# Politecnico di Torino

Department of Environmental and Land Engineering

Master Thesis

# *Water footprint of the agri-food product chain in the province of Cuneo, Italy*


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# Abstract

Water, being both a fundamental and limited-global resource, requires a specific estimation of its demand because of its direct dependance on population growth and dietary shift. The relationship between water availability and climate change relates to decreased water availability in vast geographical areas, including Western Europe. Thus, a quantification of its flows in all the flows in all fields is imperative. In Italy, Cuneo, a province in the region of Piemonte has a significant impact on both rural and industrial lives, striving to include sustainability in the agri-food industry. The aim of the present thesis is therefore to quantify the water that is used to supply the agri-food product chain in Cuneo.

The present project assessed water use needed for three animal species (i.e., cows, swines, poultry) and their respective products (milk, meat, eggs), estimating quantities for single heads and whole herd in the province. Estimates derived from thorough examinations of literature studies on a global and then local scales. The latter was obtained through regional statistical reports. Finally, estimates were compared to previous global-level assessments.

The results indicated that the primary impact of water sources and demands is deeply connected to the nutritional requirements of the three species, particularly in fodder production, which accounted for 90% of total water usage. Previous estimates aligned with the descriptive analysis presented with water quantities required per animal across species highlighting an association between animal size and water consumption. The water volumes required to breed a single bovine, normalized in $m^3$ per ton was almost two times larger than for poultries and doubled the swine requirement. Different results were observed on a herd level. Despite the poultry population in 2023 being up to twenty-fold higher than the bovines' one and the swines' one being of comparable size, water demand for bovines remained significantly higher, with an estimated requirement of approximately 150 $Mm^3$, compared to just 10 $Mm^3$ for poultry and 79 $Mm^3$ for swine. Moreover, the water estimated for milk production and its derivatives had less impact than for the meat production. Water required for slaughtered bovines resulted similar to the total water used for final production of milk and its derivatives (i.e. curd cheese, processed cheese).

The absence of current regulations on water waste in small community farms significantly impacts local water consumption at the provincial level. Similarly, the lack of guidelines on the daily nourishment of feedstock remains one of the most critical challenges for local infrastructure, highlighting the need for future interventions.

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# 1. Introduction

## 1.1 Water Access and Scarcity – A multifaceted issue

Water is a crucial good for humankind and the entire climate system. Unequivocally, the presence of water has been indispensable for life, thereby being instrumental for the first civilizations. Watercourses were necessary for the foundation of early societies, offering protection and improving survival. Many philosophies were thus acknowledging water as a holy good. The water present on Earth is surely an inviolable but limited good. Even though it has always been perceived as a fundamental resource, it was only in 2010 that the United Nations recognized it as essential, setting the necessary access to a daily quantity between 50 and 100 L per person both for personal and domestic use. (UN, 2010). [1]

Water demand specifically employed for food consumption exponentially increased mainly due to two factors: population growth and dietary shift. Population growth is not a new phenomenon, dating back at least two centuries, with technological advances introduced by the Industrial Revolutions considerably reducing average mortality rates. Specifically, improvements in healthcare infrastructures drastically reduced mortality, especially in economically privileged countries. This trend has progressed quite consistently, with the UN predicting a global population of 10.3 billion by 2080 [2]. Such unprecedented population growth, however, adhered to an uneven distribution, leading to more than half of the global population living in underprivileged economic areas, with quite limited water access – a situation worsened by the challenges linked to the climate emergency. Among the others, Central Africa areas, such as Nigeria or Rwanda, experience considerably elevated birth rates, estimated to double natality within the next 30 years. Notwithstanding, these population trends are clearly inconsistent with the food availability of the countries, which is especially affected by low availability of safe and drinkable water employable to produce food [3]. It is forecasted that more than 40% of the world population will live in regions affected by water scarcity within the next 10 years [4]. Critically, the structural issue represented by water scarcity does not have to be confused with drought, whether agronomic, hydrological or environmental. [5] Drought consists of a temporary reduction in water availability due to precipitation deficits or decreased groundwater. Water scarcity, on the other hand, occurring when the consumption of finite fresh water resources surpasses their sustainable renewable rate, necessitates long-term water and land management strategies, such as adoption of efficient irrigation systems and macro and micro scale policies aimed at the mitigation of such stress [6]. As of 2023, 750 million people faced water scarcity and more than 8% of the world population had no sanitation water at their health care facilities, as reported by the Water Sanitation and Hygiene (WASH) health monitoring program developed by the World Health Organisation (WHO) and United Nations International Children's Emergency Fund (UNICEF) [7]. These figures, considerably higher than those collected in the mid-60s, underwent a 20% increase not only because of the scarcity of some products, but also due to dietary changes and economic availability. [8]

The socioeconomic issue of uneven water distribution posits the need to better understand how to improve management and equality of water distribution to ensure current and future population needs are met. Among the existing possibilities, reducing water waste is a priority, with appropriate assessments of water use and misuse being imperative. To this respect, the term “virtual water” has been coined, referring to the quantity of fresh water that is consumed or polluted at any stage of the global chain production, collectively encompassing the production, transportation, consumption and stocking of a good, hence representing a relevant index when assessing water depletion across countries [9]. Critically, one should not be deceived by the terminology, as virtual water refers to an actual amount of water, hence allowing for quantitative comparisons between nutritional requirements within the value chain. Thus, the right to an appropriate water access is not only linked to healthcare but also entails the volumes of virtual water, used to guarantee adequate food and additional uses, and adapted to satisfy personal and domestic needs.

The relationship between climate change and water availability has recently been the focus of previous analyses. Previous studies [10] highlighted how the most populated latitudes are those in which water is at its higher scarcity levels. In these regions, agricultural water use is more dominant than in other parts of the globe. ***Figure 1***, based on the Falkenmark indicator (i.e., values below $170^3 cap/year$ indicating water shortage), pinpoints how future projections indicate a considerable shortage of water availability, especially in Southwest Europe [11]. Notably, climate change is already affecting this area, with significant variations in maximum and minimum temperatures, along with high variability of precipitation. Extreme indices have an enormous effect on these regions, primarily related to prolonged periods of drought followed by extreme rainfall, resulting in a depletion of arable land and flood-associated damage. Lastly, soil damage linked to technologies used to improve the arability of the land, such as fertilizers and pesticides, are affecting water quality in the long run, with the consequent need for chemical restoration. This conditioned a change in research trends exclusively focusing on scarcity towards the evaluation of effective water management strategies [12].

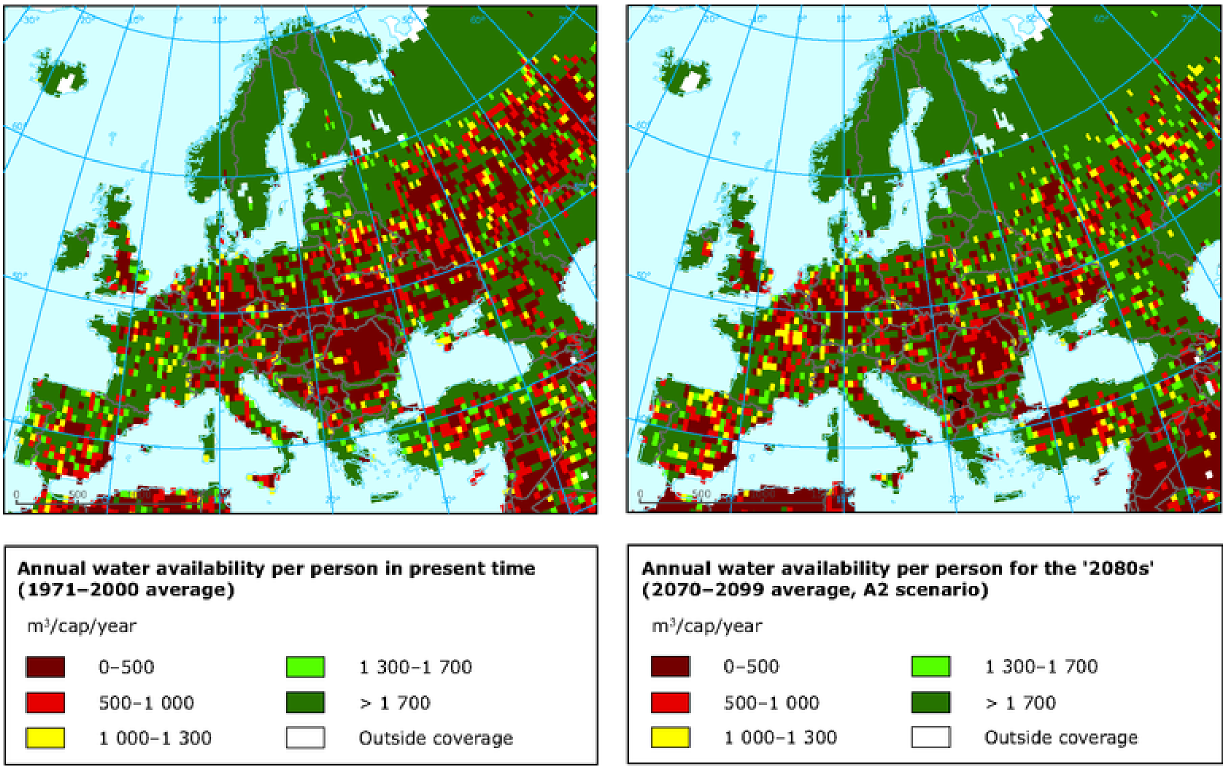



***Figure 1****. Present and projected annual water availability per person in Europe.* Water availability in the future (right) is predicted to significantly decrease as indicated by an increase in the low-quantity regions (red) and a decrease in high-quantity ones (green). The most affected area appears in the South West. (Figure from [11])

The water availability-use discrepancy across the globe has been central to debates and analyses from previous years concerning water scarcity and water security. The analysis of this mismatch relies on the average daily food intake needed across countries. [13] Reports from FAO estimated a value of 2800 kcal per day for the entire population. However, while reports and statistics estimated an individual daily intake between 2400 and 3400 kcal in the EU, daily food intake in developing countries is at least 500 kcal lower [13]. Within this context, another crucial aspect is the incidence of malnourishment, tightly linked to food availability. Data provided by food balance sheets, based on the ratio between production and trade of food commodities, are the final estimation to consider when assessing nutritional habits across countries, especially when estimating the water demand related to them. Recently, water demand for the agricultural sector has been accounting for almost 70% of total annual abstracted water from hydro sources. Following this regime it has been declared that by 2025, almost 1800 million people will probably live under conditions of absolute water scarcity [14]. Despite concerns over water scarcity, a major paradox exists in the global food system. According to recent reports, approximately 2 billion tons of food are wasted annually due to inefficiencies in post-harvest processes and excessively high consumer/market standards. This surpasses the total food production in irrigated agriculture, underscoring the need not only for improved water use efficiency but also for reducing food waste as a critical strategy for global food security and resource conservation [15].

## *1.2 Towards a systematic evaluation of water use – the water footprint*

The indicator that is used to compare the relative availability of water and the effective usage withing a particular sector is the Water Footprint (WF), used to quantify both direct and indirect consumption, in relation to the consumer and the producer [16]. Developed by Hoekstra in 2002 [17], the WF complements the ecological and carbon footprints and underscores the significance of human consumption and global perspectives in achieving effective water governance. It has thus emerged as a crucial indicator for monitoring human impact on freshwater resources. With respect to the agricultural and livestock frames, WF assessment is one of the main methods used for the quantification of the amount of water consumed or necessary to eliminate the pollutant produced during the entire cycle. The focus of this study was represented by water characterization based on its source and purpose. Specifically, green water was related to rainwater resources, while blue water referred to water consumption of water coming from surface and groundwater sources, such as rivers or ponds. Water used for assimilating the load of pollutant during the production chain is referred to as grey water. The latter is often calculated independently because it can be mentioned as a different type of water needed when comparing water uses, though being always included in the final calculation [17].

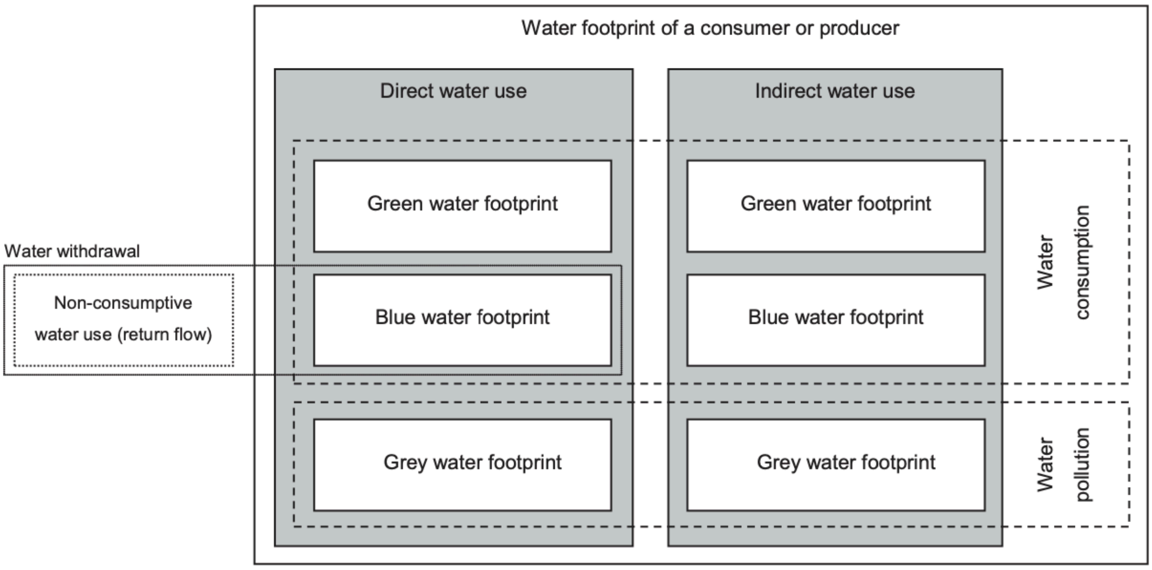



***Figure 2***. *Representation of water footprint components for consumers and/or producers.* Water footprints pertaining to different sources are classified in terms of consumption (green, blue) and pollution (grey) for both direct and indirect water use. (Figure from [17])

## *1.3 European Legislation & the Italian Scenario*

During the last decade, many international and local authorities started to consider water availability and its relative scarcity, ultimately aiming at the proper administration and usage of this precious constituent. Within this framework, the Target 12.3 of the Sustainable Development Goals (SDGs) [18], calling for the *per capita* global reduction of food waste by 2030, is one of the first challenges developed by the European Commission to ensure a sustainable action against climate change. Similarly, FAO's report on the State of Food and Agriculture (2019) was fully dedicated to the issue of food loss and waste, further underpinning the importance of addressing the issue. In the water management sector, the Water Framework Directive [19] has been the first official guideline to provide a legal framework based on the regulation of water management inside the European territory. Not only did it provide objectives based on quantity of underground water, but also in terms of quality of surface water, imposing standards to attain the final achievement as per the Environmental Quality Standard Directives (EQSD).

In Italy, the trends are in line with the European context. According to the Italian National Statistics Institute (ISTAT) (2022), the volume of water withdrawn for drinking use amounted to 9.14 billion $m^3$, an amount used to ensure not only daily water uses of the population but also those of small businesses, commercial services, and requests of public bodies and hospitals. Within the Italian area, the agricultural sector is the primary responsible for water demand. This was firstly emphasized by Massarutto (1999) [20], discussing the role of underground water within the territory and the "intermittency" of water river flows, highly dependent on the utilization of water resources for irrigation. This can help disentangle why almost 2/3 of water resources are used for agricultural purposes in Italy. During the last decades, however, due to new irrigation technologies and mainly to water scarcity, this value decreased, though still representing a considerable threat. [21]. When considering the pollution of the water table caused by intensive farming, the issue is particularly emphasized because of the integrity of drinking water supply systems that are the main source for most of the country.[22]

To quantify the described trends, several lines of evidence estimated WF in different periods and countries, considering variables such as climate, land use, and social habits. In Europe, Italy is among the countries with the largest WF, being 25% higher than the average, with a value of 1836 $m^3$ capita/year, and higher than most neighboring countries, including France and Germany. Green water has a predominant role in agriculture because 100% of the total green water (99 million $m^3$) is consumed for agricultural purposes and meat production accounting for a third of the total amount. The second main component of the water footprint is generated by the consumption of vegetable oils (11%), cereals (10%), and milk (10%). Altogether, food consumption solely related to both agricultural and animal requirements accounts for 89% of Italians' total WF, while the consumption of water for domestic purposes such as cleaning or cooking covers only 4% and water employed by the industrial product chain is equal to the 7% of the total water needed [23]. Thus, more robust estimations of water employed in the agricultural and food sectors are warranted, especially when considering that current estimations are performed for quite large areas, failing to identify nuances in regional and local needs.

# 2. State of the art

## 2.1 Water footprint assessment

The quantification of the water footprint is relevant to various disciplines, enabling the assessment of both the volumes of water and the pathways crossed throughout the entire production cycle of a product, service, or specific entity [25]. This facilitates the estimation of water consumption at a population level, offering insights into water usage and waste across different global regions. In industrial contexts, water footprint assessments are employed to determine water flows required at specific production stages, encompassing the water necessary for machinery operation and potential wear-related losses. Additionally, the concept of virtual water is integral to this assessment, referring to the indirect water use occurring in secondary or intermediate production stages, such as the water embedded in the manufacturing of goods or in livestock farming. [25]

The concept of virtual water, introduced by the British geographer John Anthony Allan in 1993, provided a framework for addressing worldwide water scarcity issues. In his geographical and political studies, Allan was the first to define water as a capital good to be considered in trade between various countries. By quantifying its flows among nations, he effectively highlighted the water-related challenges faced by different regions; Allan pioneered the management of these movements through empirical studies, aiming to achieve global conflict management.[26] In the context of an open global economy, international trade theory suggested that nations benefit from trading goods produced using abundant local resources for those requiring scarce resources. Specifically, water-scarce countries may opt to import water-intensive goods, thereby alleviating pressure on their internal water resource. Conversely, water-rich nations might consider exporting virtual water to sustainably utilize their resources and contribute to international trade. [27]

The initial national-scale water footprint assessments were conducted by Hoekstra and Hung in 2002, followed by Chapagain and Hoekstra in 2003. Their framework considered not only direct water usage but also encompassed all natural processes within the assessed timeframe, including evaporation, field runoff, and water incorporated in surface bodies when evaluating necessary rainfall volumes.

According to Hoekstra et al. (2011), the assessment of the water footprint follows a systematic approach that evaluates the consumption of different types of water throughout various production phases. It comprises four fundamental steps; it is crucial to first identify the specific product or system under analysis, clearly delineating process boundaries and various stages to be examined. This initial step ensures clarity regarding the scope and limitations of the assessment. Subsequently, it is essential to determine the spatial and temporal dimensions of the process. The definition of both the geographical water withdrawals required and the timeline necessary to comprehend the production duration of a particular product is outlined. Therefore, there are three primary levels of detail that can be adopted in such assessments. Level A employs global average water footprint data sourced from comprehensive databases, reflecting multi-year averages. However, this approach lacks precision in analyzing specific localities and actual inefficiencies within each area. To address this limitation, Level B incorporates data averaged at national, regional, or site-specific levels, allowing for the identification of hotspots responsible for water inefficiencies at a more localized scale. The water footprint of a nation, for example, comprises both internal water footprint (IWFP) and external water footprint (EFWP) components. While the former refers to the utilization of domestic water resources for the production of goods and services consumed by the population, the latter represents the annual volume of water resources utilized in other countries to produce goods and services consumed by the residents of the nation in question. The most detailed, Level C, involves analyses that are highly specific both spatially and temporally, focusing on the water footprint of a company or household over a short timeframe. The minimum spatial resolution at this level corresponds to small catchments (approximately 100–1,000 $km^2$), with the possibility of field-level analysis when data permits, aiming to provide accurate estimates of actual local water consumption and pollution, ideally verified through on-ground observations. The third step requires the quantification of different types of water required for production or decontamination from the release of specific pollutants necessary to produce a certain product.

Finally, interpreting the results to evaluate the efficiency of water use and the sustainability of a given product or company is crucial. Key parameters considered include spatial and temporal variations in water withdrawn and used depending on the type of territory analyzed or seasonal variability. Another critical parameter is water scarcity related to this type of manufacture, examining how the production of a certain product or process waste can impact a community or an entire country. Fundamental implications involve adopting targeted strategies and improvements in various process stages to develop more sustainable methods for obtaining that product; For example, implementing different irrigation methods when discussing a field or various livestock management practices concerning the administration of feed to different animals. However, these early evaluations were considered rudimentary by later research, prompting efforts to enhance the assessments through more accurate data, inclusion of a broader range of products, and refinement of methodologies where necessary.

## *2.2 Water footprint of the agri-food production chain*

Concerning agriculture and animal livestock water footprint, first comprehensive reports were developed Mekonnen et al. in 2011, with the global estimation of green, blue and grey water footprint of crop and derived crop products [28]. Accurately assessing water use in agriculture necessitates the application of various methodologies, notably the CROPWAT program [28]; This approach analyses different water types required based on factors such as evaporation and crop characteristics. For annual crops, yield data can be sourced from agricultural statistics, while in the case of perennial crops, it is essential to consider the average annual yield over the crop's full lifespan.  Process water footprints are commonly expressed in cubic meters per ton ($m^3$/ton) or equivalently liters per kilogram (L/kg); The main asset is delineated through the quantification of three type of water footprint: firstly, water sourced from surface and groundwater bodies, represented by the blue water component; then, the green water footprint component, which accounts for rainwater stored in the soil and used by plants, essential components for the effective water resource management. Statistics often report total water withdrawals for irrigation rather than consumptive blue water use, which represents the actual volume of water evaporated, transpired, or incorporated into crops. Even with comprehensive ET measurements, distinguishing the proportion attributed to blue water remains challenging. Consequently, water balance models that integrate data on climate, soil properties, crop characteristics, and irrigation practices are typically employed to estimate blue water consumption.

The grey water footprint component, firstly identified by Hoekstra in 2011, quantifies instead the volume of freshwater required to assimilate pollutants, ensuring that water quality standards are maintained. Pollutants typically include fertilizers (such as nitrogen and phosphorus), pesticides, and insecticides. Only the fraction of these chemicals that leaches into freshwater bodies is considered in the grey water footprint calculation. Hoekstra focused the assessment on the most critical pollutant—the one for which the calculation yields the highest water volume requirement.

In 2012, Hoekstra et al. conducted a comprehensive global assessment of the water footprint associated with livestock production. This study meticulously analysed the production processes and individual stages within the life cycles of various livestock species, quantifying the water required to produce secondary animal products. The methodology employed was an enhancement of previous analyses, incorporating diverse livestock farming practices. The water footprint for each animal species was calculated by summing the indirect water used in crop cultivation for feed and the direct water consumed for daily drinking and service purposes. Service water encompassed all water necessary for cleaning farm facilities and equipment.

# 3. Aims of the project

Based on the discussed predominance of the agricultural and food sectors related to water use, the main objective of this thesis is to estimate the quantities of water used in the agri-food sector at a local level, within the province of Cuneo, in Piedmont. The selection of this case study was based on its relevance in the economic field, as it is the first province in the region in terms of import/export of agricultural products, on the sustainability of the supply chain, and on the implementation of policies aimed at the sustainable use of water in all productive processes involved in the chain. To achieve the presented goal, a multifaceted approach was adopted, incorporating literature evaluations with statistical and data registries.

In our study, we aimed to analyse the water flows necessary to produce secondary goods, specifically those derived from animals, within the circumscribed area of Cuneo. Initially, we used global and continental-scale databases (Level A) to observe general water requirements and to refine the most appropriate methodologies for our analysis. Subsequently, national databases were employed to achieve a more detailed assessment, incorporating national and regional censuses related to land use and livestock composition. For water footprint quantification, we referenced the same methodologies and study objectives outlined by Hoekstra. The third step, corresponding to Level C detail, is planned for future consideration. This will involve regional analyses and estimates to establish a solid foundation for obtaining more consistent results. In the absence of direct observations, we rely on censuses that quantify regional elements to estimate necessary quantities under optimal conditions. This localized assessment will provide insights into regional water use patterns and inform strategies for sustainable water management in animal-derived product industries. By superimposing spatially and temporally explicit water footprints onto water-stress maps, we can develop detailed impact assessments, facilitating the identification of periods and regions where water use may exacerbate scarcity conditions.

## 3.1 Case Study – Cuneo and its relevance

Characterized by more than 76000 industries and more that 6500 agricultural sites, Cuneo and its surroundings represent both the 1st province in Piemonte in terms of covered area and economic activity. A diverse landscape, which includes both Alpine ranges to the West and South, hilly areas in Langhe and Roero, and fertile plains to the East, guarantee an exceptional agricultural richness and a core role in the agro-industrial sector. Report from the last Agricolture Censure (Censimento Dell'agricoltura) [25], analysed two main components for the harvested area: the Total rural surface (SAT), which accounts for all surfaces not directly aimed to farming purposes, and the Utilised rural area (SAU), which includes all arable and perennial woody crops (i.e. orchards, olive groves). Result of this comparison lead to significant results; a consistency of 36142 hectares in the entire province of Cuneo saw a decrement of 12% in the last decade, leading to a total surface of 27609 in 2020. Of this area, only the 76% is related to SAU, while the 13,7% is covered by woods and the 4% given by the area not used for arable intentions. Concerning the SAU, 30% of the arable land are associated of mountainous territory, while the 26,7% is related to hill land and the 42,7% comprehends lowlands. Finally, of the total SAU the 48,1% of the total production is composed by arable land, while the 40% is composed of fodder crops.

Accounting for the livestock composition, a diversified incidence compared to the national consistency shows the strong relationship between regional and provincial results: beehives, cattle and pigs are species that contributes most to the national totals, since the only province of Cuneo cattle contributes to the 53.6% of the regional consistency, while swine are almost 70% of the totality.

Regarding the economic enterprises of the region, it is noteworthy the higher proportion of these business across all size categories, with Cuneo surpassing both regional and national targets for enterprises with a high economic scale (i.e. >€500000 of profits). Consequently, 2 are the primary production chain analysed: dairy (specifically cheese) and traditional cured meats.

Data provided by the Annual statistical report of the Piemonte region in collaboration with ISTAT, about land use variations in the last decades allows to understand how and why agriculture sector had to invest to improve its results. [26] From 2016 to the current year, three are the main comparison essential in the validation of change in land use: A decrement of more than 7000 hectares of agricultural land, due not only to the closure of more than 5000 agricultural industries, but also to an effective loss of arable land caused by climate change. Secondly, harvested crops, defined as the ratio between the used land and the effective production of the intended [27] showed a consistent shift for almost all crops except for maize. Thanks to efficient innovations in technology and prevention from microorganisms such as oliar fungicides, the latter crop showed an increment of productivity 4%. Finally, livestock consistency went up to a significant loss in terms of cattle, except for the poultry one, that had an increment of more than 70000 units.

One of the most remarkable aspects of this territory is the application of local guideline and cooperatives set to promote the efficiency of small businesses and support them during the necessary energy transition. Inside the Agrifood business, Marketing strategies for quality agri-food (SMAQ) is one of the projects promoted inside the province of Cuneo with the aim of helping small realities. The objective of SMAQ, through the conscious use of digital communication tools and the creation of a community aimed at exploring new markets or models, is to combine innovation and tradition by making the opportunities offered by digital innovation available to the productions that characterize the regional territory. [27] The "Cuneo Food Valley," as designated by the National Institute of Statistics (ISTAT), has long been distinguished by an optimal balance between high-quality food production and the province's intrinsic characteristics. Protected Designation of Origin (PDO) products have significantly contributed to establishing the province's esteemed reputation and securing funding for the advancement of the agronomic sector. The success of Cuneo's agri-food industry is attributed to its adept integration of traditional practices with modern technologies. Cooperative models, such as the Consorzio di Tutela (Protection Cooperative), ensure that producers adhere to stringent quality standards while promoting sustainability and environmental stewardship. [28]

### *3.1.2 Cuneo Water Sources and Challenges*

The primary water sources for the agricultural sector in the province of Cuneo are the Po and Tanaro rivers. These rivers are preferred over smaller streams, which often exhibit intermittent and limited flow rates. Situated in the southwestern portion of the Alps, the Cuneo plain faces challenges in water supply due to the absence of significant glaciers, leading to limited water availability. [29] Additionally, the fragmentation of irrigation management among more than 15 second-level consortia has hindered the development and implementation of effective interventions to address water scarcity. [30]

In recent years, climate change has impacted both precipitation patterns and water availability across the entire province of Cuneo. According to the Agenzia regionale per la protezione ambientale (Piedmont Environmental Protection Agency) (ARPA), [31] average daily temperatures have increased by 2°C over the past 60 years, while minimum temperatures have risen by 1.5°C. Furthermore, precipitation records indicate more frequent local anomalies, with an increase in periods of scarcity affecting the flow regimes of many torrents within the province. Over the past decades, precipitation patterns have changed by more than 9%, underscoring the critical need for more careful and sustainable water resource management to address the challenges posed by climate change.

The latest report from the Associazione Nazionale Consorzi di gestione e tutela del territorio e acque irrigue (National Association of Land Reclamation and Irrigation) (ANBI) [32] highlights two key investment areas to combat water scarcity in the region: enhancing efficiency in water resource management and promoting environmental sustainability. On one hand, this involves the digitalization of water infrastructure to monitor water resources and identify losses; on the other hand, it includes the development of water basins for the collection of rainfall, aiming to mitigate the increasingly frequent periods of drought.

# 4. *Methodology*

This is a secondary data analysis on previous databases, requiring a selection of the sources (section 4.1) and an integration of previous methods for fodder and animal-specific estimates of water use (sections 4.2, 4.3). Finally, the descriptive nature of the study, its design, and the variables of interest are presented (section 4.4).

## *4.1 Database selection*

The primary local datasets were obtained both from governmental and national guidelines and from local sources, offering a detailed representation of water usage within the agricultural sector; the ISTAT and the Agricultural Registry of Piemonte provided reliable documentations for all the statistical data necessary for the quantification of products present locally. The former provided official agricultural statistics based on systematic data collection both at national and regional levels. The latter is instead the core of the Agricultural information system of Piemonte (SIAP) [33] in which personal and structural data of entities such as agricultural companies and associations within the region are developed. Within the Agricultural Registry the OpenDataWarehouse [34], an open access platform of statistical information about farms and land use can be consulted by reports or graphs. Given that under specific types of harvesting or feeding less information are available in terms of exact percentage of composition or amount of water consumed daily per animal or per single crop, some of this specific information were selected by non-peer reviewed journals or newspapers (i.e., Atlante Zootecnico, Ruminantia). Data collection was performed on data until November 11th, 2023, corresponding to the end of the annual crop production cycle.

## *4.2 Fodder composition estimations*

Fodder composition estimations were achieved by incorporating local data on agricultural and livestock production and tailoring them to the specific conditions of the study area. The comparison of these values with possible methods of crop management was mainly based on the climatic condition. The structure of the analysis follows a dual classification approach, considering both yield rotation system and the intended purpose of each crop.

The first category was based on the type of crop rotation, which primarily depends on the profitability of crops across different seasons and their durability over time. In this context, crops were categorised into three main groups, being permanent surfaces, alternate crops, and industrial crops. Permanent surfaces included all the non-rotation herbaceous forage crops on the land for a period over five years, which were further subdivided into permanent meadows and permanent pasture. The former refers to the agricultural land use of perennial grass species and other herbaceous forage plants, either natural or cultivated, which were not included in any other rotational cropping system for at least 5 years. The primary function of such meadows is forage production, typically harvested through periodic mowing. Permanent pastures, on the other hand, fulfill the same longevity criteria but are primarily responsible for direct grazing by livestock, thereby playing a fundamental role in extensive and semi-intensive livestock farming systems [35].

Alternate crops refer to herbaceous arable crops that are cultivated as part of a rotational system, ensuring that the same land is not occupied by the same species for more than five years. Crop rotation was widely recognized for its agronomic benefits, including improved soil fertility, enhanced nutrient cycling, and reduced incidence of infestations and disease. Alternate crops are further divided into rotational grasslands and fast-growing forage crops. The former consisting of forage species that persist on the same field for multiple consecutive agricultural cycles, after which they are replaced by other crops within the rotation scheme. These grasslands are predominantly composed of leguminous species, either in monoculture or in mixtures with grasses if legumes constitute at least 80% of the biomass. In contrast, fast-growing forage crops are characterized by their short vegetative cycle and rapid biomass accumulation, making them particularly suitable for intensive feed production. This group is dominated by cereal crops grown for silage, such as maize, which is widely used in livestock feeding due to its high energy content and ryegrass, exhibiting great regrowth capacity, and all the other fodder grasses cultivated for their high digestibility and palatability [35].

Industrial crops represent a distinct category, as they are not meant to be directly consumed raw by humans nor by animals, hence requiring further industrial processing before their final use. These species provide raw materials an added value because of their nutrients, essential in the production of fodder especially in extensive farms [35].

The second classification method focuses on the functional role of crops within the agricultural system, ensuring compatibility with the standardized crop groupings proposed by Hoekstra's Water Footprint Assessment (WFA) framework [36]. This approach allows for a better comparison of crops production at micro and macro scales, essentially centered on the primary agricultural function. The first main group within this classification included fodder crops, which are cultivated primarily to sustain livestock production through direct grazing or harvested forage. Crops are characterized by high biomass yield and nutritional quality, providing essential fiber, protein, and energy for ruminant feeding. The second group consisted of stimulant crops, defined as plant species that promote physiological growth, increase stress tolerance, and improve overall plant health through bioactive secondary metabolites. These are often used in organic and precision agriculture as natural growth enhancers. Finally, pulses represent a key group of the legume family, due to their distinctive seeds, harvested and dried before consumption. Pulses play a crucial role in agroecological farming systems, as they serve not only as an important protein source but also enhance soil nitrogen fixation, thereby reducing the need for synthetic fertilizers [37].

Relevant aspects such as supplements (i.e. vitamins and salts), enhancing the nutritional value of the food and stimulating productive functions of the animals, and bran, realised from the milling of wheat, enhancing the sustainability of the fodder, were excluded from the calculation of the amount of water needed for the total production. This was due to assessment difficulties which could affect the overall estimation. [37]

## *4.3 Animal-specific estimation*

The quantification of water requirements in animals was normalised over a year for the total herd and over the entire lifespan for a single animal. This enabled the differentiation between production and sale of secondary goods produced in the selected area. Concerning the animal compartment, local journal classifications were selected and compared with global definitions. Since most guidelines did not provide information regarding the specifics for each age stage in terms of growth, quantity of feed or secondary products, an average of the samples obtained from the literature were analyzed in this project. Finally, the quantity of outcome produced, consumed and subsequently imported or exported throughout the province was considered for more reliable estimates of specific water requirements per animal, available for self-consumption.

## 4.4 Statistical methodology

All data processing and visualisation were performed on Microsoft Excel 16.93.1 [38], which facilitated data organization.

A data-driven approach was used, integrating multiple sources to obtain a comprehensive assessment. For each stage, glossaries were provided. All the definitions regarding the different types of crops were obtained from official national organizations that were later compared with official international sources.

Calculations were predominantly linked to descriptive analyses and comparisons to previous evaluations from Hoekstra and Mekonnen (2012). The absence of individual-level direct observations precluded the use of inferential statistical tests, thereby limiting conclusions to trends observed in aggregated data. Nevertheless, valuable insights into production patterns and behaviors within each product chain emerged through the systematic description of trends, shedding light on potential areas for improvement in current agricultural practices.

The main variables of interest for the presented study, along with the relative equations included are presented and relevant to all evaluated animal species. These included the harvested area in terms of field width in hectares and the harvested quantity in quintals converted to the units used by Hoekstra and Mekonnen (2012) ($m^2$, ton) for meaningful comparisons.

$$(1.1)\quad Harvested\ area\ (m^2) = Harversted\ area(Ha) * \ 10000$$

$$(1.2)\quad Harvested\ quantity\ (ton) = Harversted\ quantity\ (q) * 0{,}1$$

Another variable is the total amount of drinking water (DW) in $m^3$, calculated as a direct water amount, and considered as blue water in the final water footprint estimation. Where n is equal to the total number of weeks intended for the stage of life considered.

$$(1.3)\ DW(m^3) = \sum_{x=1}^{n}(DW_x)$$

$^*$*Where n is the total number of weeks in the evaluated life stage for each species.*

The fourth variable considered was the quantity of feed (QF) for a single head per day to compare different quantities of crops based on the different inclusion percentages necessary for every animal. Subsequently, the total fodder amount (TF) required for one head for the entire specific stage of life was calculated. With the same procedure it was possible to obtain the quantity of feedstock for the total livestock ($TF_{cattle}$)

$$(1.4)\ QF\left(\frac{ton}{day}\right) = \sum_{x=1}^{n}(I_x * IR_x) * 10^{-6}$$

$^*$*With n being the total number of ingredients included in the fodder.*

$$(1.5)\ TF\ (ton) = \sum_{x=1}^{n}\left( QF_x\left(\frac{ton}{d}\right) * 30\right)$$

$^*$*Where n corresponds to the living months of every animal.*

$$(1.6)\ TF_{Cattle}\ (ton) = TF * cattle\ composition\ (h)$$

$^*$*With h corresponding to the total number of living animals considered for the estimation of the results.*

Another variable was the water consumption per total livestock ($WF_{cattle,\ total}$) was obtained by extending the individual estimation of water consumption per head. The latter was then quantified as the sum of the daily drinking water ($DW$ ($m^3$)), which represents the amount of water required for the animals' daily hydration, and the water used for feed production ($WF_{Fodder,Cattle}$), which accounted for the water needed to cultivate the forages and feeds necessary for livestock nutrition. Despite $WF_{Fodder,Cattle}$ being an indirect source of water consumption, it accounts for a substantial proportion.

$$(1.7)\ WF_{Cattle,Total}\ (m^3) = \sum(WF_{Fodder,Cattle} + DW)$$

For all animals, another variable was the water footprint of the fodder for a single head ($WF_{Fodder}$), computed as the product of the sum of the total amount of green, blue and grey water (from [17]), and the quantity of feed (QF) for an individual head. Water consumption for the fodder in the total livestock ($WF_{Fodder,Cattle}$) was then obtained by extending the estimation for single head ($WF_{Fodder}$) based on the total fodder per herd ($TF_{cattle}$).

$$(1.8)\ WF_{Fodder}\ (\frac{m^3}{Head}) = \sum((WF_{Fodder,Green} + WF_{Fodder,Blue} + WF_{Fodder,Grey}\ ) * QF_{Calf}\ (Ton))$$

$$(1.9)\ WF_{Fodder,Cattle}\ (m^3) = WF_{Fodder}\ (\frac{m^3}{Head}) * TF_{Cattle}\ (ton))$$

Variables specific to the individual production chains were also evaluated and presented below.

### *4.4.1 Bovine Milk Chain*

For the milk production chain and derivatives, a detailed analysis of the crops that are included in the livestock feed was performed. The harvest, the primary nutritional source of the cattle, was assumed to be watered with identical irrigation systems for the entire province, ensuring homogeneous estimations of water inputs. What was highlighted is the analysis of the cultivated species, in terms of agricultural characteristics and water requirements. As already mentioned before, most of the records were obtained from the OpenDataWarehouse, providing visualization for both the agricultural yield of all the crops intended for this project and the altimetric zone of each colture [39]. The type and composition of fodder were estimated based on local availability. Dietary requirements for this species were approximated using data from specialized literature, ensuring an appropriate nutrient balance for optimal growth [44]. considering the amount of water to be given *at libitum,* even if recognised as the most used method into smaller farms for calves, literature studies provided by Atkeson et al (1934), provided the right estimation and balance between water and milk intake. [45] After accounting for the permanent forages (i.e. permanent meadows and pastures), the types of temporary forages that were classified as necessary for the composition of the cattle forage included corn, barley, soya, sunflower, sugar beet, and barn.

Following this, the total amount of water necessary for each head and for the herd in the selected area (i.e., the biological unit responsible for milk production) was estimated. To achieve this, an accurate evaluation of the total livestock population was required including calves (first six months of life). Finally, the analysis of the production of milk inside the region and its import and export on the territory, including also the one used for the self-consumption inside every farm was considered.

In particular, the total amount of milk produced (MP), underscoring the change of behavior of cows during the lactation periods, with associated changes of drinking and feeding requirements was calculated as:

$$(1.10)\ MP\ (L) = \sum_{x=1}^{n} (MP_x)$$

*With n = 3 referring to the number of lactation periods.*

The total water footprint related to industrial milk and its derivatives, was computed as the ratio of the sum of the total amount of green, blue and grey water ($WF_{Milk,\ Derivatives}$), converted in m^3/ton, and the product fraction (PF) selected from literature tabled by Hoekstra.

$$(1.11)\ WF_{Milk,\ Derivatives} = (\sum((WF_{Milk,Green} + WF_{Milk,Blue} + WF_{Milk,Grey}) * MP\ (ton)))/PF$$

### 4.4.2 Bovine Meat Chain

For the bovine meat chain, the species of interest was the *Piemontese* species, with the estimations of water use and crops required being identical as the aforementioned ones for the bovine milk chain. Thus, the total amount of meat produced (MeP) was assumed based on the product of the total number of slaughtered bovines in Cuneo in 2023 reported in the literature [] and the estimation of WF per head previously presented. Notably, differentiations based on specific meat types were prevented by the lack of data pertaining to the *Piemontese* cows in the evaluated datasets. Thus, the total water footprint related to industrial meat production was estimated as the product of the sum of the green, blue, and grey WF involved in meat production and the total amount of meat produced.

$$(1.12)\ WF_{Meat}(m^3) = \sum((WF_{Meat,Green} + WF_{Meat,Blue} + WF_{Meat,Grey}) * MeP\ (ton))$$

### 4.4.3 Egg chain

As for bovines, crop management, poultry breeding and egg production were considered. A similar lack of accurate guidelines concerning appropriate amounts of food to every animal, some assumptions were included to identify the ideal balanced feeding for the total poultry. The main components of poultry dietary were therefore identified as corn, barley, soya bean flour, sunflower seeds and seeds oil, along with plant-based fibers. To evaluate poultry quantification, animals were classified by age, type of breeding and sex [62]. Finally, egg production per hen with relative water footprint was estimated. Specifically, the variable of annual egg production (EP) per head (hen) was computed as

$$(1.13)\ EP = hen * 0.8 * 365$$

As for milk, the total WF for eggs (WF$_{Egg,Total}$) per head was obtained through product of the sum of green, blue, and grey WF involved in egg production and the total amount of eggs produced per hen.

$$(1.14)\ WF_{Egg,Total}\ (\frac{m^3}{hen}) = \sum(WF_{Egg,Green} + WF_{Egg,Blue} + WF_{Egg,Grey}) * \text{EP}$$

### *4.4.4 Pork meat chain*

For swines, the calculation for the fodder was based on the main crops intended for the mixture production. Swine fodder formulation is tailored to the specific nutritional needs that evolve throughout the animal's life cycle. In early life, piglets receive a diet rich in proteins, vitamins, and minerals to promote rapid and healthy growth. Immediately after weaning, the focus shifts toward a balanced diet that supports both muscle development and controlled fat deposition by increasing the proportion of carbohydrates and fats. During the grower phase, the diet is gradually adjusted to further enhance feed efficiency through increased carbohydrate content, while pregnant sows require high-quality energy and protein to support fetal development. Finishing pigs, in contrast, are provided with a diet that encourages moderate weight gain, reflecting their distinct physiological needs.

Secondly, concerning cattle nourishment, the analysis of fodder composition was fundamental in determining the required quantity of each crop type necessary for optimal feeding. The selection of appropriate percentages was based on reports from local newspapers and corporate documents concerning livestock species within the territory. For these species, calculations were conducted following the guidelines outlined in technical agricultural databases. The methodology comprised three distinct phases. Initially, the inclusion percentages for various crops that could potentially be incorporated into the diet of pigs, depending on their age, were determined. The selection of industrialized crops was not solely based on territorial availability, as in other cases, but also on a worst-case scenario approach—considering the most finely processed product—to ensure an overestimation of the water requirements. Subsequently, these percentages were examined in relation to different growth phases. It was observed that gestational sows, for instance, required significantly higher quantities of corn, while piglets needed powdered milk administration in the early weeks of growth, followed by a rapid reduction in its intake. Further data obtained from an external repository allowed for the quantification of the exact amount of feed to be administered to each animal per week, expressed in g/d [60]. Finally, the calculated inclusion percentages were compared with the appropriate daily intake, enabling the precise quantification of the crop amounts required to sustain each individual animal throughout the production cycle. For the first week, the average of the initial two percentage values was used. From the second to the nineteenth week, calculations were based on sows weighing up to 120 kg, while from the twentieth week onward, pigs were considered up to a final weight of 160 kg. To verify the robustness of the dataset provided, all the harvests' macronutrients were balanced in order to obtain the best result in terms of energy balance [61]. Despite the existence of many nutritional guidelines, no official procedure was found. Thus, the focus was mainly on a comparison of the available crops and the macronutrients requirements, leading to the identification of the crops needed as including oats, wheat, corn, manioc, barley, potatoes, rice, and rye.

The analysis of the species present within the territory was then performed based on the different weights during different stages of life tailored to feeding, housing, and healthcare in each developmental stage [57]. However, results are limited as the analysis of WF related to pork meat was interrupted due to timing restraints, thereby warranting further investigation.

# 5. Results

## 5.1 Calves

Prior to the distinction between the dairy and the meat product chains, an overall evaluation of calves (non-specific for purpose) is presented. However, this calf-specific evaluation has not been carried out by [17], therefore the comparison of our results will be specific to the product chains, which will also include the percentages of calves involved in dairy and meat productions.

### 5.1.1 Calves Quantification

Data on the total number of animals for the milk and meat production chains were obtained from two national sources according to two different purposes. On one hand, data available on Open Data Warehouse allowed the quantification of the totality of dairy and beef cattle mainly categorized by age. On the other hand, through statistics obtained from national governmental websites (i.e. Vetinfo.it) [40], assessment based on different breeding methods within the territory were calculated. This kind of categorization was crucial as highlighted the two main species living in the territory, namely *Frisona* for the dairy cattle and *Piemontese* for the meat one.

This distinction enabled the study of different breeding methods for dairy and meat species, considering not only their daily drinking water needs but also the daily rationing of fodder and the corresponding water required for its provision. Regional reports [67] indicate that the province of Cuneo accounts for 45% of the regional herd. Among approximately 4,000 farms in the region, 80% are oriented toward meat production, with only 13% dedicated to dairy cattle. Additionally, according to the ISTAT dataset for 2023, most cows, at the census time, are older than 24 months and are thus classified as ready for slaughter, while nearly 60,000 animals fall within the 12–24-month category and over 100,000 are between 6 and 12 months. [41]

The distribution of calves designated for breeding versus meat production is summarized in ***Table 1***, with herd composition being quite heterogeneous. An important assumption regarding the total number of calves during the whole year in the territory can be observed; since the dataset was representative of the specific situation at the end of the year, it was estimated that the total number of animals in a year was twice the number provided in the database. This adjustment was valid because calves remain in this category for less than six months. Thus, the total number of calves risen in Cuneo during the farming year is reported to be 118334, with an estimated 18208 slaughtered before completing the calf phase, while the remained 100136 for breeding.

| *Type* | *Breeding* | *Slaughtered* | *Total* |
|---|---|---|---|
| <6 months Female | 33183 | 3704 | 36887 |
| <6 month Male | 16885 | 5400 | 22285 |
| **Total** | **50068** | **9104** | **59172** |

***Table 1.*** *Categorization of calves herd by age and type of breeding.*

### 5.1.2 Calves Description

Calves were described in terms of growth patterns, daily water requirements, and fodder-related water requirements.

The growth curve within the first 6 months of calves' lives (***Figure 3***) aids the evaluation of physiological and metabolic needs, relevant to the estimation of the daily drinking requirement per calf.

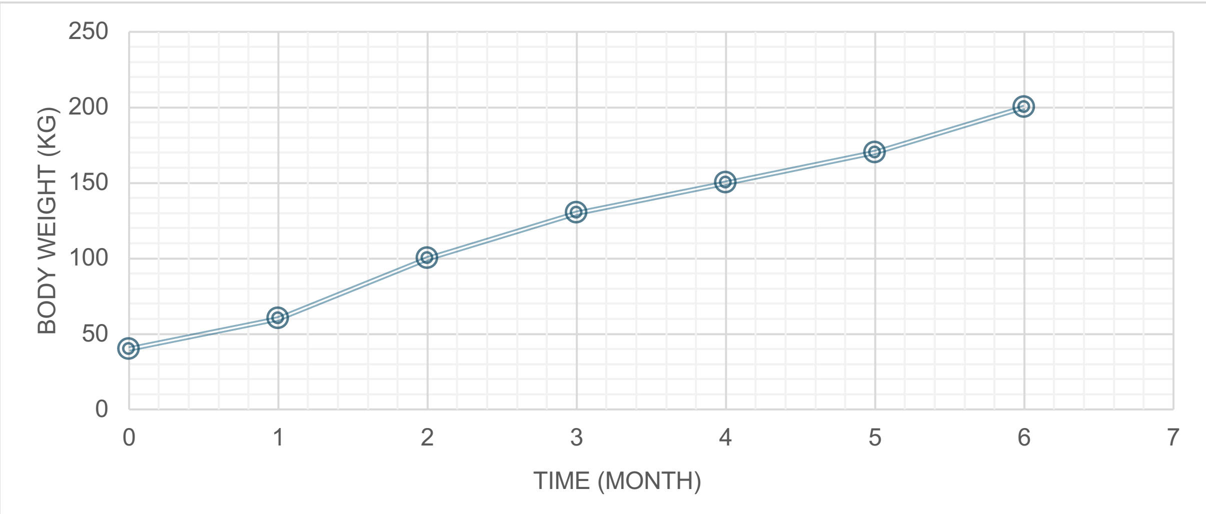



***Figure 3.*** *Growth curve of calves over 6 months.*

The daily water need per calf over time was assessed. ***Figure* 4** shows the linear relationship between growth and water daily intake, with up to 20 L/day requirement by six months of age. The calculation for the total amount of drinking water (DW) for one single calf was obtained from the sum of daily drinking water over time and equivalent to 2.55 $m^3$, while for the whole cattle was 301.77 $m^3$.

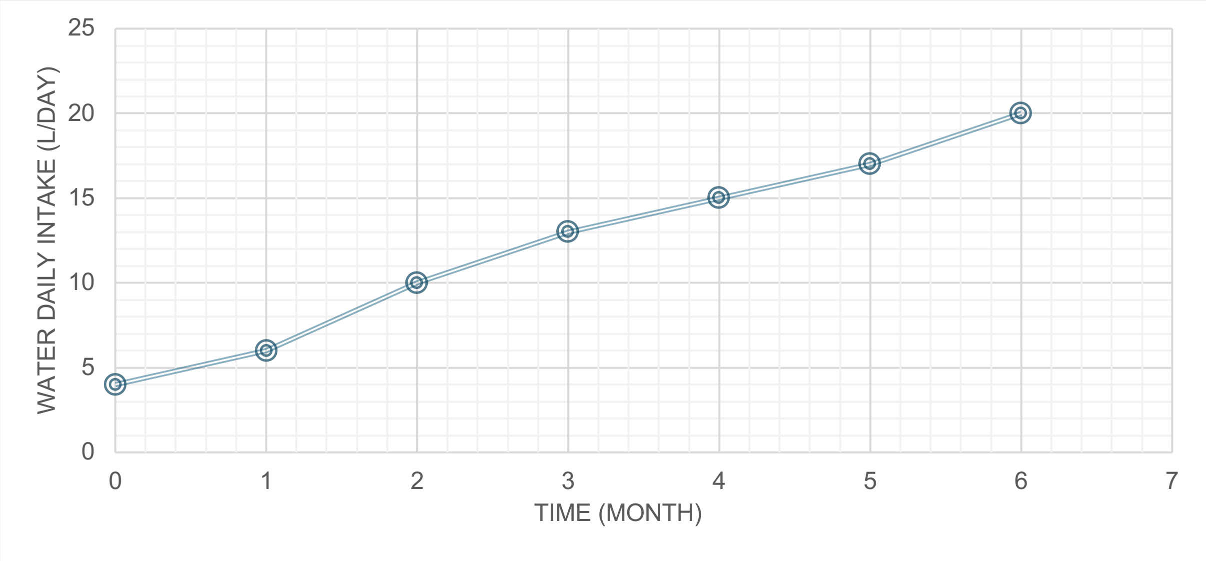



***Figure 4.*** *Water daily drinking intake for calves (L/day).* The total amount of drinking water requirement per calf is obtained through the sum of daily drinking water across the whole period.

In terms of fodder and milk, daily feed ratios required for each calf and the associated required water were evaluated. At this stage of development, milk is considered essential for the proper growth of calves. It must be administered from the first days of life to provide the necessary energy and ensure the proper development of bones and tissues. The calculation of milk intake followed reference guidelines that prescribe a progressive increase in milk quantities according to the growth of the animal, with sex differences in peak-reaching times, followed by a gradual decrease starting from the $12^{th}$ week [46]. In Figure 5, the daily milk requirements over the entire lactation period are represented, indicating that each calf in Cuneo consumes a total of 1279.43 liters of milk. Given that each dairy cow produces an average of 3997 liters during their lifetime, these figures confirm that the milk supply for calves is entirely natural, without any need for artificial supplementation. Under a worst-case scenario, which assumes higher nutritional demands for male calves, the cumulative milk requirement for all provincial calves is estimated at approximately 122.58 million L, corresponding to 152276 tons.

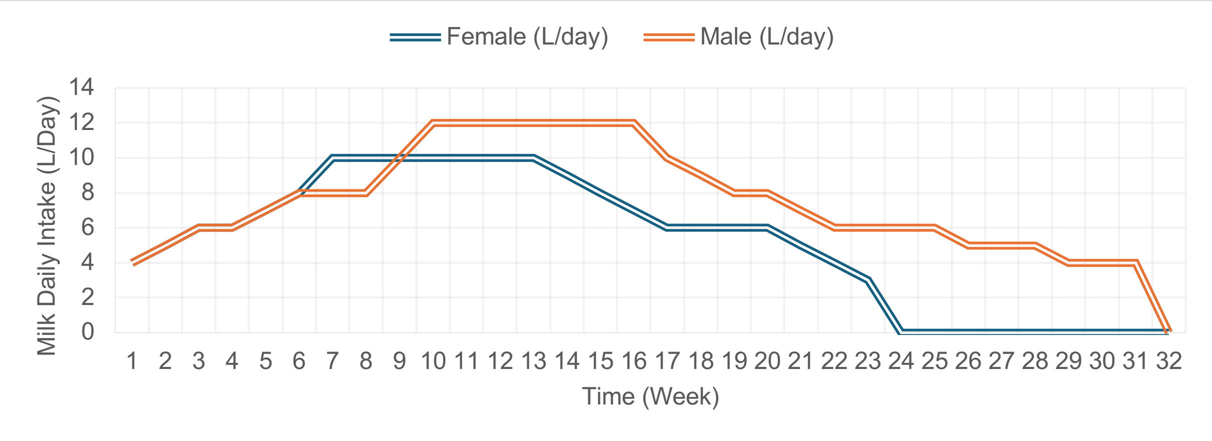



***Figure 5.*** *Milk daily intake for calves divided by sex (L/day)*

While milk is fundamental for health, side fodder is mainly employed to establish a social bond with the breeder. In particular, trust enhancement is achieved by administrating a tiny quantity from the first weeks of life. However, for the purposes of our research, it was assumed that the ratio became relevant starting from the 8$^{th}$ week, when side fodder begins to be administered averaged on the animal weight [47].

Many non-peer newspapers recommended different fodder proportions. Here, we report averaged values for ingested nutrients granting a balanced diet considering land availability [48, 49] (**Table 2**). Based on this, the total amount of feed for one calf (g) and for the cattle (ton) were evaluated and reported over the six-month period. (**Table 2, Figure 6**). Notably, corn and soybeans constitute most of the herd's fodder composition, primarily due to their macronutrient profiles, especially in terms of protein content. Soybean meal, for instance, offers the highest protein content among common oilseeds or grains, supplying a comprehensive source of plant-based protein. Corn, while lower in protein compared to other feed grains, provides a significant energy source, containing approximately 72% starch on a dry-matter basis.

| **Crop** | **Averaged value (%)** | **Quantity per calf (g)** | **Quantity per cattle (ton)** |
|---|---|---|---|
| Maize | 30 | 3345 | 198 |
| Barley | 5 | 557,5 | 33 |
| Soy | 20 | 2230 | 132 |
| Sunflower | 16 | 1784 | 106 |
| Corn | 6 | 669 | 40 |
| Bran | 10 | 1115 | 66 |

| | | | |
|---|---|---|---|
| Chard pulp | 12 | 1338 | 79 |
| Vegetable fat | 0 | 0 | 0 |
| Vitamin supplement | 1 | 111,5 | 7 |

***Table 2.*** *Percentage of inclusion of each ingredient for fodder composition*

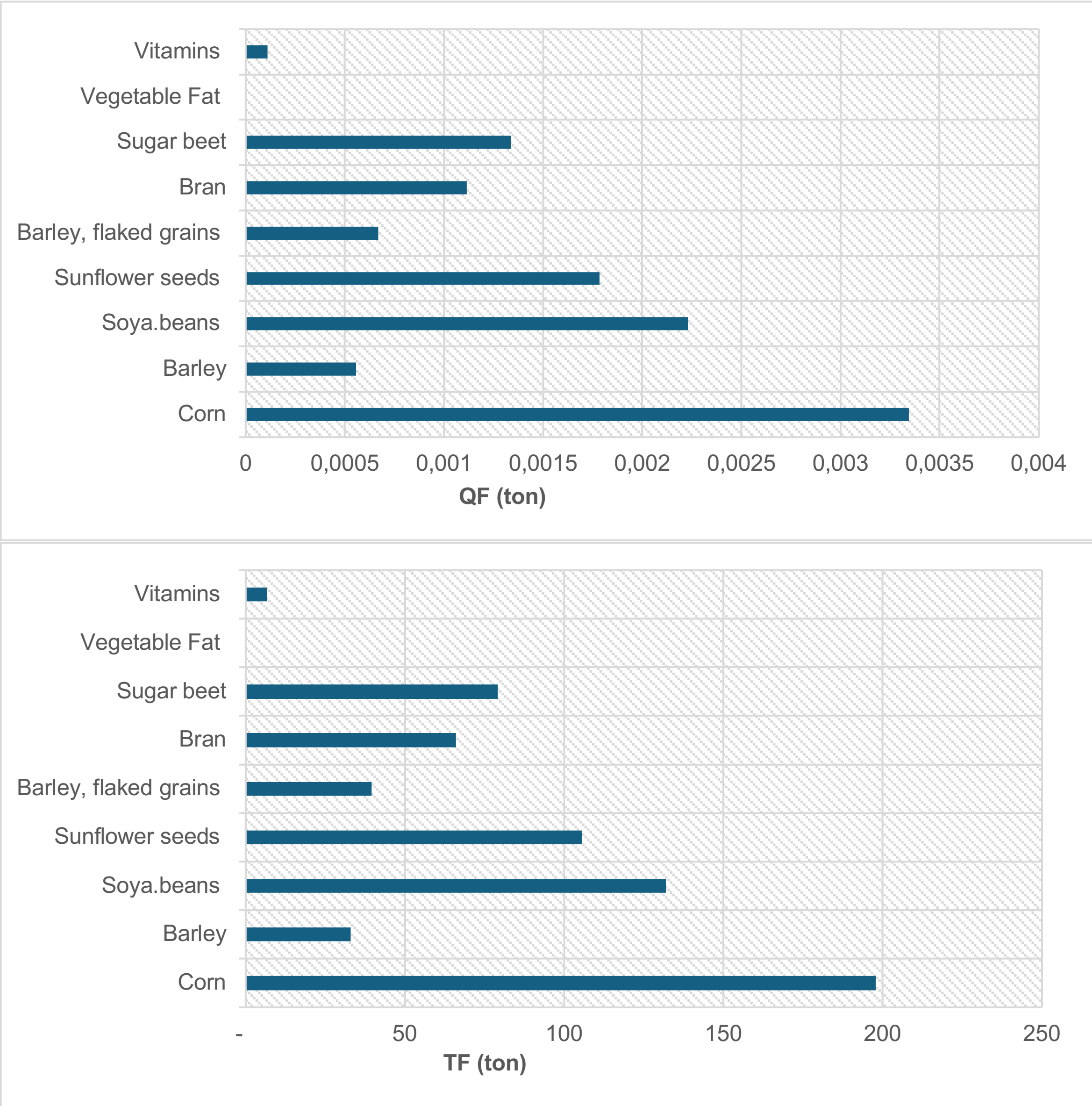



***Figure 6.****Total amount of crops for calves and cattle's fodder production across first six months.*

## *5.1.3 Calves' Water Footprint Estimation*

The final water calculation was based on the sum of all the water needed for every stage of the process for single animals and the whole species. Forage-related water footprint ($m^3$)

and its subtypes (Green, Blue, Grey) per calf and per cattle were reported in ***Figure 7*** based on quantities of fodder (Table 2). For one calf, total water footprint was 17.27 m$^3$, while for the cattle it was 1021973 m$^3$.

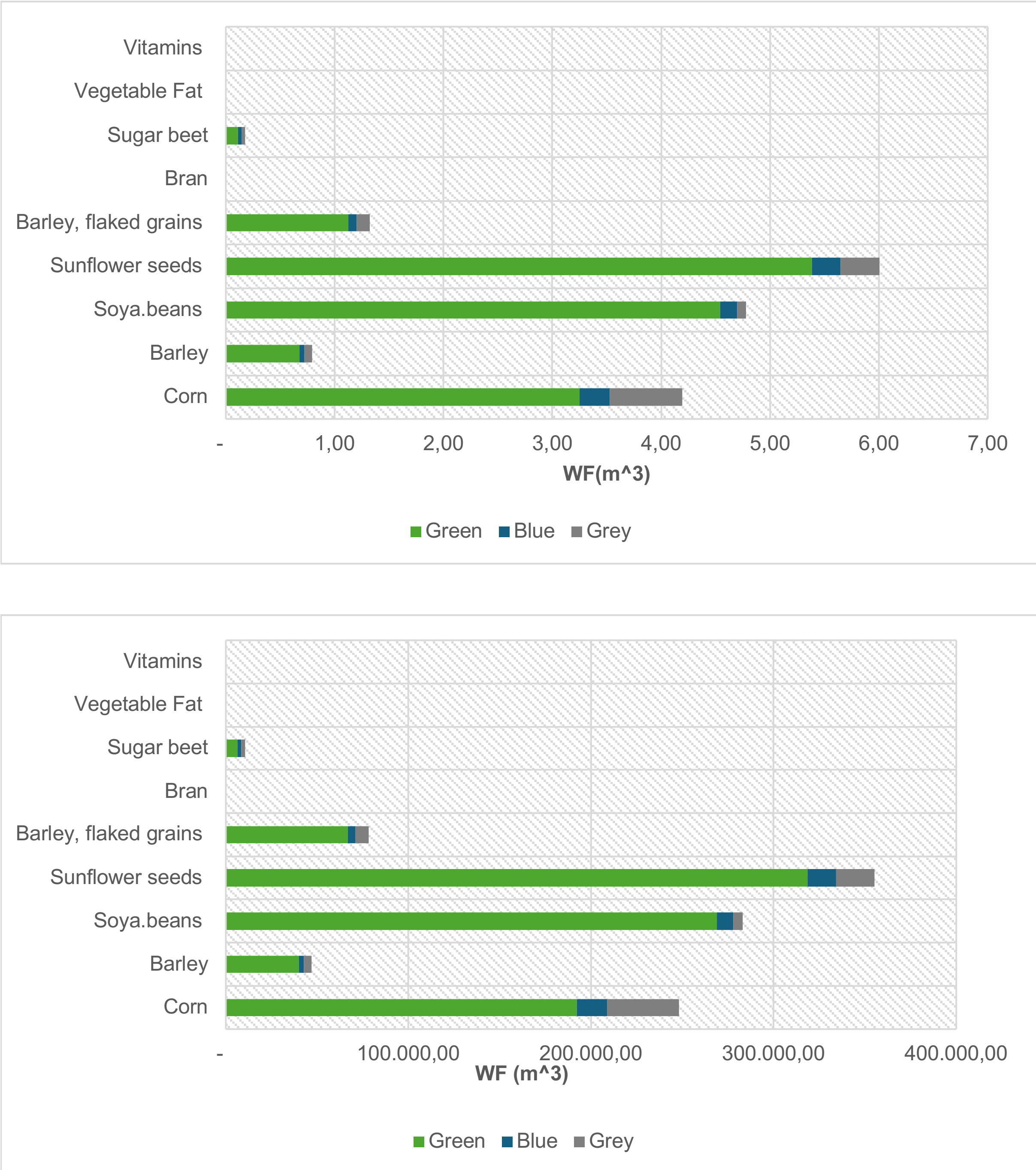



***Figure 7.*** *WF of fodder production for a single calf and the total herd in 2023.*

Based on forage-related water footprint (17.27 m$^3$/calf, 1021973 m$^3$/cattle) and total drinking water requirements (2.55 m$^3$/calf, 301.77 m$^3$/cattle), total WF per calf in Cuneo corresponded to 19.82 m$^3$, whereas total WF per cattle corresponded to 1323751 m$^3$ (***Figure 8***). Notably, milk-related water was not relevant for the total WF estimation as no industrial milk was used. The findings clearly demonstrate that green water constitutes the majority in forage production for these animals, totaling 15 m$^3$ per animal.


***Figure 8.*** *Total water footprint for one single calf and for the total herd*

## 5.2 Cattle

According to statistical datasets, 42% of the cattle population in the province of Cuneo relates to the *Piemontese* breed, while 37% consists of the *Frisona* one. Therefore, it was deemed appropriate to focus on the characteristics and behaviours of these two species as their fostering is the most widespread in Cuneo [50].

### 5.2.1 Dairy Cattle Quantification

Frisona dairy cattle, raised specifically for milk production, require distinct dietary and water needs to maintain a constant milk yield. Data from vetinfo.it allows to estimate the composition of the total herd in 2023, with a total number of 120700 heads. When accounting for age, more than half of the cows were 24 months or above. Calves of less than 6 months amounted to 22385, while cows from 6 to 12 months were 12780.

Dairy cattles were described in terms of weight, growth patterns, daily water requirements, fodder-related water requirements, and milk production.

Weight estimates for dairy cattle (***Figure* 9**) were primarily based on data collected up to 24 months, since the growth curve becomes more variable afterwards due to physiological changes associated with pregnancy, parturition, and lactation [43].

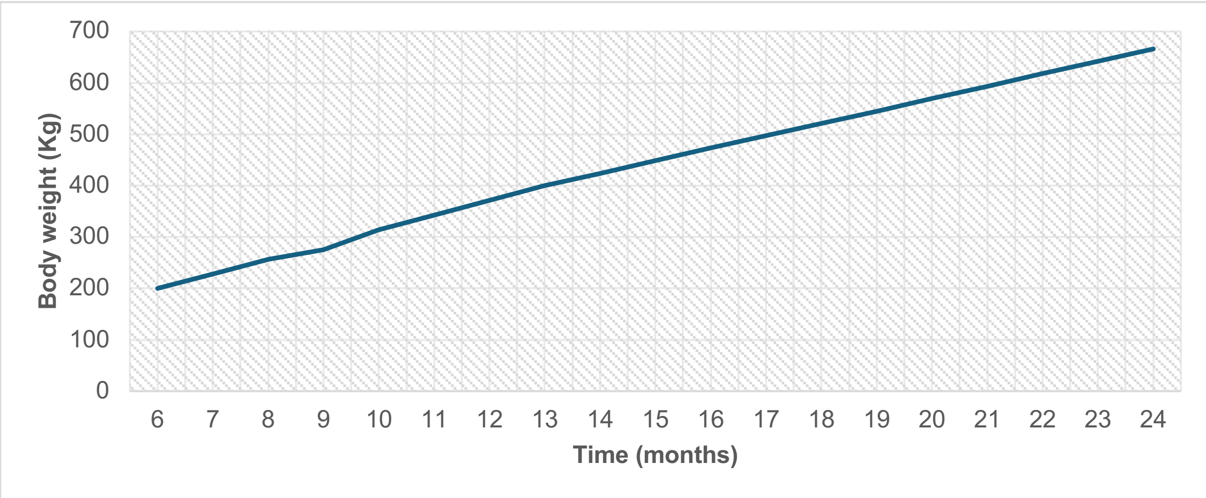



***Figure 9**. Growth curve of the Frisona species.*

The daily drinking water requirements vary throughout the bovine lifecycle, as illustrated by distinct consumption curves. An average estimation of daily water consumption for dairy cattle is provided in ***Figure 10***, highlighting inhomogeneous consumption patterns across different life stages. The figure identifies a critical period between weeks 22 and 24—coinciding with parturition and the onset of lactation—during which daily water demand increases to approximately 80-100 liters. This elevated intake is necessary to compensate for fluid losses due to milk production and to satisfy the heightened nutritional demands associated with lactation. The average daily water intake calculated over these 24 months is 49 L/d per cow, closely aligning with Hoekstra's reported value of 55 L/d per cow. The minor discrepancy arises because our study considers cattle up to 24 months of age, whereas lactating Frisona cows (excluded from our analysis) can require up to 140 L per day in subsequent months, thereby increasing the average value.

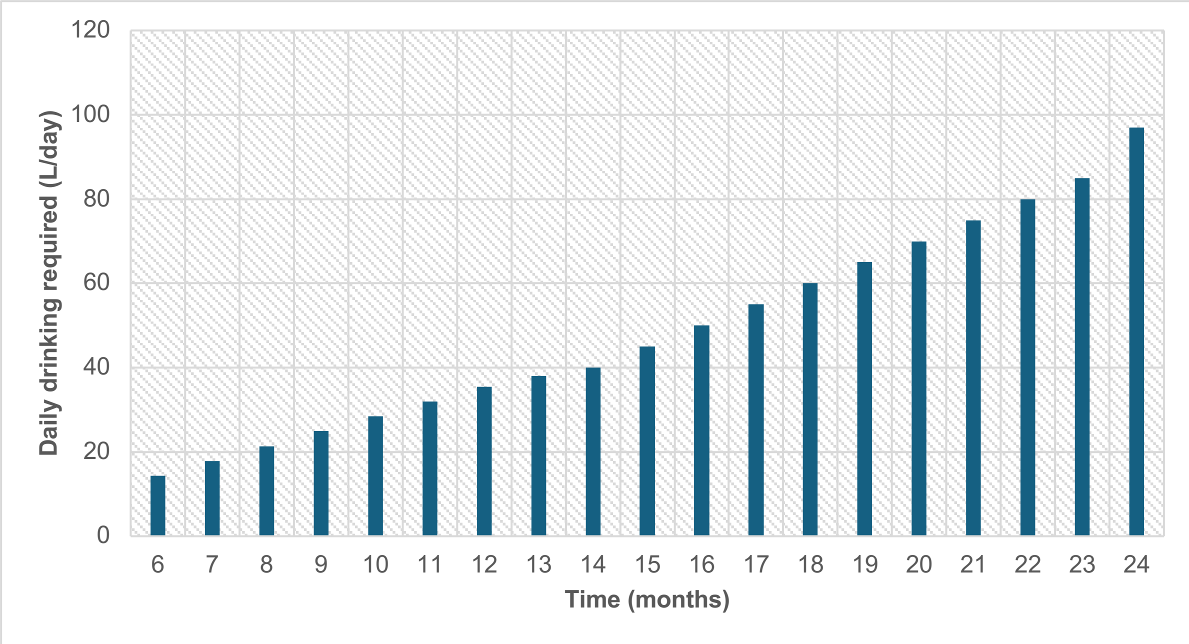


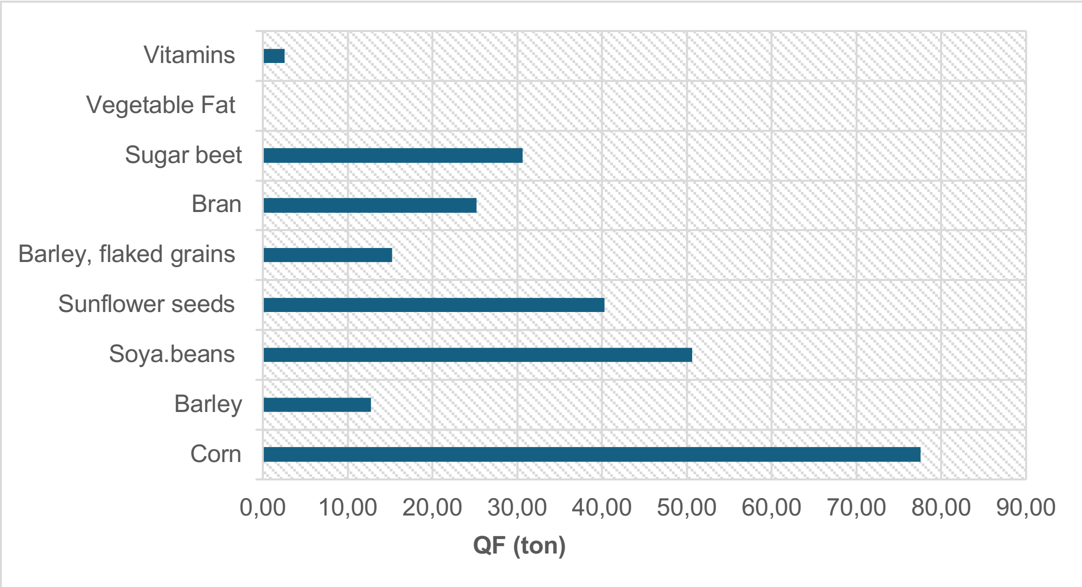

***Figure 10.*** *Daily Dairy Cattle Drinking Requirement*

Concerning livestock feed requirements, crops ratios were quantified according to the daily nutritional requirements, as previously presented for calves. The optimal quantities for each feed component were determined through extensive observations and by consulting multiple reference manuals relevant to provincial agricultural practices and the primary species reared. The feeding regimen was into the weaning phase and the fattening phase [51]. The weaning phase pertains to the diet administered to cattle aged between 6 and 12 months, the typical age range for heifers' pregnancy. The fattening phase encompasses the adult stage of cattle, when the diet is standardized until the end of the animal's life. In ***Table 3*** the average values of fodder components for both the weaning and fattening stage are reported [52]. While the weaning phase marked the dietary transition, gradually incorporating appropriate portions of solid feed, during the fattening phase, the animal is intended to be fed with a targeted diet to optimize weight gain [42]. The key assumption here is differential fodder requirement based on developmental stage, hence on body weight. As for calves, the daily quantity of fodder necessary for one single head and for dairy cattle was calculated. ***Figure 11*** summarizes the tons of crops required per cow and as aggregated monthly needs for the entire provincial herd.

| *Type of crop* | *Weaning (%)* | *Fattening (%)* | *Quantity per cow (ton)* | *Quantity per cattle (ton)* |
|---|---|---|---|---|

| | | | | |
|---|---|---|---|---|
| Corn | 30 | 48 | 77,59 | 266976,40 |
| Barley | 5 | 5 | 12,77 | 28589,05 |
| Soya | 20 | 12 | 50,65 | 71937,52 |
| Sunflower seeds | 16 | 6 | 40,33 | 38461,60 |
| Barley | 6 | 4 | 15,22 | 23702,19 |
| Bran | 10 | 8 | 25,18 | 21735,78 |
| Sugar beet | 12 | 12 | 30,65 | 68613,73 |
| Vegetable Fat | 0 | 2 | 0,06 | 5427,71 |
| Vitamins | 1 | 3 | 2,58 | 8367,95 |

***Table 3***. *Inclusion percentage of crop and total quantities of crop per cow and per cattle.*



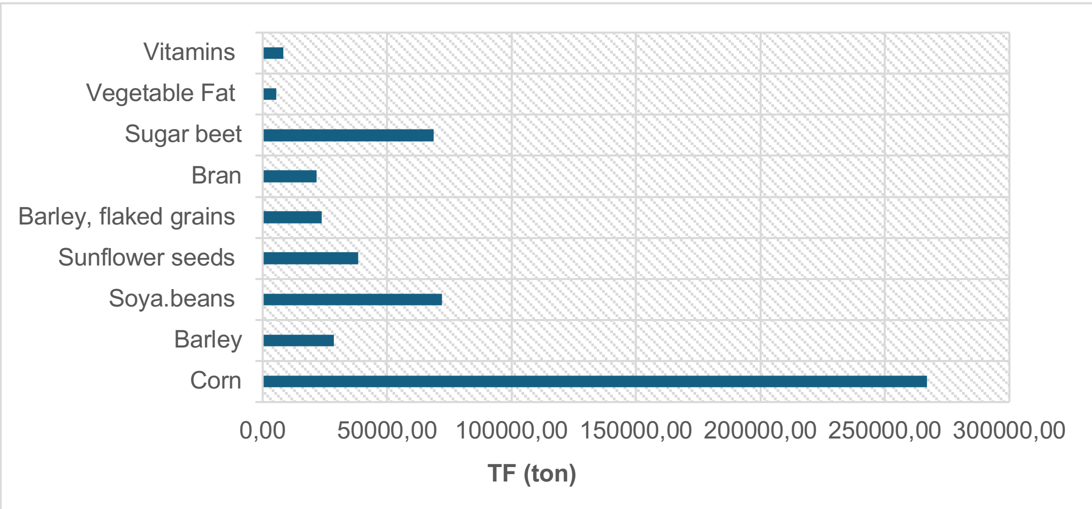
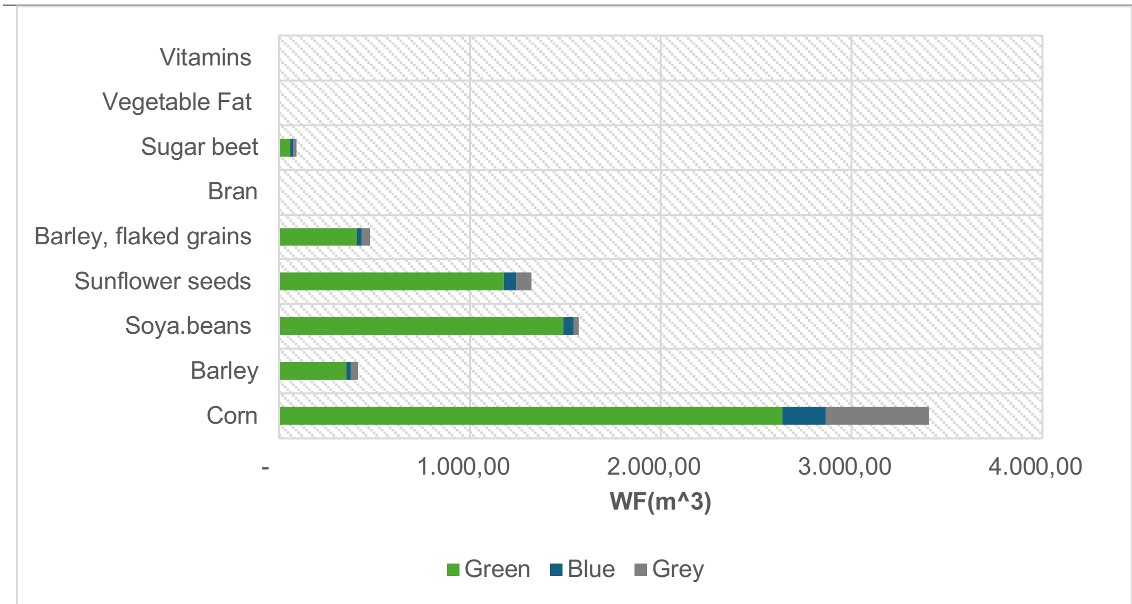




***Figure 11***: *Tons of crop required for dairy cattle*

### *5.2.1.1 Water footprint for dairy cattle*

As for calves, the total WF is calculated by summing the values of the drinking water required each day and the water needed for fodder production.

The WF needed for one specific crop per head and per herd was calculated in terms of green, blue and grey water, normalized in $m^3$ as depicted in ***Figure 12.*** Altogether, the total WF per calf was X and per herd was Y. Compared to the calves' results, a relevant impact of corn requirement is observed in adults, with this type of crop being essential in their diets. Green water appears once again as the predominant water source driving fodder production [68].



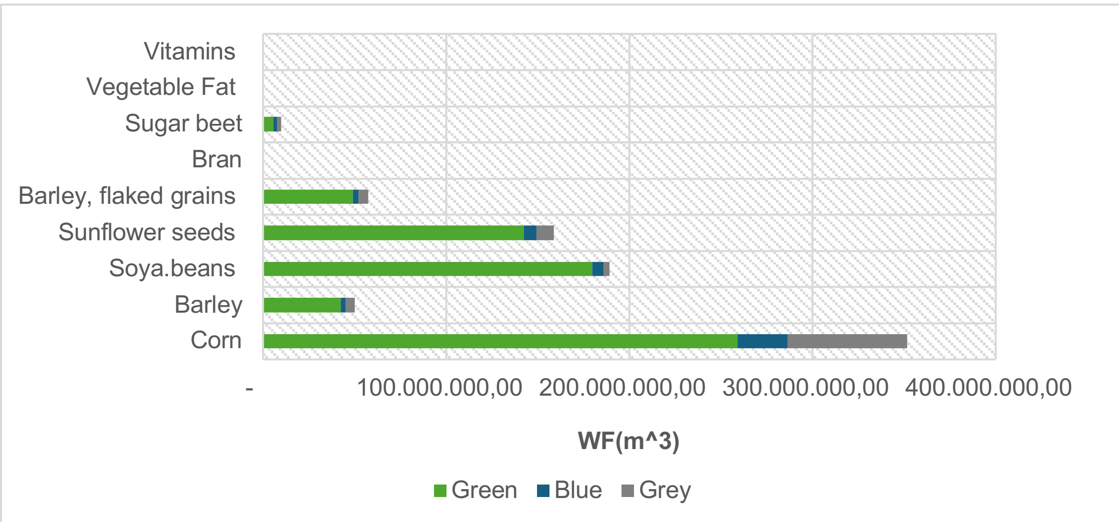




***Figure 12***. *Water footprint associated with crop production for dairy cattle*

The total WF from fodder-related water and drinking water requirement therefore amounts to 7340 $m^3$ per cow over the lifespan considered. The total WF, compared to the approximate 15400 $m^3$ per ton reported by Hoekstra's estimates, is 10794 $m^3$ per ton. However, service water was excluded by the present analysis due to limited data availability within the evaluated production system, while it accounted for 80 L/day in Hoekstra's estimates, thereby exerting a considerable effect on the final estimated value. On the other hand, the inclusion of drinking water per cow and per cattle in the presented estimates could have a negligeable effect when its proportion is compared to forage-related water (***Figure 13***).

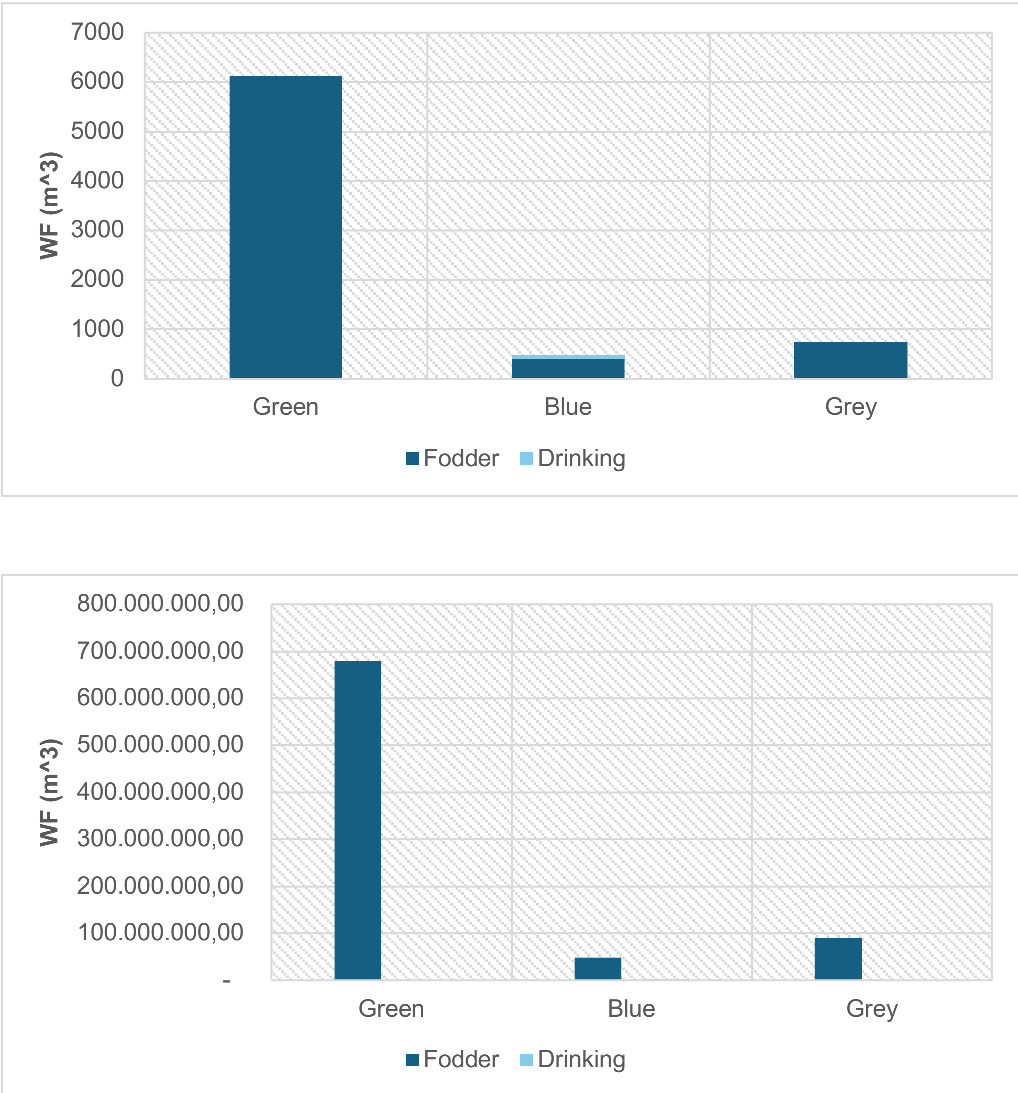



***Figure 13.*** *Total water footprint for one single head and for the total herd of dairy cattle*

### *5.2.1.2 Milk production and derivatives consumption comparison*

The quantity of milk produced was considered based on previous results by Erdman and Varner (1992) [53]. It was assessed that the gestation of the cows lasts approximately ten months. Given that the optimal interval between births is around one year, the second calving is expected to occur at about three years of age, with subsequent calvings following this annual cycle. Consequently, the standard unproductive period, known as the dry period, is approximately two months (60 days). From this consideration it was possible to calculate the amount of milk produced from one single cow during every pregnancy. For the sake of the present project, this value was estimated to one year of production, allowing to infer the quantity of produced milk per animal throughout the lifespan. The values of milk produced ($MP_x$) in one year are instrumental for a comparison with the quantity of milk industrially produced and sold in the territory within the same timescale.

Insights into milk production trends are provided in ***Figure 14***, which estimates that each dairy cow undergoes at least three pregnancies during its lifetime, thereby qualifying as a tertiary producer. Total milk production for the entire cattle population was calculated under the best-case scenario assumption that all cows produce milk on at least three occasions during their lifespan. The milk production curve demonstrates a significant reduction in output between the 9th and 12th month—a reduction that facilitates weaning by encouraging calves to transition to increased solid food intake.

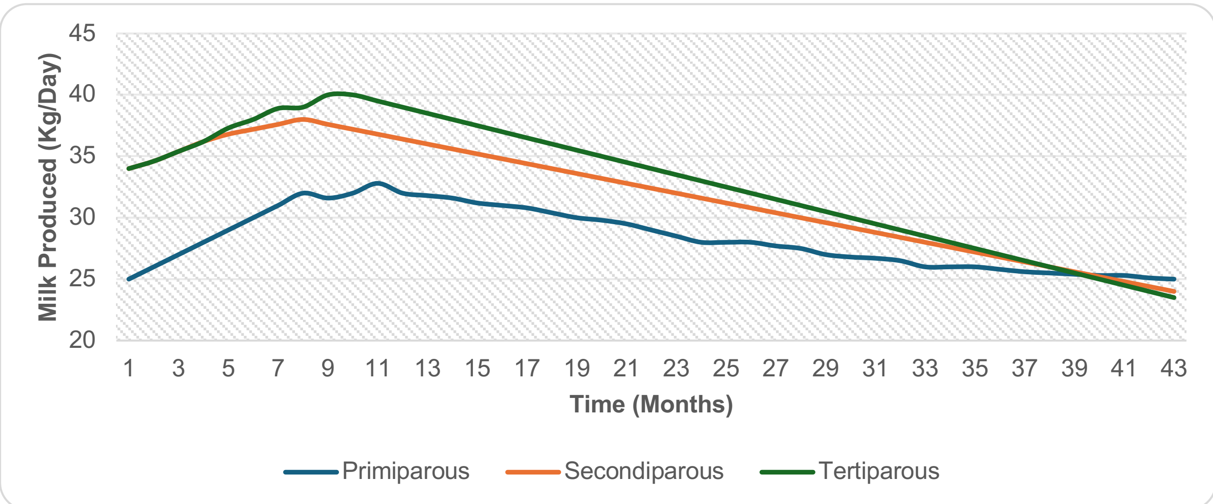



***Figure 14.*** *Milk production curve.*

The final step of this analysis focuses on the transition between the milk that is effectively produced and its sale within the territory. Data for this study was sourced from the

ISTAT dataset, which provides information on milk production in quintals per year, along with details on various milk derivatives. For this project, milk and its derivatives were categorized into whole milk that is produced and sold, classified according to its fat content and all milk derivatives, where the percentage of milk content in each product was analysed. The water footprint related to the milk production was then calculated based on literature studies by Hoekstra. Regarding the first classification, milk was divided according to fat content, as for Hoekstra (2011); Whole milk is assumed to contain 6% milk fat. Reduced-fat milk, commonly labeled as 2%, offers a balance between flavor and lower fat content. Low-fat milk, labeled as 1%, caters to consumers seeking further fat reduction while maintaining some creaminess.

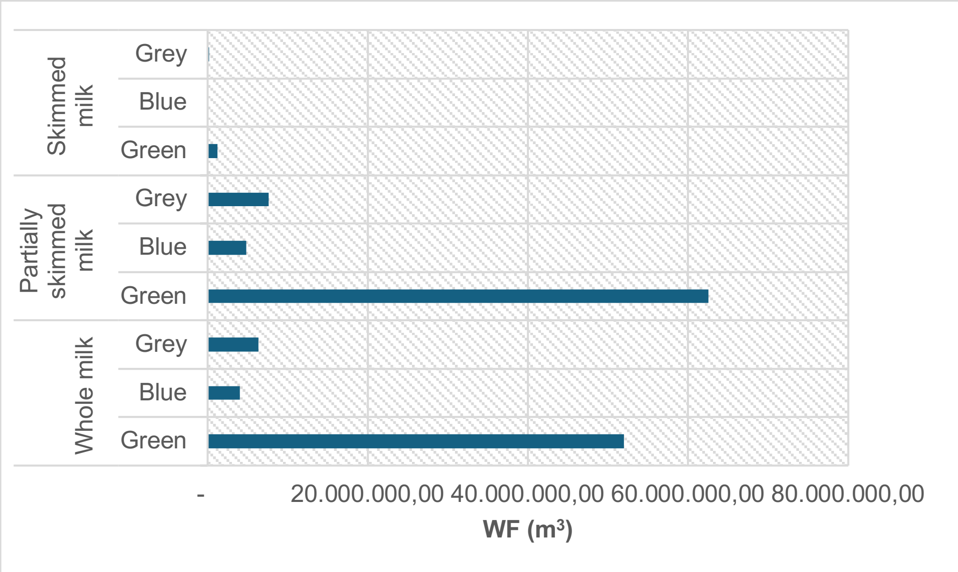
Literature analysis and statistical reports gave the possibility to assess an estimation of the amount of import/export of milk in the province. From official reports of the Regione Piemonte, it emerged that the quantity of milk produced in Cuneo in 2020 amounted to 55% of the total production. Interestingly, validation data from statistic websites such as Ismeamercati [54] and Arapiemonte [55] allowed to assess the amount of import/export inside the region and in the province. Based on the latest annual data from CLAL, of the 1209000 tons of milk delivered across the Piedmont region, 50% was produced in the province of Cuneo [69]. Regional reports consistently indicate that Cuneo contributes approximately half of Piemonte's total milk production. Assuming that all dairy cows in the area act as tertiary producers—achieving peak milk yields—the estimated total milk production per cow is approximately 9890 kg over a 10-month lactation period. Of this quantity, around 1300 L are allocated for early calf feeding, leaving approximately 8 tons per cow available for milk processing and dairy production.

In 2023, ISTAT data recorded a total bovine milk production of 585,700 tons. However, our model estimates a final production of approximately 637,855 tons due to the selection of the best-case scenario (i.e., third lactation period for all cows). From this total, 213000 tons are allocated for calf nourishment. Of the remaining volume, only 0.07% undergoes hygienic processing—equivalent to 29,739.95 tons of milk intended for direct sale, classified by fat content—while 0.1% of the total output (42,485 tons) is allocated for cheese production.

Furthermore, the Consortium for the Protection of Grana Padano identifies Cuneo as one of the leading producers of Parmigiano Reggiano. In 2024, approximately 42,828 wheels of Parmigiano Reggiano were produced. Given that a single 40-kg wheel requires roughly 600 liters of milk, it is estimated that 25,696 tons of milk were dedicated exclusively to Parmigiano Reggiano production.

### 5.2.1.3 Water footprint for milk and cheese

Considering the aforementioned classifications for milk types (whole, skimmed, and partially skimmed) and its derivatives (unfermented fresh cheese and processed cheese), the specific WF are summarized in ***Figure 15***. Specifically, the total WF were 62338343, 75007632, and 1445076 for whole, partially skimmed, and skimmed milk, respectively. Similarly, the WF were 172036235 and 5011924 for processed cheese and unfermented/curd cheese, respectively. As before, green water sources were the predominant ones.



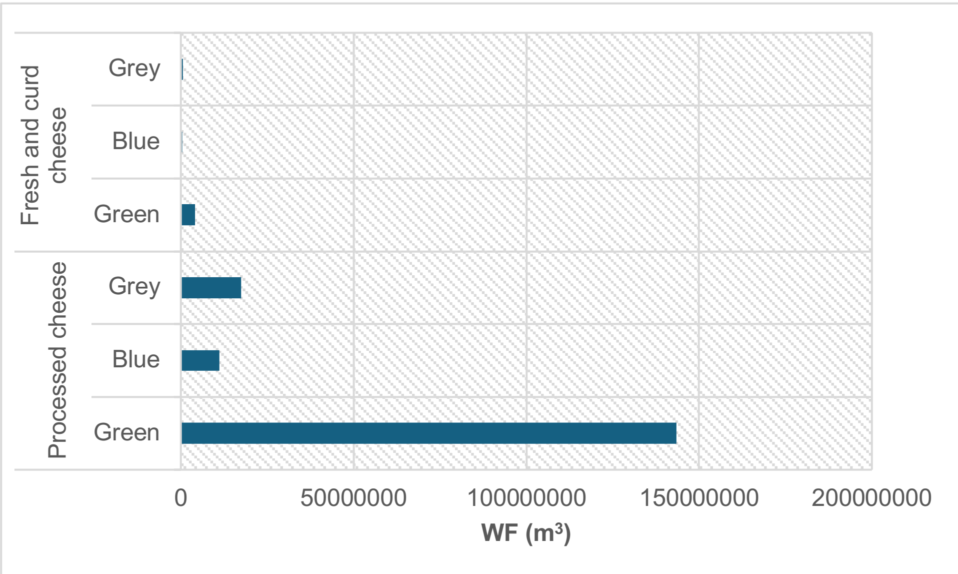




***Figure 15.*** *Water footprint for milk and its derivatives produced in 2023 in Cuneo.*

## *5.2.2 Meat Cattle Quantification*

The last group consisted of the *Piemontese* beef cattle, bred for meat production, equally undergoing weaning and fattening phases, ultimately resulting in slaughtering. Most of the scientific studies were based on the appropriate strategies for breeding the *Piemontese* species, renowned for unique genetic traits granting lean meat with low cholesterol levels. The study of this breed dates back to centuries, but it was the scientific analysis that led to identify the perfect approach for ideal growth. This analysis focused on a 32-month rearing period, the typical lifespan before slaughter.

As before, meat cattle were described in terms of weight, growth patterns, daily water requirements, fodder-related water requirements, and meat production.

In terms of weight (***Figure 16***), a linear trend is observed from the end of the calving period (6 months) until reaching 12 to 15 months. During this period, beef cattle are provided with protein-enriched diets to optimize muscle development and meat quality. Growth generally stabilizes around 24 months, necessitating the maintenance of optimal health conditions to ensure high-quality meat upon slaughter.

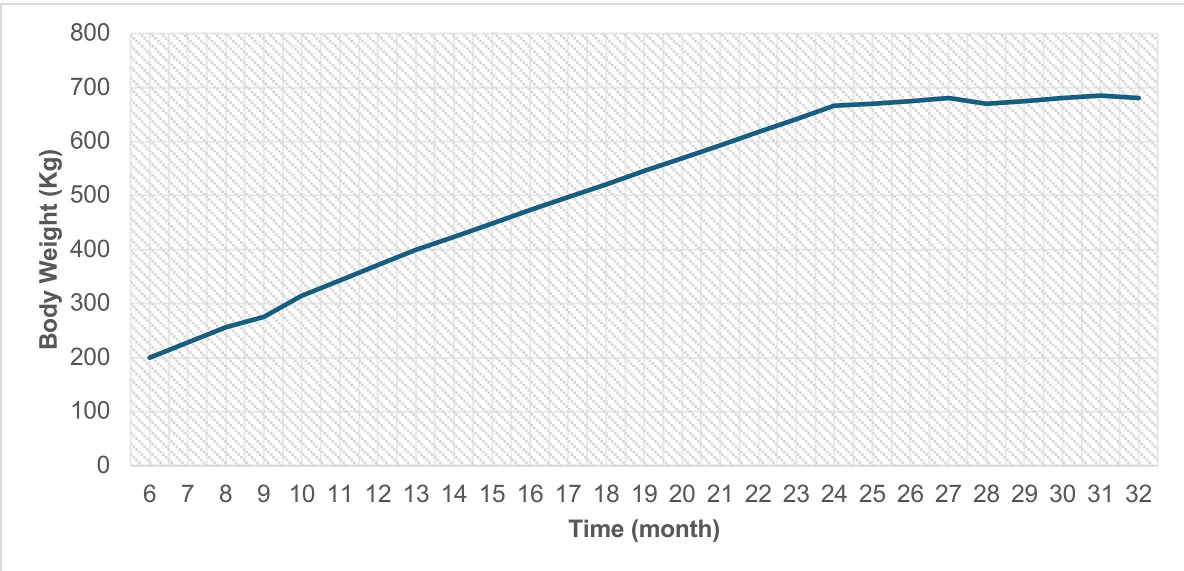



***Figure 16****. Meat cattle growth curve*

The growth curve is correlated with the daily drinking water requirements to estimate the total water consumption for each individual animal (**Figure 17**). This approach allows for the tracking of water needs throughout development. Overall, the total drinking water requirement per cow was 46140 L, while per cattle it was 2394188040 L. A slight fluctuation in water requirements between 24 and 28 months of age could be accounted by cattle adapting to stabilized body weight and corresponding feed intake. This stabilization period may lead to minor variations in daily water consumption, reflecting the animal's adjustment to its steady physiological state. Compared to Hoekstra's estimate, however, the average daily drinking water requirement for dairy cattle in this analysis was 55 L/d compared to 27 L/d in theirs. This considerable discrepancy could be accounted by our reliance on non peer-reviewed sources, possibly leading to overestimations, highlighting once again the need for more meticulous recordings.

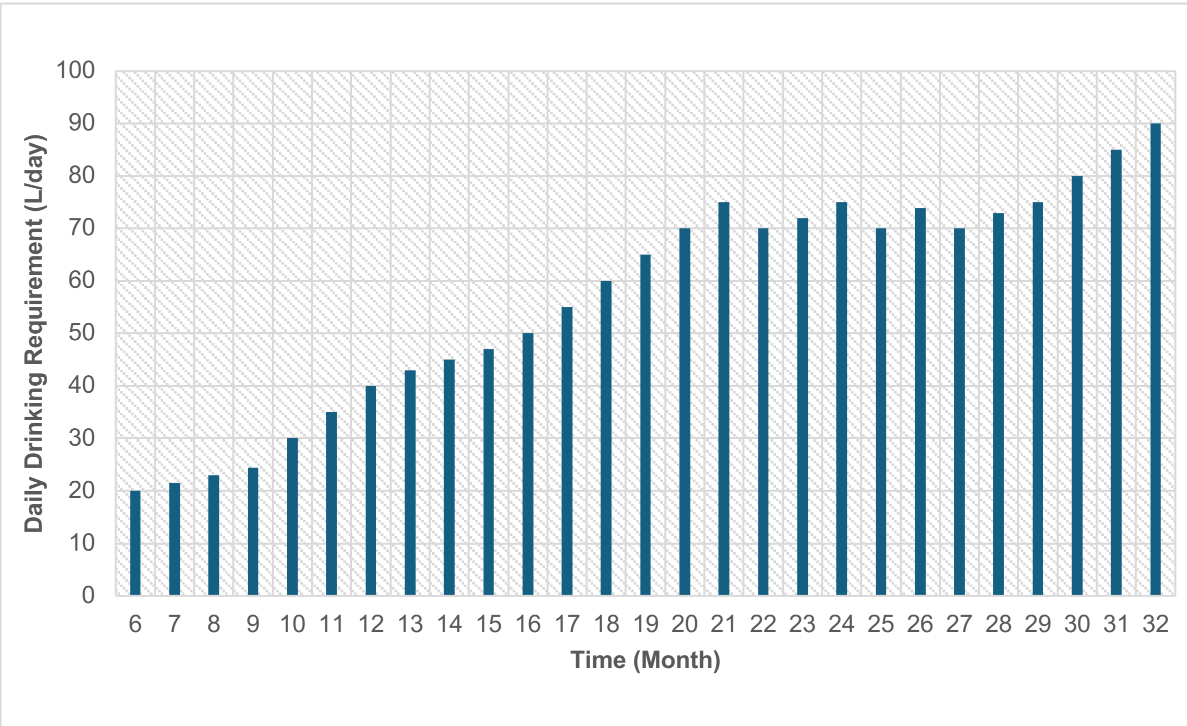



***Figure 17.*** *Daily drinking requirement for meat cattle (L/day)*

In terms of forage, the quantity of feed was firstly assumed for a single head, with crops proportions being the same as for the dairy cattle (***Table 3***). The total crop requirements in tons for a single head and for the cattle are depicted in ***Figure 18***.

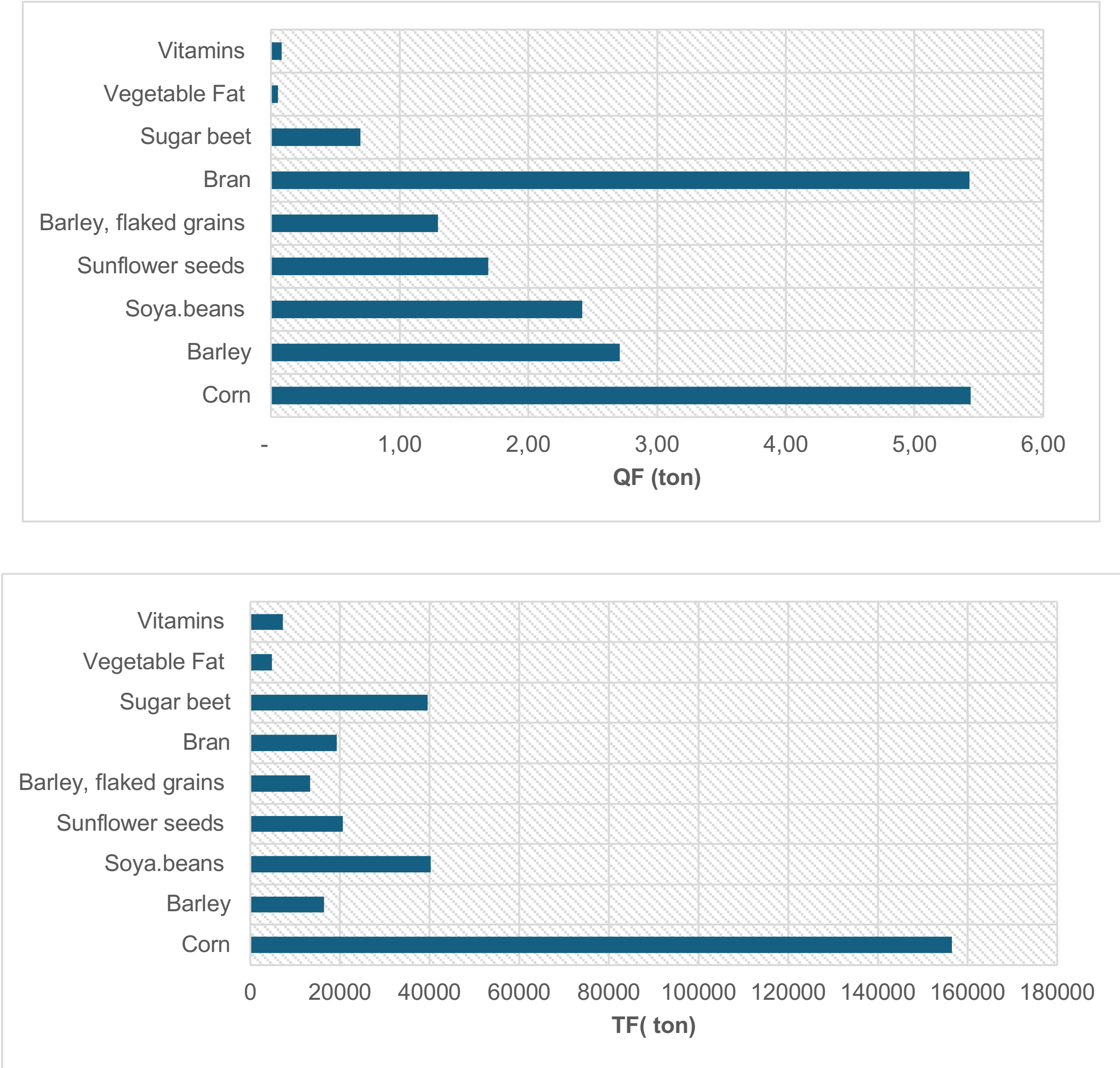
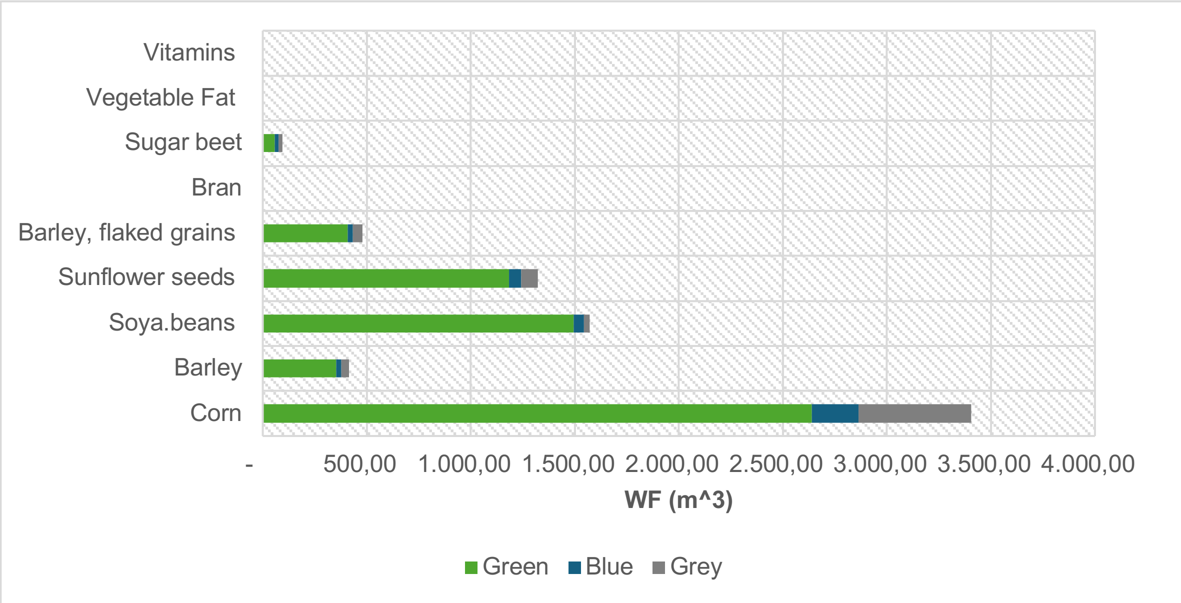



***Figure 18****.Tons of crop required for one meat cow and total cattle.*

### *5.2.2.2 Water footprint for meat cattle*

The total WF was again calculated based on forage-related water and drinking water requirements and reported in ***Figure 19***. The total forage WF for a single head was 7309 $m^3$ while for the cattle was 808161243 $m^3$. As before, a more central role of corn crops is highlighted in the adults compared to calves' requirements [68].



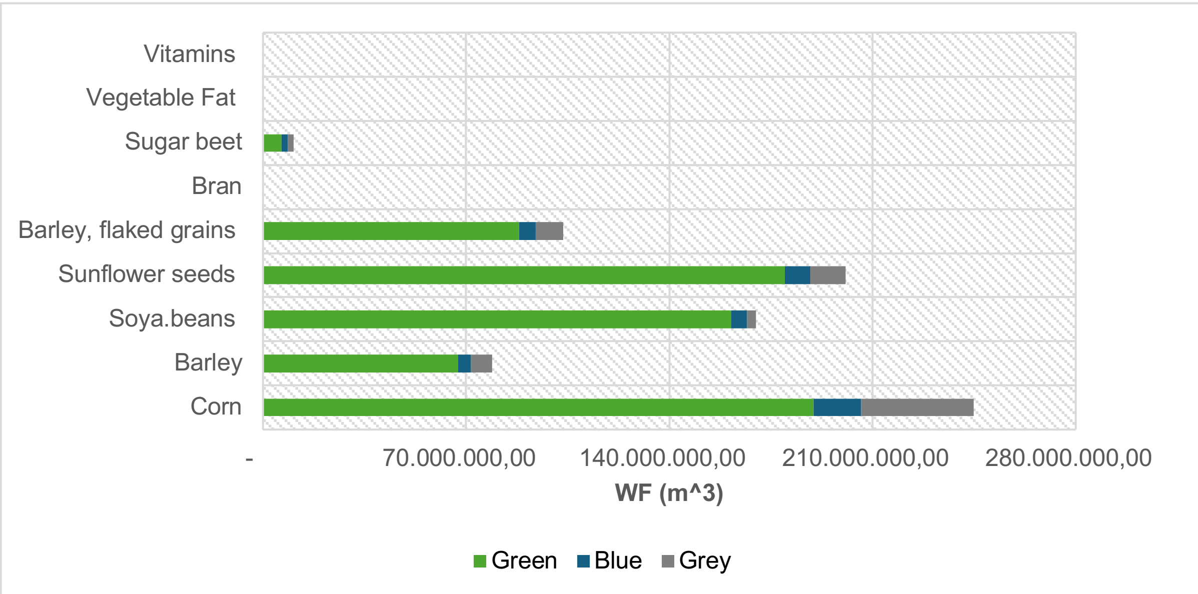
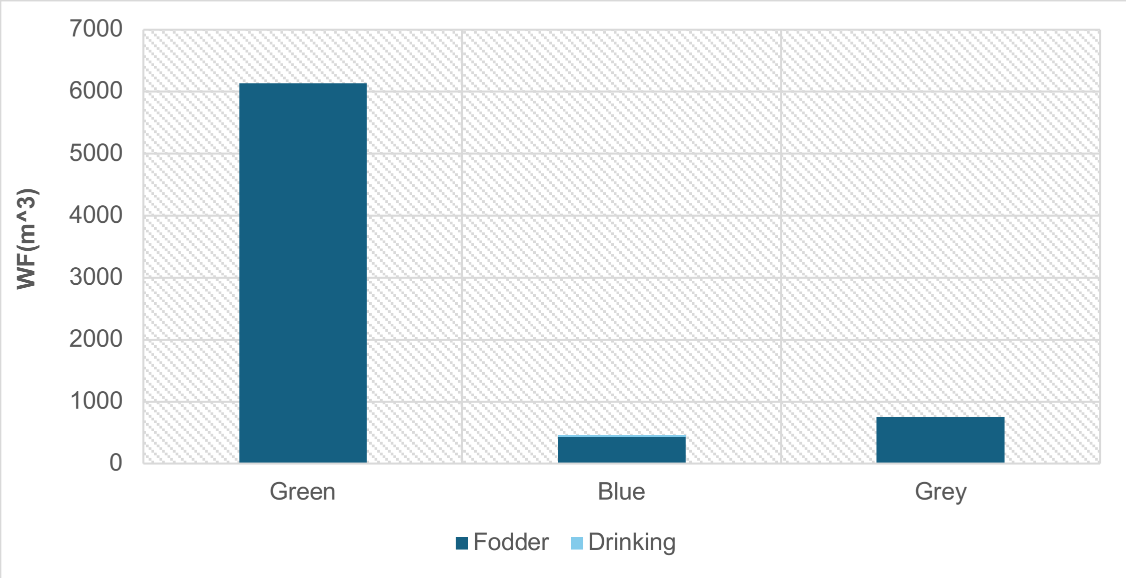




***Figure 19.*** *WF for fodder production*

The total WF when considering forage and drinking water was 7355 m$^3$ per animal and 810654932 m$^3$ per cattle (***Figure 20***). The total WF, compared to the approximate 15400 m$^3$ per ton reported by Hoekstra's estimates, is 10507 m$^3$ per ton. These results suggest that beef cattle may have a higher overall virtual water footprint compared to dairy cattle, possibly due to the longer lifespan of *Piemontese* cattle. When comparing the total WF of the present analysis to Hoekstra's estimates (15415 m$^3$ per ton), our significant lower estimate could be accounted by different weight estimations and the exclusion of service water as described in dairy cattle.



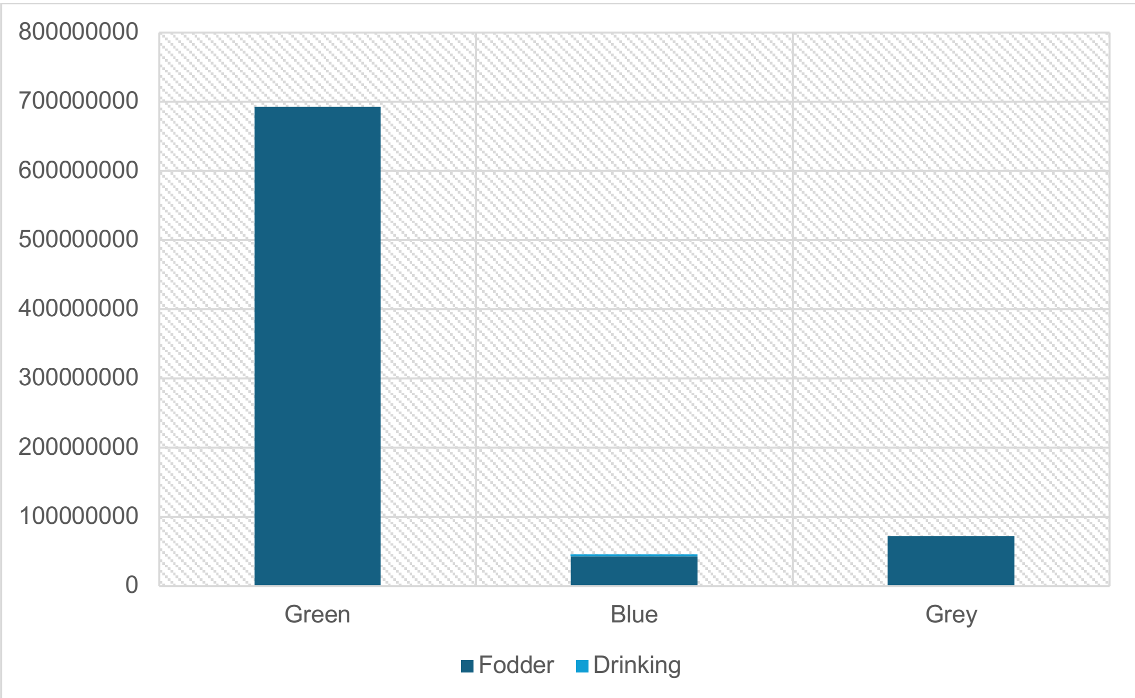




***Figure 20***. *Total WF of single head and meat cattle*

### 5.2.2.3 Meat production and consumption

Based on the 2023 data collected by Ismea [69] on the meat sector, the European Union ranks fourth in production, with approximately 6.3 million tons of beef meat produced. At the national level, the per capita consumption across the entire country is estimated at around 16 kg. The Piemonte region ranks first in terms of livestock numbers, with a total of 477000 animals dedicated to meat production. The data recorded by the BDN cattle registry confirm our findings regarding daily weight gain, slaughter age, and livestock consistency. Regarding national imports, the Italian market is highly dependent on foreign supplies. Imports of fresh and frozen beef account for 4.3% of national demand, with Poland contributing 22% of total imported beef and France 12%. Concerning live cattle, approximately 8% of the national stock originates from French imports, 78% of which comes from French beef farms. Beef ranks second in terms of meat demand in the national market, significantly lower than poultry consumption but higher than pork consumption. [69]

According to the BDN, as of January 1st, 2023, the number of cattle slaughtered in the nation accounts for 15% of the total cattle slaughtered nationwide. Observations related to the province of Cuneo are consistent with our calculations, with estimates for 2023 indicating that the total number of cattle slaughtered in Cuneo was 217167. This figure includes all causes of animal death, of which only 0.02% were not destined for slaughter. [40]

Considering our calculations on the amount of water required to produce cattle intended for meat consumption, we note that the total water requirement for meat-producing livestock in the entire province in 2023 amounts to approximately 1589319100 m³ (***Figure 21***).

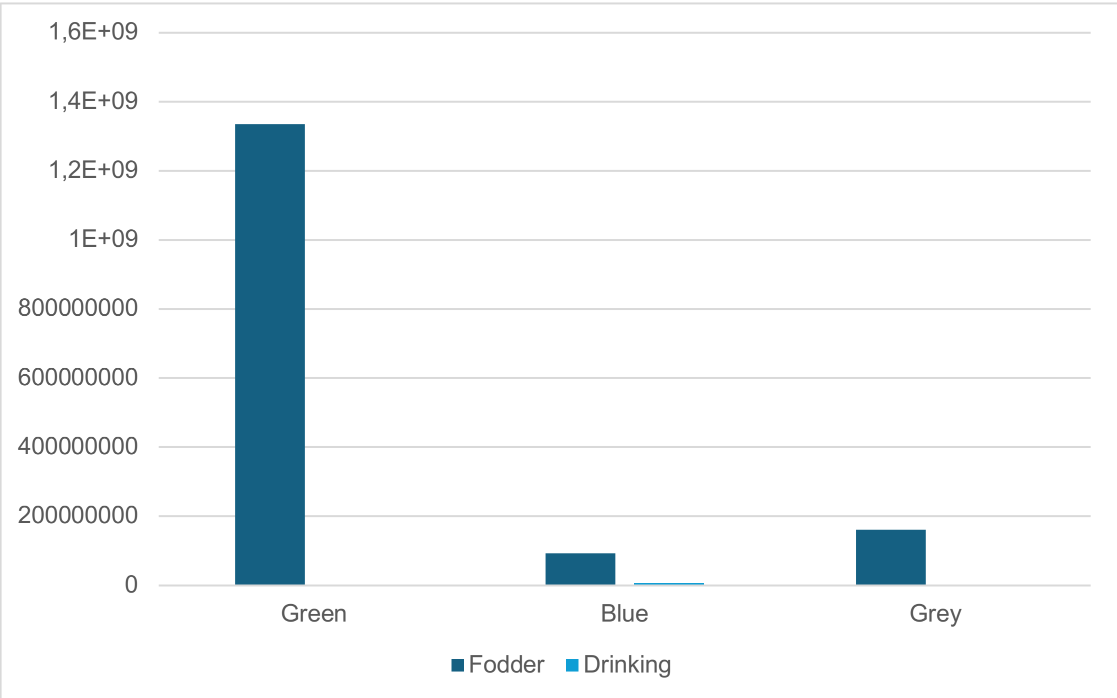



***Figure 21.*** *WF for total slaughtered herd*

## 5.3 Poultry

Poultry were divided in four age groups, namely, chicks with an age below six weeks (poultry covered with down prior to gradual replacement with mature feathers), pullets of age 7-19 weeks, being female chickens that are not able to produce eggs, laying hens (21-70 weeks) capable of laying eggs, and hens in the declining phase (above 70 weeks) along with all male chickens aged between 20 and 36 weeks. As for meat chickens, they were excluded from the calculation of the final product but had a significant weight in the quantification of water coming from feed. Even though in nature these animals can survive up to 7-8 years, in farms their lifespan is reduced to 36 weeks, hence explaining our assumptions.

In Cuneo, the "all-in/all-out" farming system was employed in this approach, encompassing housing units populated with a homogeneous group of poultry, which, after reaching market value, are sold, while the facilities are emptied and sanitized before initiating a new production cycle. This method was considered optimal as it allows for thorough disinfection of the housing units prior to each new cycle [64]. Additionally, it facilitated the quantification of animals over a consistent lifecycle, thereby homogenizing data and enabling a more robust assessment of egg production.

Poultry was described in terms of weight, daily drinking requirements, fodder-related water use, and egg production.

### *5.3.1 Poultry Quantification*

***Figure 22*** illustrates the growth curve of the Livorno hen, the most prevalent poultry breed in the province of Cuneo. The quantification of the water needed started from the growth curve. Literature studies from the University of Padua showed that the curve initially follows an exponential trend followed by a linear one. The growth curve is segregated by sex, revealing an oscillatory trend beyond 300 days of life (approximately 10 months). However, data are presented only up to 270 days due to concerns over reliability beyond this timeframe. This fluctuation is attributed to the stabilization of body weight as hens reach their peak physiological development. The data further indicate that female chickens achieve a higher final weight than males, reflecting inherent differences in metabolic rates and growth efficiencies between the sexes.

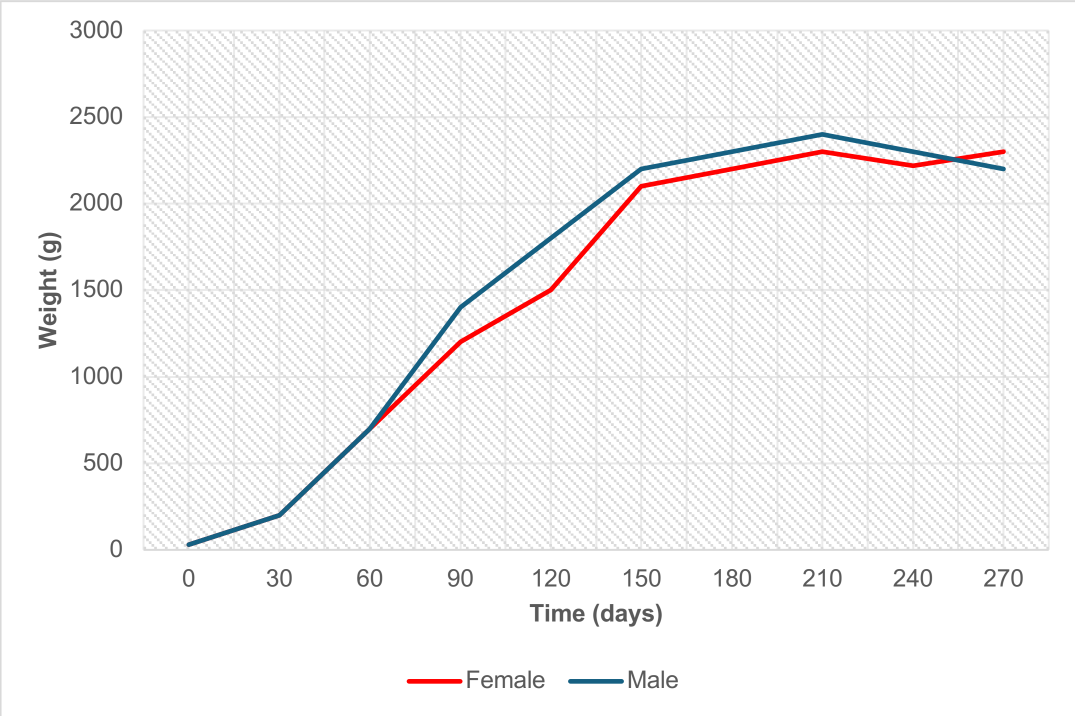



***Figure 22.*** *Poultry growth curve divided by sex*

***Figure 23*** summarizes the evolution of water consumption in poultry over a 32-week period, with measurements taken with four-week intervals. The data, based on the premise that water intake is directly proportional to body weight, reveal that male birds ultimately exhibit a higher average body weight and corresponding water consumption than females. This consistent proportional relationship throughout the growth period suggests a stable metabolic efficiency in poultry. Additionally, the observed differences between the sexes highlight inherent variations in growth dynamics and physiological needs, underscoring the potential benefits of tailoring nutritional and hydration strategies to optimize production performance. Beyond age, we accounted for the daily water intake assuming it to be thrice the animals body weight (BW) as indicated by previous data concerning the *Livornese* species and potential sex differences. Specifically, daily water intake ($DW_{Poultry}$) was computed as

$$DW_{Poultry}\left(\frac{L}{week}\right) = BW\ (g) * 3$$

Total drinking water for the worst-case scenario per head was 0.19 m³ and per herd was 10787.83 m³.

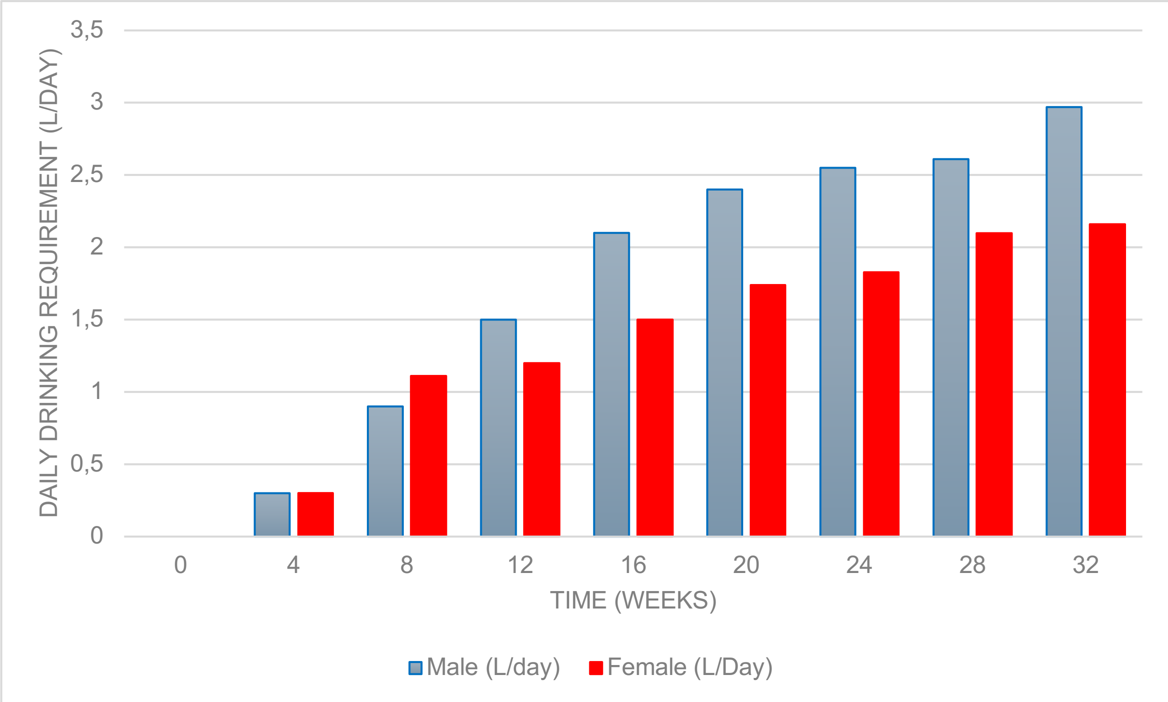



***Figure 23****.Weekly drinking requirement for poultries distinguished by sex.*

As for cattle, the estimation of the quantity of fodder needed for one head and for the entire species were calculated [65]. As before, we adhered to local guidelines to evaluate the appropriate proportions of each crop intended for feeding. The fixed amount of fodder given to every chick daily was assumed to be 125 g. Different percentages for each age group were calculated based on their specific necessities. For instance, animals' macronutrients requirement differed according to sex, with males requiring 22% of proteins compared to 18% for females. Similarly, age differences were evident when evaluating soybean size consisting of a 10% increase for younger individuals. A low-growing poultry breeds requires strategies tailored to them ensure the animals' wellbeing and not using it as a growth accelerator. Observations and studies provided that an overly dense ration can in fact lead to rapid growth predisposing poultry to stress and increasing susceptibility or to overcoming diseases. On the other side, unbalanced diets can weaken chickens, making them more prom to diseases [63].

***Figure 24*** presents the quantitative distribution of the primary feed ingredients used at various stages of the animal life cycle, highlighting a distinct shift in dietary composition over time and significant variations in soybean meal content. During the early growth phase of chicks, the diet is formulated to include a high proportion of soybean meal—approximately 28%—to ensure sufficient protein intake for early skeletal and muscular development. As the poultry transition into the pullet and laying hen phases, the soybean meal content is reduced to around 18%, while the relative proportions of wheat and corn increase to provide the necessary energy balance for optimal egg production. Concurrently, the intake of sunflower seeds and dietary fibers is lower in laying hens compared to younger birds, suggesting that a high fat content is less critical in mature birds and that dietary adjustments are implemented to maintain digestive efficiency. Altogether, these ingredients total approximately 480,286 tons, underscoring the substantial volume of feed required to support the entire poultry production system in the province of Cuneo. The findings further indicate that corn is a fundamental component in the feed formulation, with an especially high volume of water required solely for its production.

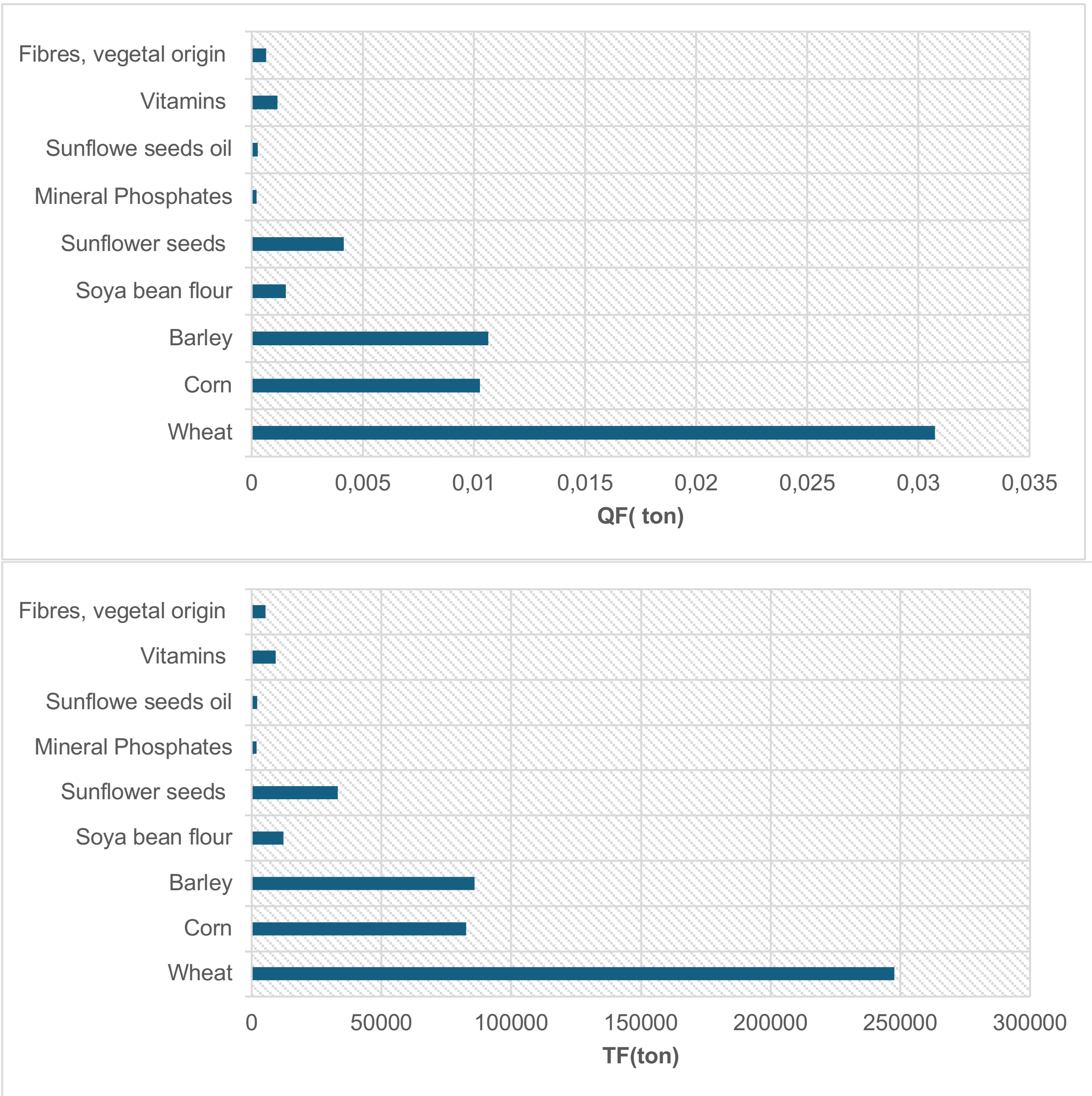



***Figure 24.*** *Crop requirement for one head and total poultry (ton)*

### 5.3.2 Water footprint for poultry

WF for fodder composition amounted for 8.37 $m^3$ for a single animal and 1496567.32 $m^3$ for the total herd. (***Figure 25***).

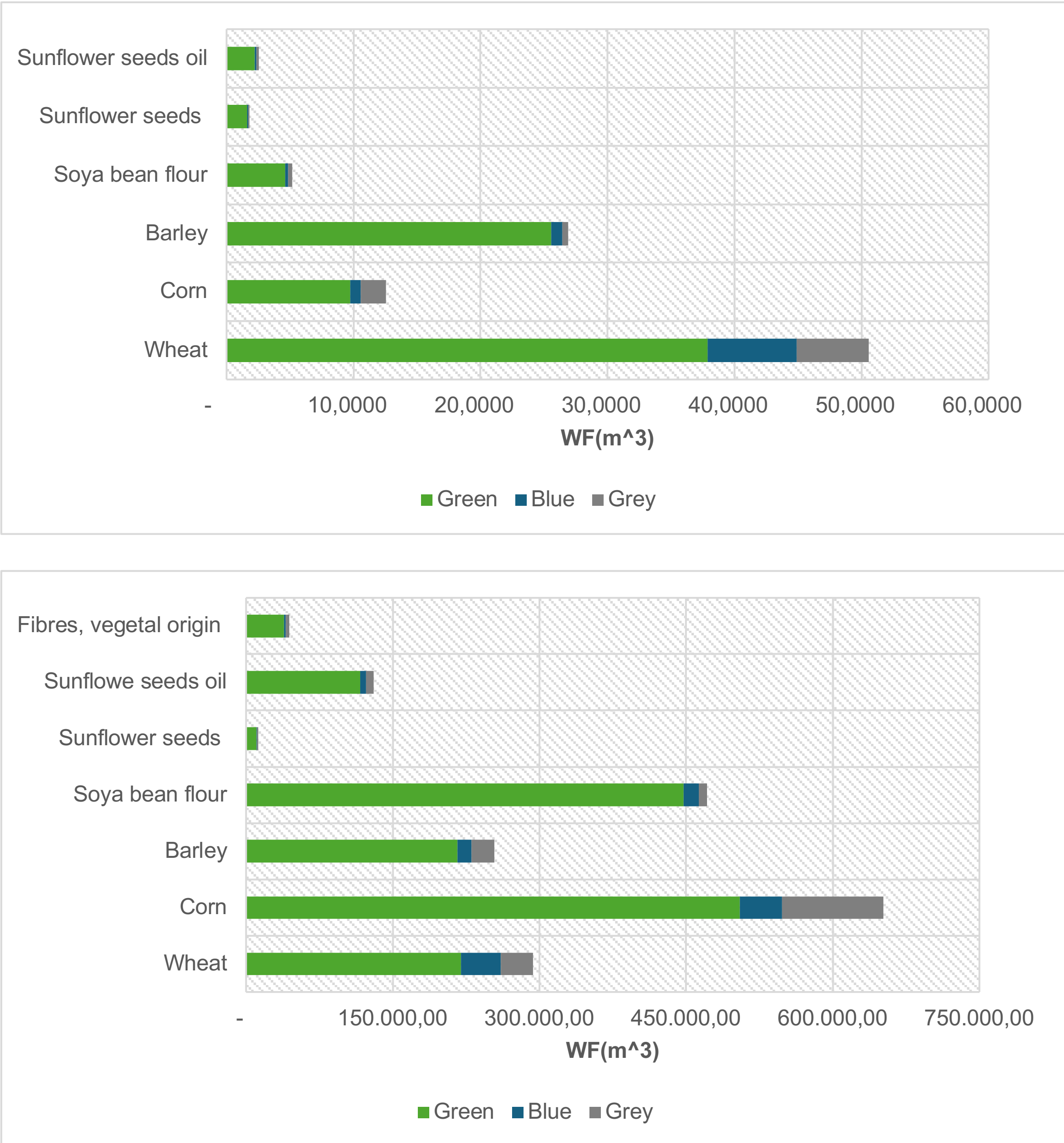



***Figure 25.*** *WF for poultry fodder production*

Combining the drinking water requirement and the fodder production, the total WF requirement for poultry was computed and corresponded to 53.21 $m^3$ for single unit and 1507355 $m^3$ for the whole herd (***Figure 26***). The total WF, compared to the approximate 4897 $m^3$ per ton reported by Hoekstra's estimates based on mixed breeding, is 7635 $m^3$ per ton. Results are inconsistent to Hoekstra's, due to lack of observation regarding service water and cleaning processes.

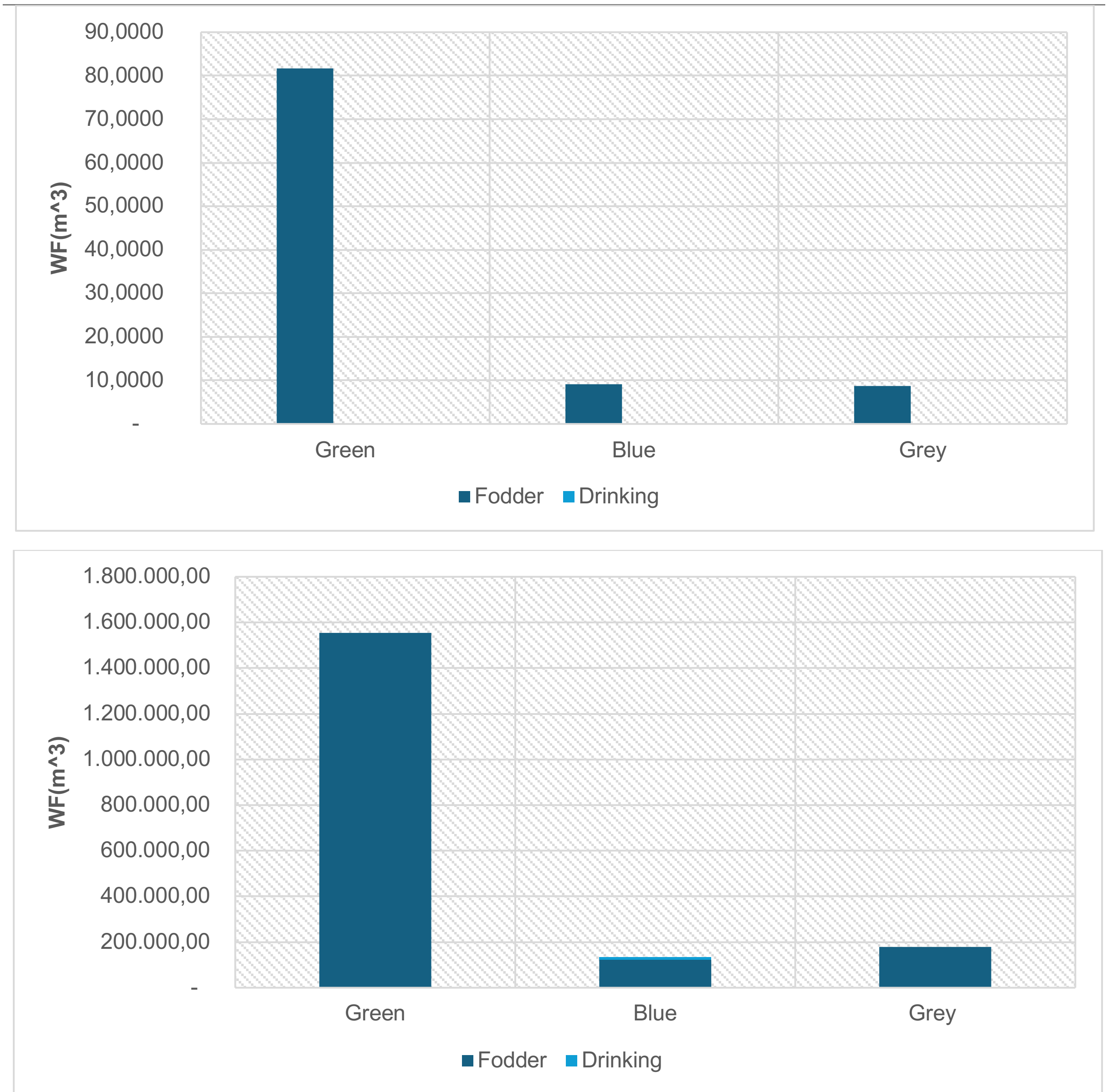



***Figure 26.*** *Total WF for poultries, calculated on m³ per animal and per herd.*

### 5.3.3 Egg Production

In the first two year of life, chickens of the *Livornese* species are estimated to produce 0,8 eggs a day, totalling almost 290 eggs a year [62]. Over a one-year period, the overall egg production by the entire population of laying hens is calculated by multiplying the number of eggs produced per hen by the total number of living hens. In 2023, this calculation yielded a total production of 349370250 eggs. The Total WF related to egg production in Cuneo is equal to 445447000000 m$^3$ per the totality of egg produced in 2023. Results are consistent with ISTAT data pertaining eggs produced in Cuneo.

## 5.4 *Swine Chain*

The farming of swine species within the province, predominantly focused on the production of heavy pigs, for traditional products like Parma ham was also considered [56]. Swine herd composition was estimated using data from the Single Agricultural Registry (Anagrafe Agricola Unica), with animals classified by age and breeding purpose. The total swine population in the province amounts to 934066 heads. Notably, nearly 60% of the herd comprised fattening pigs destined for the charcuterie industry—a sector of considerable economic importance in the province that contributes to 67% of Italy's total production. Among approximately 800 farms, data indicate that 70% are dedicated to the open-cycle production of pigs for charcuterie, while only 12% focus on breeding operations.

The classification starts with piglets, young pigs that have recently been weaned, typically weighing between 5 to 30 kilograms. As they continue to grow, they enter the weaner stage, which includes pigs that have been fully weaned from the sow and reach a weight of approximately 30 to 40 kilograms. Following this phase, pigs were classified as growers, referring to those in the active growth stage, generally ranging from 40 to 70 kilograms. As they approach market readiness, they enter the finisher stage, where they undergo final fattening before slaughter, typically reaching weights between 70 and 160 kilograms. Additionally, pigs intended for reproduction were categorized as breeding stock. This group consists of adult pigs maintained for breeding purposes, including sows (female pigs) and boars (male pigs), usually weighing over 160 kilograms.

### *5.4.1 Swine Quantification*

Swines were analysed based on weight, drinking water, and fodder-related water requirements. The analysis started from the study of the growth curve of the heavy pigs (***Figure 27***), taken as guideline for the entire species. From literature studies of the Professional Swine Community (Comunita' Professionale Suina) [58] it was possible to calculate the growth curve of heavy pigs comparing the duration of stays with the living weight. As before, crops proportions for a balanced diet were evaluated. The outcome of the research showed how they were typically raised to reach a weight of about 160-165 kilograms over approximately 180 days.

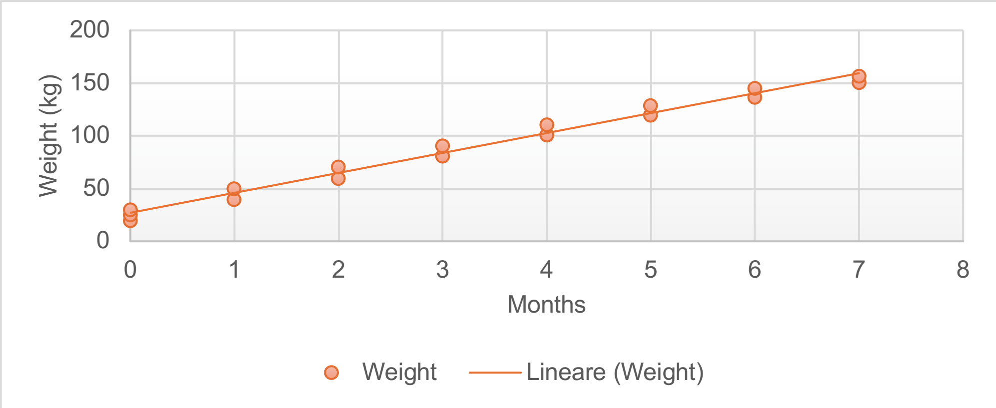



***Figure 27.*** *Swine growth curve*

Given that the outcome of animal drinking and feeding behavior is primarily determined by the combination of duration of visits, intake per unit time and number of visits to the drinker, assumption based on different authors made possible to estimate the daily drinking requirements. [59] Consequently, the analysis was conducted based on the average lifespan of production pigs. Previous reports indicate that the average lifespan for pigs raised for charcuterie is approximately 7 months at the time of slaughter. Moreover, the swine growth curve exhibits a linear trend from birth to market weight, with piglets starting at an average weight of 20 kg in the first month and reaching a final weight of approximately 160 kg. Similar to the analysis conducted for cattle, the growth curve of swine is a fundamental parameter, particularly when evaluated alongside their breeding purpose. Daily water intake is estimated at approximately 20% of body weight and is adjusted according to the animals' weight and age. The early stage of life (month 0-2) is especially critical. During this period, the growth curve exhibits a steep increase. Due to the initially diluted dry matter in the daily ration, the water requirement in these early weeks is markedly higher than at later stages. The total amount of water needed for the herd was then calculated instead by summing the amount of water needed per head for every single animal. Overall, the total drinking water requirement was 54,405 $m^3$ for individual animals and 50817860.73 $m^3$ for the total group (***Figure 28***).

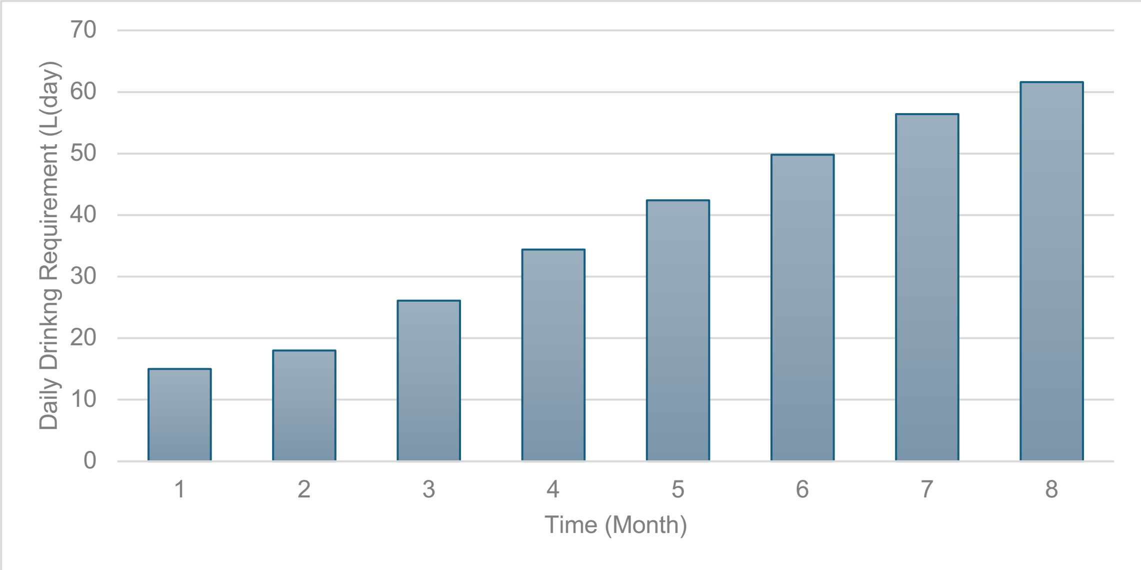
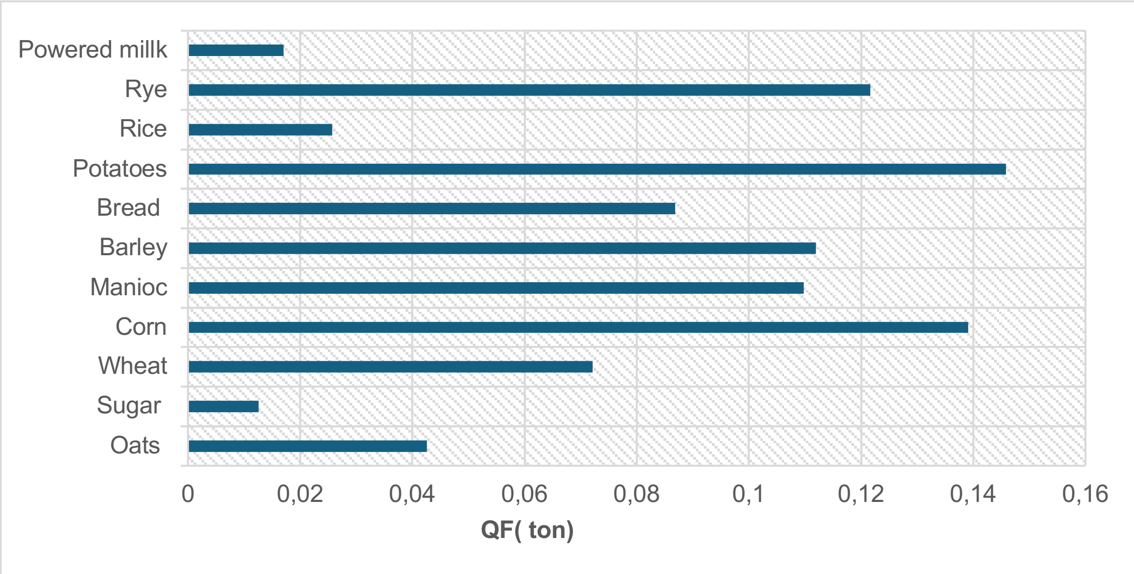



***Figure 28****.Daily drinking requirement for each swine*

In terms of fodder composition, crops proportions are presented in ***Figure 29***. Results suggest that oats are used at levels of up to 17.5% in piglets' diets to provide balanced energy that is gentle on the digestive system, whereas wheat is consistently maintained between 17.5% and 25% throughout all production phases to support sustained growth. Corn, recognized for its high digestible energy content, plays a major role during the growing phases by promoting lean muscle mass development. High-energy ingredients such as corn and potatoes are allocated in larger quantities, reflecting their role as primary energy sources essential for rapid growth and efficient feed conversion during the grower and finisher phases. Conversely, powdered milk is provided in smaller amounts due to its high nutrient density, cost considerations, and the necessity for precise nutrient balancing. Additionally, the inclusion of sugar and rice in modest amounts fine-tunes the energy profile of the diet, ensuring optimal performance at every stage of production.



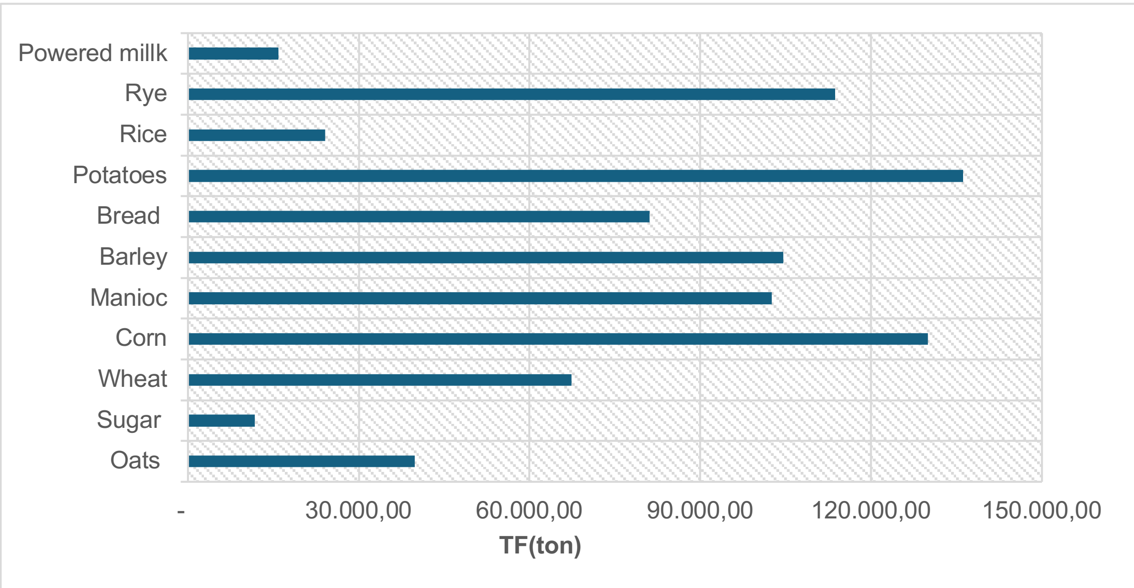
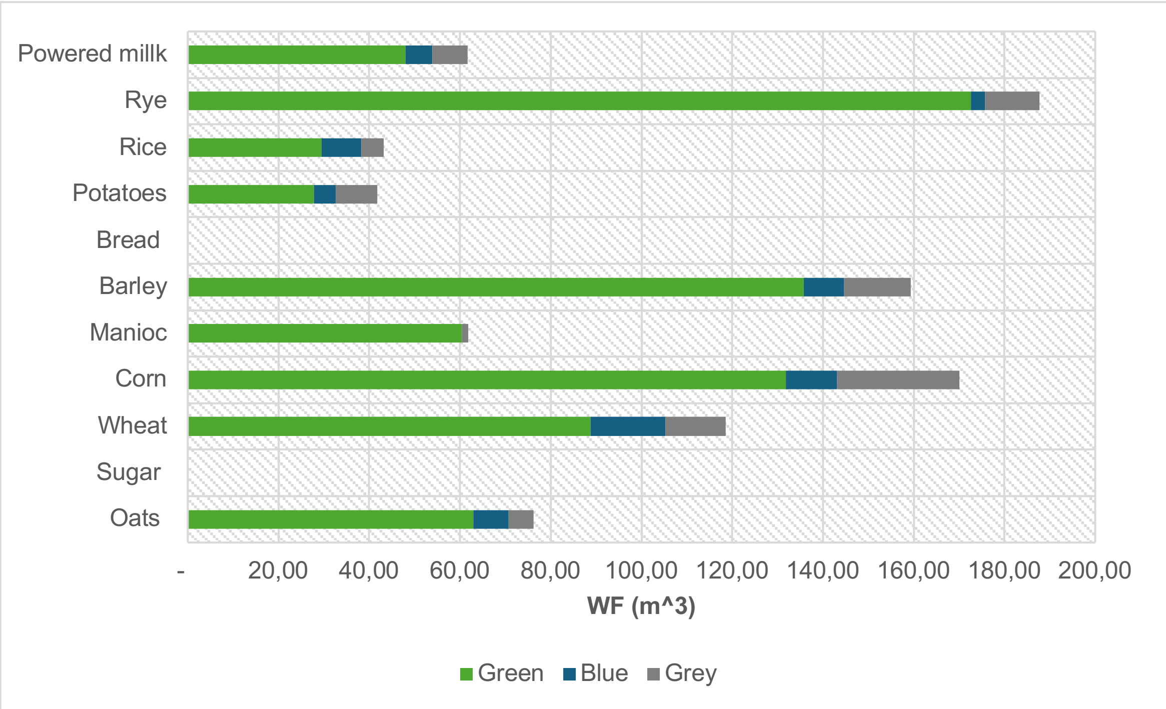




***Figure 29***. *Ton of crops required for fodder production*

## *5.4.2 Water footprint for swine cattle*

To compute the total water footprint, we evaluated firstly the fodder-related water use in m$^3$ for a single animal and then for the total herd, amounting to 920.19 m$^3$ and 859522727.06 m$^3$, respectively (***Figure 30***). These were then summed with drinking water requirements for the final WF estimation (***Figure 31***), corresponding to 986.60 m$^3$ for individual units and 921549379.79 m$^3$for total herd. The total WF, compared to the approximate 5224 m$^3$ per ton reported by Hoekstra's estimates, is 5750 m$^3$ per ton. Results are barely consistent with Hoekstra's once, with the final requirement for one pig being overestimated with respect to the world average, possibly due to the very high amount of water needed for their fodder and to the exclusion of service water from our estimates.



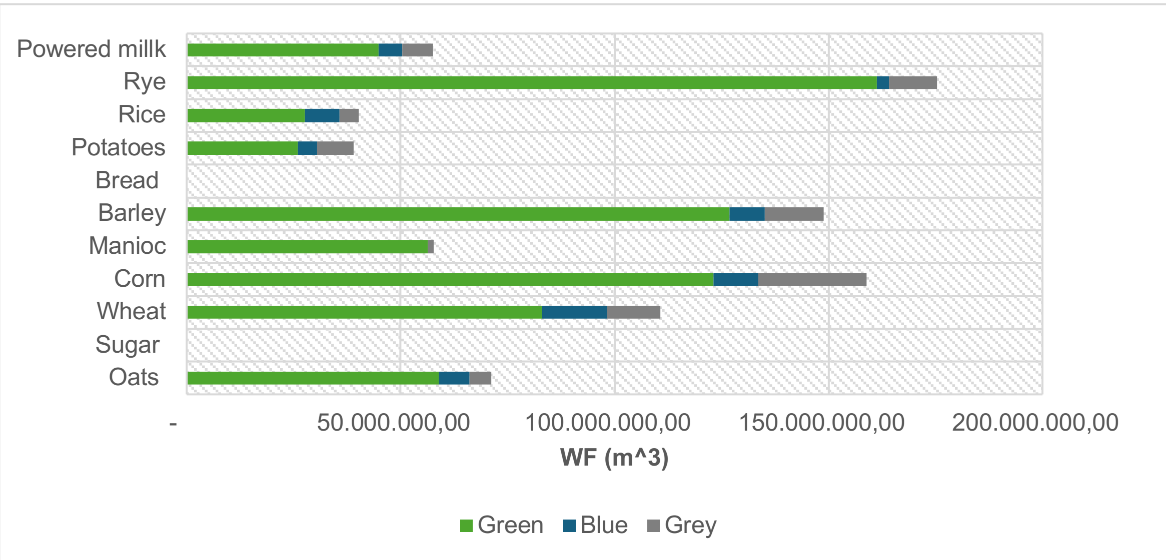
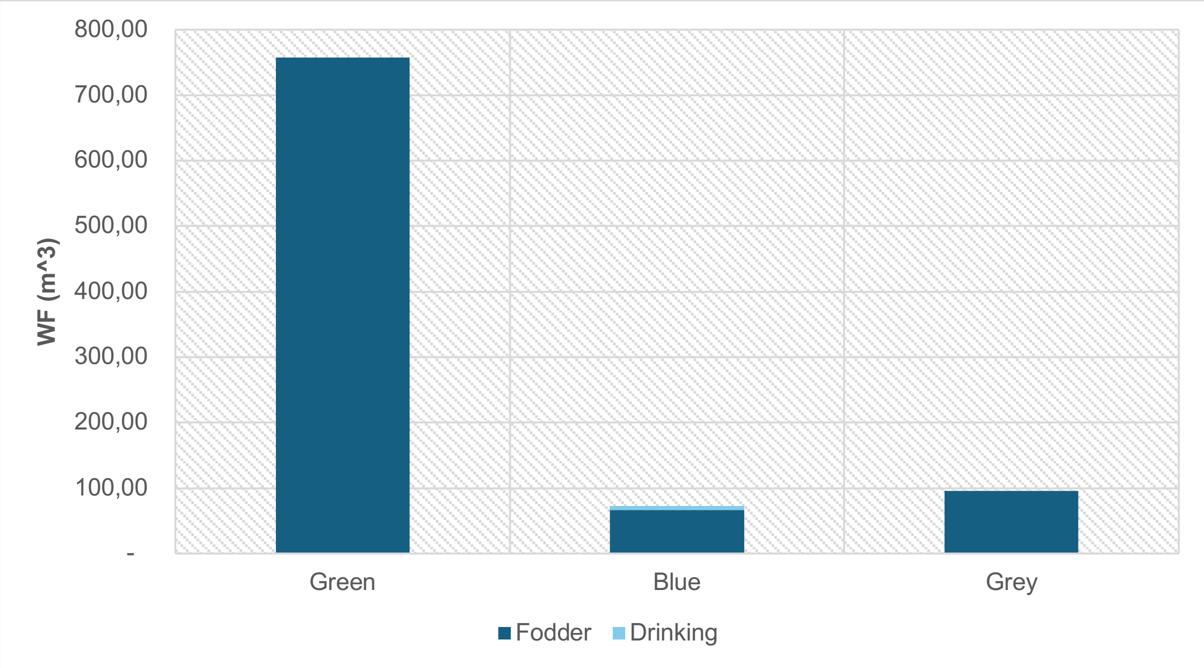




***Figure 30.*** *Ton of crop required for a single swine and the total herd.*



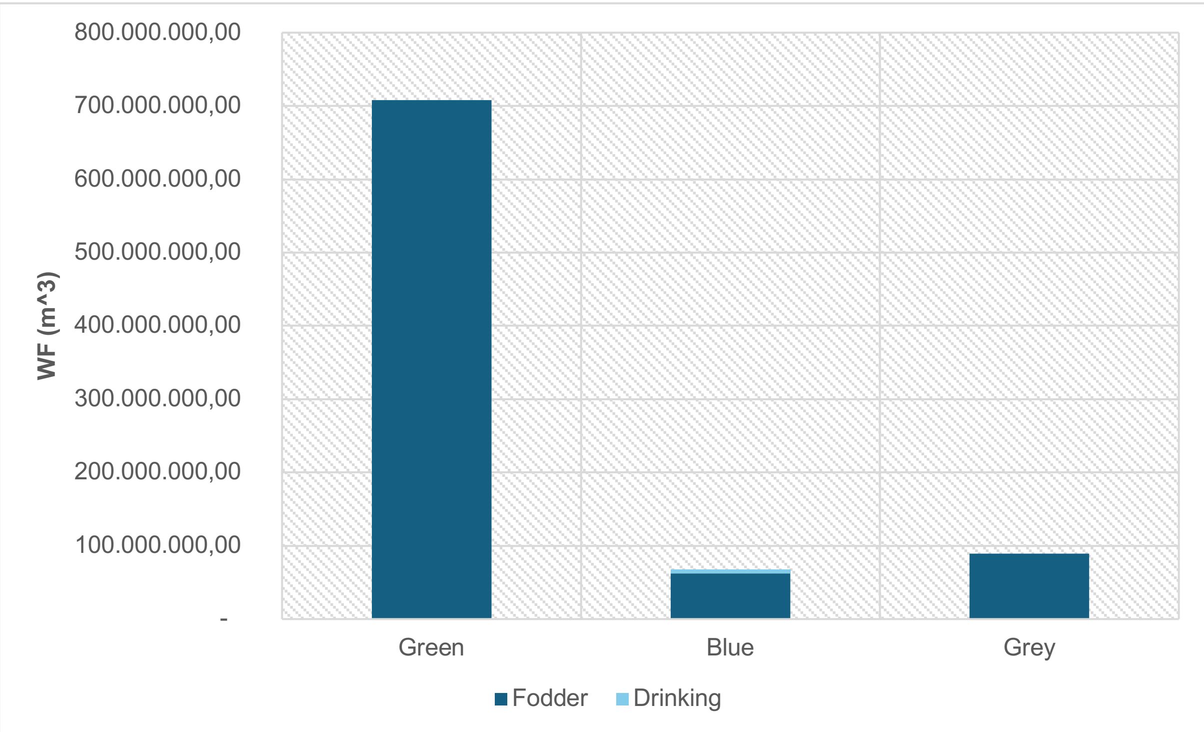




***Figure 31.*** *WF for each swine and for the total herd*

## 5.5 Animals Comparisons

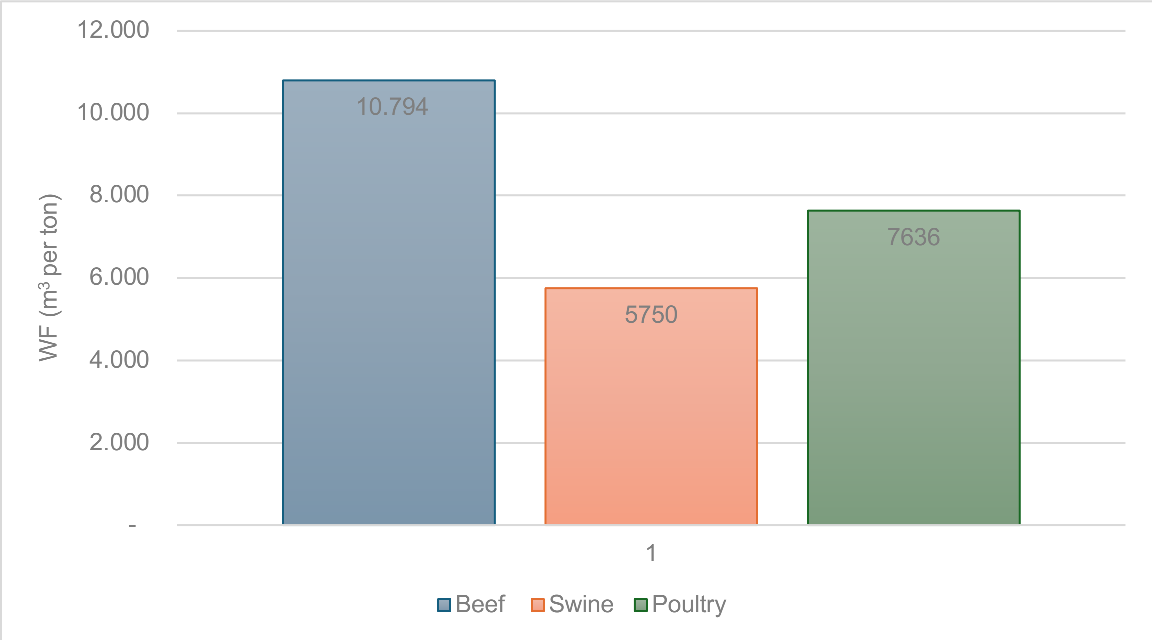



***Figure 32***. *Comparison of water needed per head per species ($m^3$ per ton)*

When evaluating the water requirements of the three primary livestock species—cattle (milk production plus dairy calves), pigs, and poultry—over a normalized time period, a striking pattern emerges. Graphical analysis (***Figure* 32**) reveals that the water demand for cattle is almost two times higher than that for pigs, while water demand for poultry is almost two-third of the cattle one per ton of animal. This disparity largely reflects the resource-intensive nature of bovine production, particularly in dairy systems, where water is essential not only for direct consumption but also for indirect uses such as fodder irrigation and feed production.

Considering the entire herd within Cuneo, despite the local chicken population being five times larger than that of cattle, the respective is ten times lower in poultry. Similarly, pigs, while still resource-intensive, consume only about half the water per animal unit compared to cattle (***Figure 33***). These comparative assessments provide a compelling argument for re-examining livestock production strategies in the context of water resource limitations and for considering a strategic shift toward more water-efficient species.

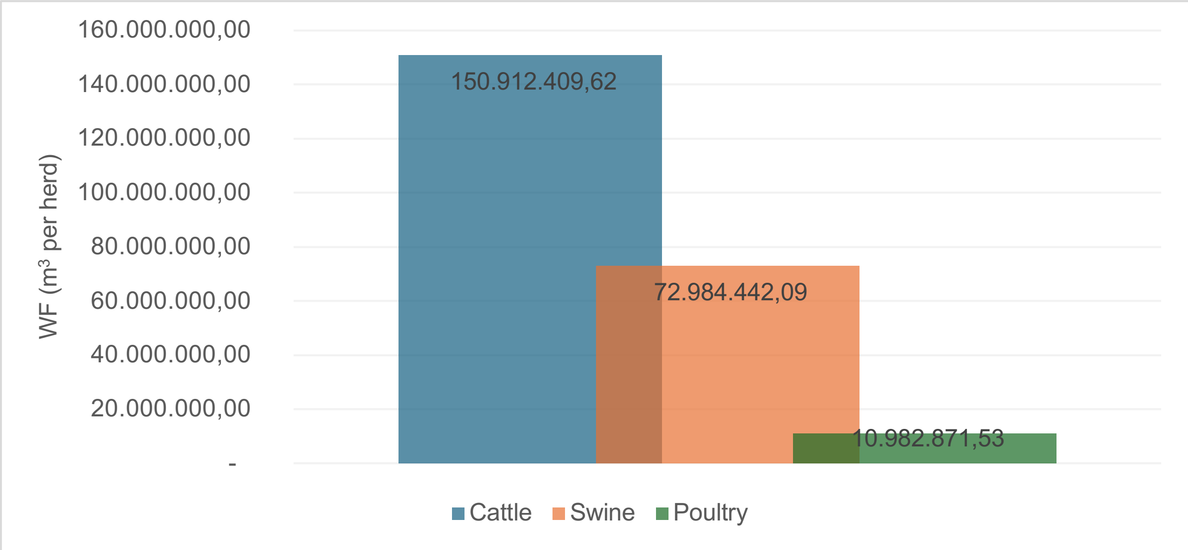



***Figure 33***. *Comparison of WF for the different cattle species in 2023*

# 6. Discussion

## 6.1 Result analysis

The study focused on quantifying the water footprint within the province of Cuneo in 2023. The primary supply chain analyzed was milk production, initially considering the forages included in the feed composition necessary to nourish the existing livestock. Subsequently, an analysis of the livestock density across the province yielded specific results regarding the water required for farming, identifying green water as the most essential for their growth. Finally, the theoretically produced quantities of milk were compared with the actual amounts produced and sold in Cuneo, along with their derivatives. Secondly, similar analyses were conducted for the beef meat and egg supply chains. The results of the three supply chains were classified and compared to obtain a comparison based on a single animal and on all the farms present in the territory. In both cases, the density is based on the cattle sector, with water consumption up to two orders of magnitude higher than that of poultry, with approximately 10800 $m^3$/ton for cattle compared to only 5700 $m^3$/ton for swine. Additionally, the data indicate that, considering the entire livestock sector within the province, the water footprint associated with cattle farming remains the most substantial. In contrast, poultry farming, despite having a population up to twenty times larger, exhibits the least impact in terms of water requirements. This disparity is primarily due to the larger body size of cattle and their consequent higher feed demands, which are key factors influencing water consumption within the livestock production chain.

These findings underscore the importance of improving water management efficiency in livestock production, especially in regions facing increasing water scarcity. Enhancing irrigation methods, optimizing feed conversion ratios, and adopting water-saving practices could substantially reduce the water footprint associated with cattle farming. In contrast, the lower water requirements of pigs and poultry suggest potential sustainability benefits, reinforcing recent research advocating for diversified livestock systems that prioritize water resource conservation.

## 6.2 Main component of water requirement: Fodder production

Water consumption in livestock production is predominantly influenced by indirect factors, notably the cultivation of animal feed. In regions where intensive livestock farming is prevalent, the water demand extends significantly beyond direct animal hydration and farm operations, positioning feed production as a critical determinant of overall water usage.

Accurate estimation of the water required for feed production within a province necessitates precise data on locally produced and imported feed quantities. To address this, it is essential to enhance local community censuses by incorporating data on national imports and exports, as well as tracking deliveries from each municipality to other locations. Developing a municipality-level database could mitigate the current lack of precise data, hence ameliorating estimations [70].

Agricultural censuses in developing countries face several challenges that impact data quality. Firstly, due to their high costs, many developing nations are unable to conduct agricultural censuses every ten years as recommended by the FAO. [71] Secondly, censuses often lack complete coverage; practical and financial constraints can lead to the exclusion of smallholders or entire regions, necessitating estimations for missing data. Thirdly, the extended duration of data collection—spanning three to five months or more—can result in inaccuracies, especially if livestock movements are not accounted for, as the reference date for livestock numbers is typically the survey date. To enhance data quality, it is advisable to establish a fixed reference date for livestock counts and minimize the data collection period. Lastly, prolonged data processing times can cause significant delays between the reference date and the dissemination of results, rendering the data outdated upon release. While the ISTAT provides regional census data, access to provincial-level information remains limited. Implementing a comprehensive data collection framework at the municipal level would facilitate more accurate assessments of water usage in feed production, advocating for the development of integrated data systems to enhance the quality and consistency of agricultural statistics.[70]

Another important result lies in the lack of all the necessary quantities of fodder to feed all the species present. Despite substantial annual yields, local crop production falls short of meeting the feed requirements of both swine and bovine industries. This discrepancy necessitates reliance on external sources, further emphasizing the embedded water footprint associated with feed imports. An analysis of the Piemonte region in 2023 reveals that maize production reached approximately 443640 tonnes. However, compared to our analysis, this output is insufficient to meet the annual feed requirements, with the swine industry alone necessitating around 130000 tonnes and the bovine sector requiring about 267000 tonnes. Additionally, oat production stands at approximately 106000 tonnes, a figure inadequate to fulfill the specific demands. [71]

The disparity between production capacity and consumption needs underscores a structural dependence on water-intensive agricultural practices. Within this context, bovine farming emerges as the most resource-intensive sector, where the majority of water usage is dedicated to sustaining feed crops rather than direct farm activities. In contrast, water used for barn sanitation and milking processes represents a marginal fraction of total consumption, despite their continuous operational demands. Routine activities such as barn cleaning and maintenance of milking systems contribute to daily water expenditure, albeit at significantly lower levels compared to agricultural requirements [72]. Critically, the purpose of cattle also influences required water quantities, with meat cattle requiring significantly higher water quantities when compared to dairy cattle, as supported by our results. In many instances, inefficiencies in equipment and human oversight exacerbate unnecessary water losses, adding to the cumulative environmental impact of livestock management. Specifically, in bovine farming, over 90% of water usage is devoted to the feed crop cultivation; report from the Emilia-Romagna region estimates that daily water usage for barn cleaning and milking processes is approximately 140 L, with an additional daily loss of 25 L attributed to operator oversight or equipment malfunctions. [73] Livestock water consumption is also subjected to temporal changes, including seasonal variations and growth stages of the animals. Spatial differences, such as regional climate variations and local water availability, further complicate the assessment. The dynamic nature of these factors requires continuous monitoring and data collection, which are often resource-intensive and logistically impractical.

## *6.3 Challenges in Livestock Composition and Data Accuracy*

The major challenge in water footprint estimation in this study relied on the right calculation of forage inclusion in animal diets. The composition of forage has been inferred from multiple sources to determine the most suitable nutritional mix for each species. The main basis on which the quantities and types of forage included were estimated were essentially based on guaranteeing the best diet linked both to macronutrients and to the availability of the territory, but these data do not always respect local realities. In most farms, the food ration for each type of animal is still provided *ad libitum*. Therefore, understanding the quantities and subsequently the water waste linked to this method of food administration is a great aspect of the provincial agroeconomic sector [74]. However, without localized regulations accounting for specific territorial characteristics, achieving an accurate assessment of forage and its water footprint remains highly impractical.

Regarding the overall water footprint utilized in Hoekstra's study, our findings indicate that our data do not significantly deviate from the global average when considering methodological differences (i.e., inclusion of service water). Specifically, in poultry farming, our study found that average daily water consumption accounts for about 0.19% of the total water requirement [75]. However, it is essential to recognize that these figures may not fully reflect reality due to inherent limitations in data collection and estimation methods in this precise analysis, which could lead to over- and underestimations of water needed [76]. This was also relevant for swine comparisons. The observed discrepancy can be attributed to the regional specialization within Italy's pig industry. In the province of Cuneo, pig farming primarily focuses on breeding operations, while slaughtering and processing activities are predominantly conducted in other regions, such as Parma in Emilia-Romagna, a hub for Italy's pig processing industry. This geographical division of labor necessitates a detailed analysis of each stage in the pork supply chain to accurately assess their respective impacts on resource utilization and environmental footprints. [77]

The Regional Association of Piedmontese Breeders (ARAP) [78] manages the zootechnical registry for cattle, sheep, goats, and swine. It provides technical consultancy and support to breeders, ensuring traceability and animal welfare. For the Piemontese cattle industry, the Consorzio di tutela della razza pimeontese (Coalvi Consortium) [79] plays a pivotal role in monitoring and promoting the piemontese breed. Coalvi oversees approximately 1300 small, predominantly family-run farms in southern Piedmont, all dedicated to raising Piemontese cattle under strict guidelines that ensure gradual fattening and a diet rich in cereals and fodder. This oversight enables the consortium to collect comprehensive statistics and information on various commercial and artisanal activities within the province, facilitating a clear distinction between breeding, slaughtering, and processing phases within the supply chain.

As noted by Gerbens-Leenes [80], one of the primary limitations of this type of analysis is the lack of precise data on livestock composition throughout the year. Since it is impractical to monitor the entire livestock population daily, estimating exact water consumption for each service remains highly complex.

While the quantity of water consumed is a primary focus, the quality of water available to livestock also significantly impacts health and productivity. Contaminants such as high mineral content, nitrates, or bacterial presence can alter consumption patterns and overall water needs. However, comprehensive data on water quality across different regions and its direct effects on livestock water consumption are often lacking, leading to incomplete assessments of true water requirements. The Piemonte region, despite its abundant water resources, exhibits uneven distribution of this vital asset and cultivates water-intensive crops. Consequently, the region's agriculture has adapted to these diverse conditions by identifying and promoting crops best suited to specific areas. This approach underscores the importance of territorially homogeneous zones from both hydrographic and functional perspectives. Such zoning is regulated by the L.R2019/1 and is based on collective irrigation and reclamation activities [81].

Research studies indicate most regions exhibit a larger allocation to green water fluxes, which could jeopardize blue-water availability, making it more vulnerable to changes in precipitation patterns. This imbalance poses significant challenges for water management, especially in regions heavily reliant on agriculture and forestry. In regions like Central Africa and Latin America, where irrigation practices are intensive and infrastructure may not be as developed, the vulnerability to water scarcity is heightened. The reliance on blue water for irrigation in these areas, coupled with the effects of climate change, exacerbates the challenges of maintaining sustainable water resources. Implementing strategies that optimize the use of green water and enhance water-use efficiency is crucial for mitigating these risks and ensuring water security in these vulnerable regions [82].

These comprehensive approaches align with environmental awareness and sustainability strategies, integral components of corporate social responsibility (CSR). Businesses can actively reduce their operational water footprint by implementing measures aimed at minimizing water consumption and eliminating water pollution within their operations. To enhance transparency and accountability, companies can adopt various supplementary tools to support water footprint reduction efforts. These include establishing quantitative targets for water footprint reduction to track and measure progress effectively, conducting benchmarking analyses to compare water use efficiency against industry standards and best practices. Additionally, it is recommended to implement product labeling to provide consumers with information on the water footprint of goods and services, pursuing certification schemes to validate sustainable water management practices, and engaging in water footprint reporting to ensure regular disclosure of water use and its associated environmental impacts. By integrating these strategies, businesses can strengthen their commitment to sustainable water management, improve stakeholder trust, and contribute to global efforts toward water conservation and pollution mitigation [83].

## *6.4 Innovative solutions and future perspectives*

These findings underscore the imperative for implementing efficient water management strategies in both feed production and livestock maintenance to promote sustainability and conserve resources. Sustainable water management in livestock farming requires a holistic approach, encompassing both upstream agricultural practices and farm-level operational efficiencies. The primary issue concerning water use in sanitary environments related to animal husbandry is that these losses are often excluded from daily water consumption records, despite numerous reports submitted to regional services by enterprises [84]. Technological advancements and process optimization could mitigate water losses in farm operations. Integrating water-efficient systems in milking parlors, along with improved monitoring mechanisms, has the potential to reduce waste and enhance resource conservation. However, given that the vast majority of water usage is linked to feed production, any meaningful reduction in livestock-related water consumption must primarily address the irrigation and cultivation of animal feed [85].

Strategic interventions to improve water efficiency in livestock production are the main factor to make these processes sustainable. The Italian Ministry of the Environment and Energy Security [86] promotes living certification, which is based on four fundamental pillars: it incorporates economic, social and cultural recognition within the life cycle of the product. In an area like that of Cuneo, where DOP products are the basis of the gastronomic culture and the local economy, obtaining certifications of this kind would lead not only to a reduction in waste but also to greater trust among the population towards their companies, with a great increase in reputation and the possibility of obtaining even greater funding [87]. Efforts should focus on optimizing feed cultivation through sustainable irrigation practices, crop selection, and innovative agricultural technologies. Additionally, reducing dependency on water-intensive crops and integrating alternative feed sources may contribute to lowering the overall water footprint of the livestock industry. Precision agriculture systems or innovation related to the internet of Things (IoT) use advanced sensors to collect real-time data on various parameters, such as animal health, environmental conditions and feeding behaviors [88]. The analysis of this data allows timely interventions, reducing the need for pharmacological treatments, and improving animal welfare. Finally, Precision Irrigation Systems utilize soil moisture sensors and automated irrigation allows for the precise application of water, reducing waste and ensuring optimal soil hydration [89]. These new strategies have the potential to significantly enhance irrigation methods, thereby promoting a more sustainable approach within the agri-food sector. As a result, improvements in livestock farming would reduce water wastage at the local level, fostering an innovative, top-down solution within the primary sector [90].

# *Conclusion*

In this thesis, the production chains of three types of animal products in the province of Cuneo, Italy, were analyzed, namely milk, eggs, and beef meat. These products are fundamental for the local diet, posing the need for an estimation of water consumption and waste throughout the process.

The results demonstrated a strong association between water consumption and the amount of feed required for the daily nourishment of each animal species (i.e., cows, swines, chickens). Specifically, the study highlighted a direct link between the water used for crop irrigation and the quantity of fodder necessary for livestock sustenance.

Although this study may underestimate certain aspects of water waste, it identifies several key areas for improvement at the local level. Enhancing irrigation efficiency and optimizing animal feed through a standardized nutritional guide—tailored to species-specific needs and adapted to local agricultural resources—could significantly reduce water usage and improve sustainability within the sector.

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