensive in terms of economy and environmental impact, while in general the optimization for the environmental sustainability is strongly related also with the reduction of the cost of the diet, but in general lead to a lower economic cost together with a lower carbon footprint. The hay-based diets tested resulted more expensive from an economical point of view but more environmentally friendly.

Despite the low number of diets studied and simulation performed these results are for sure encouraging and establish a strong relationship between the economic and the environmental sustainability in dairy cattle feeding.

Possible future studies should focus on refining the calculation of the carbon footprint of crops in order to obtain more accurate results in calculating the environmental cost of rations for dairy cows. In addition, many approximations have been made regarding the calculation of carbon footprint during feed processing, as there is insufficient data in the literature. Therefore, studies could be carried out in this direction.

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