Area Analysis – Biogenic Carbon Flow with a Focus on Agriculture

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Executive Summary

Carbon is fundamental to the Earth's climate system, biological processes, and global economy. As a core component of organic material and biomass, it plays a central role in agricultural systems. Soils, which store more carbon than the atmosphere, act as critical carbon sinks or sources, depending on the balance of carbon inputs and outputs. Understanding this balance is vital for determining whether agricultural practices mitigate or contribute to climate change.

This report examines carbon flows in Sweden's agricultural sector, emphasizing its role in sustainability and climate mitigation. The ultimate aim is to enhance the management of biogenic carbon flows in Sweden's agriculture and agriculture-related industries. By addressing data gaps and challenges in tracking carbon inputs and emissions, the findings support informed decision-making for sustainable agricultural practices.

The analysis combines literature reviews, data analysis, and expert interviews to provide a comprehensive understanding of carbon flows within Swedish agriculture and related industries. The study highlights the role of agriculture-related industries—focusing on animal husbandry, feed, food, and bioenergy—in managing carbon flows.

Understanding the complex dynamics of carbon sources and applications is crucial for stakeholders navigating the challenges and opportunities of the evolving energy landscape. Key insights include detailed analyses of carbon flows across arable land, pasture, and livestock systems. Arable lands receive significant carbon inputs through photosynthesis and organic amendments, such as manure and food industry residues, but also experience losses during harvest and decomposition. Pastures, with their extensive root systems, serve as long-term carbon sinks. Livestock systems, having the biggest impact on the carbon flow, illustrate the complex interdependencies between feed production, manure recycling, and emissions. The insights from the interviews report advocates for improved data integration, digitalization, and industrial symbiosis to enhance resource efficiency and reduce waste. It calls for robust policies to incentivize sustainable practices, such as reduced VAT on eco-friendly products and potential taxes on high-emission goods like meat.

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1. Introduction

BioInnovation has identified the management of biogenic carbon flows in agriculture as an area with significant potential for increased sustainability and resource efficiency. To address this potential, BioInnovation aims to deepen knowledge about the current situation and future opportunities by mapping carbon flows, identifying research and development needs, and gathering relevant actors and expertise.

Agriculture's role as both a carbon sink and a potential source of greenhouse gas emissions is crucial to achieving climate goals. Sweden has extensive arable land and natural pastures that can play a central role in sequestering carbon, but the sustainability of these flows depends on effective agricultural methods and management strategies. To ensure long-term environmental benefits, a focus on complete value chains that take into account carbon sequestration in soil, biomass and by-products, while maintaining productivity and resource efficiency, is required.

As part of this initiative, Chalmers Industriteknik carried out an impartial area analysis of biogenic carbon flows, with a specific focus on agriculture. Conducted between April and November 2024, the analysis explored the current state of biogenic carbon flows and management practices within Sweden's agricultural and agriculture-related sectors. It mapped and quantified the flows across the agricultural value chains, highlighted data and knowledge gaps, identified key challenges and opportunities, and proposed strategic interventions to enhance the sustainability of value chains connected to biogenic carbon flows in agriculture. This comprehensive effort establishes a robust foundation for future actions aimed at fostering sustainable and climate-resilient agriculture in Sweden.

1.1. Background och aim

Carbon is the fundamental chemical backbone of life on Earth. It plays a pivotal role in regulating the planet's temperature, forming the basis of the food that sustains us, and providing the energy that drives the global economy. Organic matter, which typically consists of about 50% carbon (excluding water), is a key contributor to the soil's carbon pool. This pool is remarkably large—containing approximately three times the carbon present in the atmosphere and half the amount found in global fossil fuel reserves.

Soil Carbon Dynamics

The carbon stock at a given location is influenced by the historical balance between the supply of organic matter and its decomposition in the soil. The primary source of carbon supply is photosynthesis, a process in green plants by which sunlight converts carbon dioxide and water into sugars and oxygen. These sugars are then used, along with nutrients absorbed from the soil, to synthesize various organic compounds.

Carbon sequestration—the process of removing carbon from the atmosphere and storing it in reservoirs such as soil—plays a vital role in strategies to combat global climate change. It is often heralded as a key solution for offsetting greenhouse gas emissions, yet its implementation and outcomes are frequently misunderstood. While the potential of carbon sequestration to mitigate atmospheric carbon dioxide levels is significant, there is a tendency to overestimate its effectiveness, leading to unrealistic expectations about its role in achieving negative emissions.

Soils, for example, are often promoted as robust carbon sinks due to their ability to absorb carbon. However, many soils are simultaneously experiencing carbon losses. This means that instead of achieving net carbon sequestration, efforts in some contexts may merely slow the rate of carbon loss. Such realities highlight the nuanced and limited potential of soils to act as a long-term solution for climate mitigation.

A review of recent studies sheds light on widespread misconceptions surrounding carbon sequestration. Only 4% of the studies reviewed correctly used the term "carbon sequestration," while 13% confused it with carbon stocks (Don et al., 2024). This misinterpretation underscores the need for greater clarity and precision in discussions surrounding carbon management strategies.

Moreover, the broader impact of carbon sequestration on climate mitigation can be complicated by external factors. Non-CO_2 greenhouse gas emissions and carbon leakage—where carbon reductions in one area lead to increased emissions elsewhere—can undermine the benefits of sequestration. These challenges illustrate the complexity of relying solely on carbon sequestration as a primary tool for climate change mitigation and emphasize the importance of integrating it with other strategies to achieve meaningful progress.

Factors affecting photosynthesis and carbon dynamics in the soil

The ability of plants and ecosystems to perform photosynthesis and store carbon is influenced by a complex interplay of environmental, agricultural, and soil management factors. Although this area analysis does not address the capacity, pathways, or outcomes of soil organic carbon sequestration in Swedish soils, understanding these influences remains crucial for optimizing carbon sequestration and enhancing climate change mitigation strategies.

1. Climate and Environmental Conditions

Climate and environmental conditions are fundamental determinants of photosynthesis rates and the capacity for carbon storage. Key factors include:

- Sunlight: Photosynthesis depends on the availability of light as a primary energy source. The intensity, duration, and quality of sunlight affect the rate at which plants can fix carbon. Seasonal changes and geographical location influence light availability, impacting productivity in different regions.

- Temperature: Temperature plays a dual role. While moderate temperatures optimize enzymatic activities required for photosynthesis, extreme heat or cold can inhibit plant growth and reduce carbon uptake. Higher temperatures may also accelerate respiration, potentially offsetting the gains from carbon fixation.

- Water Availability: Water is essential for photosynthesis as it supplies the electrons needed to produce energy-rich molecules. Drought conditions limit photosynthetic activity and carbon uptake, while excessive water can lead to anaerobic soil conditions, reducing the efficiency of carbon storage.

- Atmospheric Carbon Dioxide Levels: Increased atmospheric CO_2 can enhance photosynthesis (CO_2 fertilization effect) in many plants, particularly those using the C3 photosynthetic pathway. However, this benefit may be offset by nutrient limitations or other stress factors.

- Air Quality: Pollutants like ozone can damage plant tissues and inhibit photosynthesis, reducing carbon sequestration potential.

2. Agricultural Practices

Human interventions in agricultural systems directly influence carbon fixation and storage capabilities. Key practices include:

- Crop Selection: Different crops have varying efficiencies in photosynthesis and carbon storage. Perennial plants, for example, often store more carbon in roots and soil compared to annual crops due to their longer growing seasons and extensive root systems.

- Fertilization: Nutrient availability is critical for photosynthetic efficiency. Proper fertilization enhances plant growth and carbon uptake, but excessive use of fertilizers can lead to soil degradation, emissions of nitrous oxide (a potent greenhouse gas), and reduced carbon storage potential.

- Irrigation: Adequate water supply through irrigation ensures sustained photosynthesis and plant growth. However, over-irrigation can cause waterlogging, nutrient leaching, and reduced soil health, negatively impacting long-term carbon storage.

- Plant Protection: Managing pests, diseases, and weeds is essential for maintaining healthy crops that can effectively perform photosynthesis and store carbon. Organic and integrated pest management practices can optimize this balance while minimizing environmental impact.

3. Soil Management

Soil health and management practices significantly influence the capacity of agricultural systems to store carbon. Key factors include:

- Tillage Practices: Conventional tillage disrupts soil structure, accelerates organic matter decomposition, and releases stored carbon into the atmosphere. Reduced or no-till practices help maintain soil organic matter and enhance carbon storage over time.

- Crop Residue Management: Leaving crop residues in the field can increase soil organic carbon by adding organic material to the soil. Conversely, removing residues for bioenergy or other uses can deplete soil carbon reserves.

- Soil Amendments: The addition of biochar, compost, or organic matter can enhance soil structure, water retention, and microbial activity, contributing to increased carbon storage.

- Cover Cropping: The use of cover crops during off-seasons can reduce soil erosion, enhance organic matter, and improve carbon sequestration. These crops also contribute to biodiversity and soil health.

- Organic matter decomposition: Organic matter decomposition in soil is mainly influenced by temperature and moisture, accelerating in warm, humid conditions and slowing in cold, dry climates. While practices like irrigation and tillage can slightly affect this process, control is limited. In Sweden, colder winters slow decomposition, resulting in higher soil carbon stocks compared to tropical regions.

4. Ecosystem Interactions

Beyond direct human influence, interactions within ecosystems also affect photosynthesis and carbon storage:

- Plant-Soil-Microbe Interactions: Soil microbes play a key role in decomposing organic matter and cycling nutrients, which influences plant growth and carbon storage. Symbiotic relationships, such as mycorrhizal fungi, can enhance nutrient uptake and carbon storage in the soil.

- Biodiversity: Greater plant diversity in agricultural or natural ecosystems can enhance carbon storage by promoting complementary resource use and more efficient carbon capture.

By addressing these factors holistically, it is possible to optimize photosynthesis and carbon storage, contributing to sustainable agricultural systems and climate mitigation efforts.

The intricate relationship between carbon and nutrient dynamics in the soil highlights the dual role of organic matter decomposition. Decomposition provides energy and nutrition to soil microorganisms, insects, and subsequently to higher trophic levels such as birds. This rich microbial life is essential for maintaining soil health and is a significant part of the long-term storage of carbon in the soil, consisting mainly of the remains of deceased microorganisms (Liang et al. 2019). Through decomposition part of carbon is released back into the atmosphere as carbon dioxide as part of the biogenic carbon cycle, but also recycles nutrients. Understanding these dynamics is crucial for developing strategies to enhance soil carbon storage and maintain the health and productivity of agricultural lands, adapt to sustainability goals, and mitigate the impacts of climate change.

This area analysis aims to deepen the understanding of biogenic carbon flows and thereby improve resource efficiency in bio-based production processes. Through a detailed mapping of carbon flows in Swedish agriculture and related sectors, we aim to identify areas where carbon flow efficiency can be optimized. This is crucial for reducing carbon emissions and promoting sustainable use of bio-based resources. The analysis will explore carbon flows from agricultural production to use of agricultural products, including the contribution of livestock to the biomass flow and land use and generates a comprehensive picture of carbon flows in the Swedish agriculture and agriculture-related systems.

This analysis is not only important for monitoring and optimizing existing flows but also for estimating the potential for innovative applications such as energy recovery and more efficient carbon sequestration. By integrating different sectors and actors, we aim to establish a ground for integrated strategies that address the challenges and promote sustainability. The insights from the project are intended to form the basis for future research and development and inform potential legislation, contributing to the transition towards a sustainable bioeconomy. Challenges in tracking and managing carbon flows, such as inconsistencies in input-output data and the complexity of soil carbon measurement, are addressed. Data analyses are supported by the interviews with key stakeholders.

1.2. Data collection

We adopted the analytical framework developed by Rundgren et al. (2021), which represents the pioneering carbon flow analysis specific to the Swedish agricultural sector, for our data analysis. This methodology covers the entire agricultural value chain, from agricultural operations to downstream processes involving the food, feed and bioenergy sectors. Carbon inputs are primarily traced through arable land and natural pastures and are systematically allocated to different sectors including the food industry, feed industry, animal husbandry and bioenergy sector. In addition, carbon flows back to the fields as seeds, undergoes processing, becomes waste or effluent and is consumed directly. The unutilized carbon either enhances the soil carbon sink or contributes to emissions to the atmosphere.

Our methodology utilizes a mix of official statistics (mainly the Swedish Board of Agriculture database), scientific literature and insights from interviews with industry representatives and industry associations, supplemented with information extracted from online resources and annual reports. When data is scarce, we rely on well-founded assumptions based on external sources such as FAO’s technical conversion factors. To ensure accuracy and reliability, our data aggregation involves multiple sources and different calculation methods. We carefully balance carbon inputs and emissions at each step of the value chain. Any deviations exceeding 5% are carefully investigated and corrected by recalibration or formulation of new surveys and assumptions. For example, feed consumption measures are derived by analyzing both the supply and use of the Swedish livestock operation. These figures are further validated against related data on manure production and respiratory emissions from livestock, ensuring a comprehensive reconciliation of carbon data across the agricultural spectrum.

Quantifying biogenic carbon fluxes from agricultural lands is essential for creating detailed bottom-up and bottom-up estimates of net carbon emissions that are essential for global and regional carbon monitoring. We have estimated the carbon flux from agriculture within Sweden for 2023, focusing on annual net primary production (NPP), harvested biomass, and biomass consumed by humans and livestock. These estimates are synthesized into a consolidated net carbon dioxide exchange.

For accuracy, our analysis is based on the most recent data. The estimates cover predominantly the 2023 cycle, adjusting production and consumption within the same year for consistency. Where 2023 data are preliminary and deviate less than 5% from 2022 figures, we use the latter, in particular for milk production from July 2023 to June 2024. This adjustment is justified by the continuous use of the 2023 harvest in early 2024, reflecting the rapid turnover in dairy production. Our assessments cover all carbon fluxes within the agricultural and food systems, including those from Swedish agricultural products used outside traditional food applications. However, non-agricultural products such as wild fish and game, along with most imported biofuels and non-feed-related agricultural imports such as cotton, are excluded from our calculations. Only those bioenergy flows that interact with Swedish agriculture and potentially produce feed-related residues are considered. The main data source used in the analysis is the Swedish Board of Agriculture's statistical database, from which the following data have been taken:

- Crop yields from arable land and natural pastures
- Detailed grain balance to analyse carbon flows linked to grain production and consumption
- Number of animals
- Direct food consumption
- Total food consumption
- Dairy production
- Production animal-based products (in particular milk and egg)
- Slaughter of larger farm animals at slaughterhouses by animal species
- Food consumption in the form of deliveries to consumers and other end users (restaurants, catering, etc.)
- Consumption of vegetable oil in food

These data have formed the basis for analysing carbon flows in agriculture, particularly related to harvest statistics, animal husbandry, food production and feed production and consumption patterns.

The estimation of the carbon content of different products is based on the percentage of carbon present in their dry matter. This proportion is derived from the carbon content of nutritional compounds: carbohydrates typically contain between 40% and 44% carbon, proteins contain around 53% carbon and fats vary from 55% to 78%. Typically, values of 43% for carbohydrates, 53% for proteins and 75% for fats are used in calculations. Composition data for these raw materials were taken from historical references such as Autret et al. (1953), more recent studies such as Adentona (2019). The Food and Agriculture Organization of the United Nations Food and Agriculture Organization is used to calculate the C content of agricultural products. For forage crops, the carbon content is affected by the plant species and the time of harvest. A variety of sources, including Phyllis, Bumane et al. (2015) and Feedipedia, were consulted to establish an average carbon quota of 47%. When other reliable sources such as Adentona (2019) and Wolf (2015) provided data on carbon content, these figures were also included.

The most significant uncertainties arise in determining the carbon content of live animals, in particular due to the lack of reliable data on the carbon content of skin, viscera and hooves, and their respective proportions in the total composition. For beef and pork carcasses, the available data include the ratio of fat, meat and bone, which can vary considerably depending on factors such as age, breed and breeding methods. The last count of the number of horses in Sweden was in 2016 and thus the number and feed requirements for 2023 are quite uncertain. There is also no information on other ungulates, such as donkeys, llamas, alpacas, etc., as well as deer, fallow deer and wild boar in enclosures.

1.3. Methodology

This analysis was conducted using a combination of literature reviews, data analysis, and expert interviews to gain a comprehensive understanding of carbon flows within Swedish agriculture and related industries. The methodological approach included the following steps:

Literature Review and Data Analysis

We began by reviewing relevant scientific literature, industry reports, and publicly available datasets to map and quantify carbon inputs and outputs across various segments of the agricultural value chain. Our analytical approach is based on a well-established framework developed by Rundgren et al. (2021). To ensure accuracy and reproducibility, all calculations were performed using a spreadsheet mode*. This model integrates various data points and parameters, providing a comprehensive view of carbon dynamics within Swedish agriculture and its related sectors. The model itself, including the specific equations and input values used, is meticulously documented and can be made available upon request. This transparency ensures that any third-party reviewer or researcher can validate the results, replicate the analysis, or even expand it with new data.

Expert Interviews

To supplement the quantitative data and gain practical insights, we conducted 12 interviews with experts from various agriculture-related sectors. These interviews involved professionals from diverse fields, including:

- Food Production: Experts from companies involved in the processing and manufacturing of food products.

- Feed Industry: Representatives specializing in animal feed production and distribution.

- Agricultural Consultancy: Advisors with expertise in farming practices, resource efficiency, and sustainability.

- Livestock Management: Specialists in animal husbandry and sustainable livestock systems.

- Policy and Research Organizations: Individuals from institutions focused on agricultural policy, innovation, and environmental research.

The selection of interviewees was based on their expertise and relevance to the key topics under investigation. These discussions provided qualitative insights into the challenges, opportunities, and practical applications of carbon management within the sector.

Stakeholder Contributions

In addition to interviews, we engaged with a range of stakeholders through informal discussions, workshops, and consultations. These interactions were crucial in cross-validating the findings and ensuring that the analysis reflects both scientific evidence and practical realities.

This multi-faceted methodology, combining rigorous data analysis and rich qualitative input from experts, allowed us to develop a robust understanding of carbon dynamics in Swedish agriculture. The findings are grounded in quantitative evidence while being informed by the expertise and experiences of practitioners and researchers in the field.

1.4. Steering Group

The assignment has had a steering group consisting of:

- Sverker Danielsson, BioInnovation
- Per-Anders Hansson – SLU
- Anders Brolin – StoraEnso
- Marie Johansson – RISE

The project has had regular coordination meetings with the steering group.

1.5. The scope of the report

This report provides a snapshot of the carbon dynamics within Sweden's agriculture and agriculture-related systems, but with some data gaps that have not yet been addressed. It highlights the complex interplay between carbon flows and opens the door to potentially broadening the scope of the analysis by including additional variables such as methane, nitrogen, energy or financial transactions, which could provide a more nuanced understanding of the sustainability of the system. The results highlight shortcomings in existing research and data collection, particularly in relation to waste, animal feed conversion rates and food consumption patterns. These areas represent gaps where current analyses may overlook significant interactions and flows that can impact overall sustainability assessments. By integrating these elements, future studies could provide more precise and actionable insights, promoting a more effective resource management strategy across the entire agricultural sector. In addition, the report suggests that analysts broaden their scope to consider the interconnections between different subsystems. This holistic approach is crucial to ensure that research captures all relevant factors and their interactions, thus avoiding isolated analyses that may miss broader systemic effects. Such an integrated perspective is essential for developing targeted interventions that can address multiple challenges simultaneously. To support these insights, this report includes figures and Sankey diagrams, which illustrate the analyzed value chains and identify the key stakeholders in the Swedish agricultural sector. These visual representations serve as a tool for stakeholders to see their place within the larger network and understand the flow of carbon throughout the system. This visibility can facilitate better decision-making and encourage more collaborative efforts to address the identified inefficiencies and promote sustainability in the sector.

Carbon and climate effect

The total biogenic carbon involved in agriculture and natural pastures is estimated to be around 20 million tonnes by 2023, which translates to around 73.4 million tonnes of carbon dioxide, which must be considered in the context of agricultural fossil emissions - estimated to be between 6.8 and 13.3 million tonnes of carbon dioxide equivalent (Swedish Environmental Protection Agency, 2021). While these figures are significant, it is important to note that most carbon flows within biological cycles. Plants absorb carbon dioxide from the atmosphere and convert it into carbohydrates, which are used by animals (including humans) and other organisms. These carbohydrates are metabolised and eventually release carbon dioxide and, to a lesser extent, methane back into the atmosphere. It is important to recognise that the carbon sequestered by crops is part of a cyclical process; although it returns to the atmosphere, this should not be misinterpreted as a primary contributor to climate impacts. Instead, the agricultural sector’s impact comes primarily from fossil fuel emissions, not the cyclical biogenic carbon processes. This report focuses on the sequestration and initial use phases of carbon in agriculture, including its incorporation into food and animal feed. But what happens to these feeds afterwards – the detailed tracking of carbon through animal metabolism and waste products – is beyond the scope of this study.

The impact of soil carbon dynamics on climate change is crucial, particularly through the lens of soil carbon stocks. While this report does not provide a definitive answer as to whether Swedish soils act as net carbon sinks, it does refer to external studies, such as Poeplau et al. (2015), which indicate some level of net carbon sequestration occurring in Swedish mineral soils. The paper concludes by assessing the effectiveness of different carbon sequestration methods used in arable land. But it effectively frames the relationship between carbon extraction from agricultural systems and the future storage of carbon in these soils. Furthermore, the report addresses important considerations about the longevity and reliability of carbon sequestration methods under current agricultural conditions in Sweden. These considerations are crucial for understanding the sustainable management of soil carbon and its broader implications for climate resilience and agricultural productivity. The ongoing discussion also highlights the need for more focused research to resolve uncertainties about the capacity and sustainability of carbon storage mechanisms in Swedish agriculture, paving the way for more informed policy decisions and management strategies aimed at improving soil health and mitigating climate impacts.

2. Results – Mapping of Biogenic Carbon Flows

The following sections present the results of the data analysis on carbon input and output within Swedish agriculture and related industries, structured into four key areas: arable land and natural pastures, animal husbandry, the food and feed industry, and the bioenergy industry. The findings are further summarized and visualized through Sankey Diagrams provided in the Appendix to provide an overview of the overall agricultural system as well as detailed insights for the individual related sectors.

2.1. Arable land and natural pastures

In Sweden, cereals—especially when accounting for straw—and forage crops, such as grass and green fodder, form the cornerstone of agricultural crop production. Together, they represent over 90% of the total carbon harvested from agricultural activities, underscoring their vital role in the country's agricultural carbon cycle.

As shown in Figure 1, the distribution of total harvested carbon highlights this dominance: 48% originates from grass and green fodder, while cereals (including straw) contribute 43%.

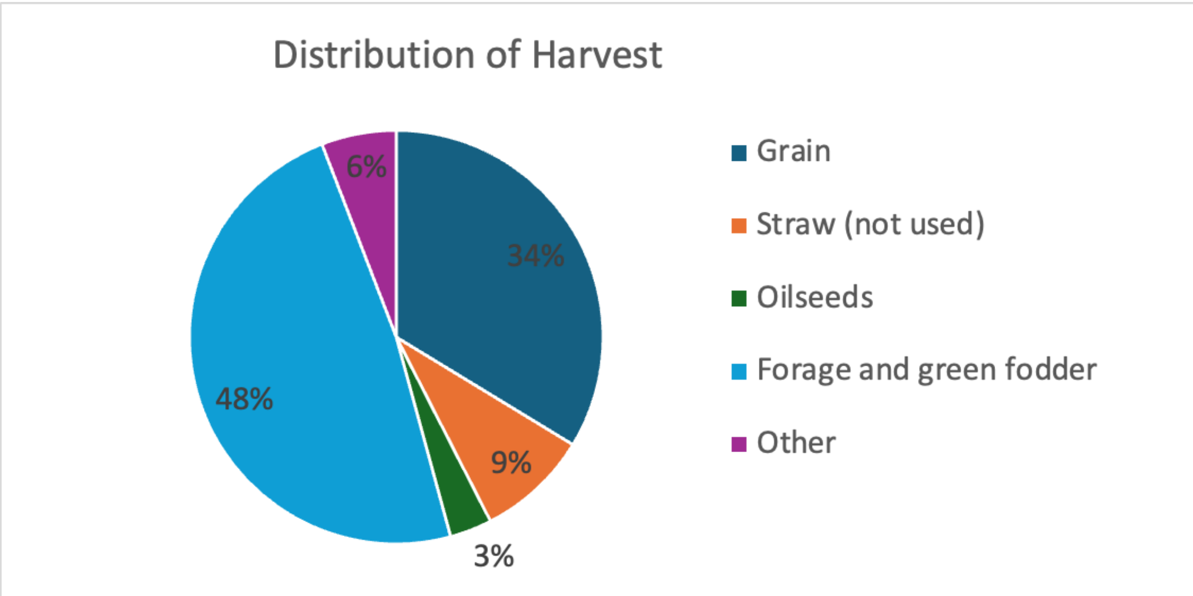

Figure 1. Distribution of total harvested carbon

In the production of cereals, winter wheat is the dominant crop, accounting for 60% of all harvested cereals. This is followed by spring barley at 17% and oats (oats) at 10%, reflecting the diversity and focus of Swedish crop production. Winter wheat, together with its associated straw, plays a crucial role in the agricultural carbon cycle, contributing 1.6 million tonnes of carbon annually, which is distributed across different sectors. Specifically, 20% of this carbon serves as direct feed for livestock, integrating crop production with animal husbandry in an important loop of resource efficiency. In addition, 15% of the carbon from winter wheat is directed to the feed industry, further supporting animal nutrition with processed feed products. A further 15% each is channelled to additional animal feed practices, the food industry and various general industrial applications including ethanol production.

Figure 2 illustrates the distribution of carbon across arable land, natural pastures, and overall agricultural areas, categorized by different plant components. These components include harvested parts, crop residues (such as stalks, leaves, and other post-harvest materials), and below-ground contributions like roots and rhizodeposition. The total net primary production from arable fields and natural pastures amounts to approximately 18.3 million tonnes of carbon. Of this, 50% is deposited in roots and rhizodeposition, while 26% is found in harvested products and the remaining 24% is found in crop residues, mainly straw, with only a part of this straw being removed from the fields.

Swedish arable lands contribute significantly to the carbon supply in agriculture, accounting for a total of 17.5 million tonnes. The majority of this carbon, approximately 15.8 million tonnes, originates from photosynthesis, a natural process that forms the backbone of agricultural productivity by converting atmospheric carbon dioxide into organic compounds. A further 1.7 million tonnes of carbon is added to these lands through the application of fertilisers and the incorporation of residues from the food industry and waste management processes.

In arable lands, harvested products remove approximately 4.5 million tonnes of carbon from crop production, representing 28% of the total carbon input. This highlights the significant role that crop harvesting plays in the carbon cycle in arable land. Roots and rhizodeposition account for the largest share, approximately 7.2 million tonnes, representing 45% of the total carbon input. This significant share highlights the importance of root biomass and underground organic deposits in storing carbon in arable land. Crop residues, including stalks, leaves and other post-harvest residues, account for a further 4.17 million tonnes, or 26% of the total carbon input, indicating their crucial role in contributing to the soil organic carbon pool.

Natural pastures, with a total carbon input of 2.47 million tonnes, show a distinctly different distribution pattern. These pastures allocate approximately 1.9 million tonnes to roots and rhizodeposition, which accounts for 77% of their total carbon input. This high proportion highlights the capacity of natural pastures to significantly enhance soil carbon stocks, particularly through underground biomass. Harvested products and crop residues each account for 0.29 million tonnes, or 11% of the total carbon input from these pastures. The comparatively lower figure for harvested products from pastures reflects the lower intensity of harvesting activities in these areas compared to croplands. In addition, 0.2 million tonnes of carbon is returned to the soil through manure, further enriching soil fertility and contributing to nutrient cycling.

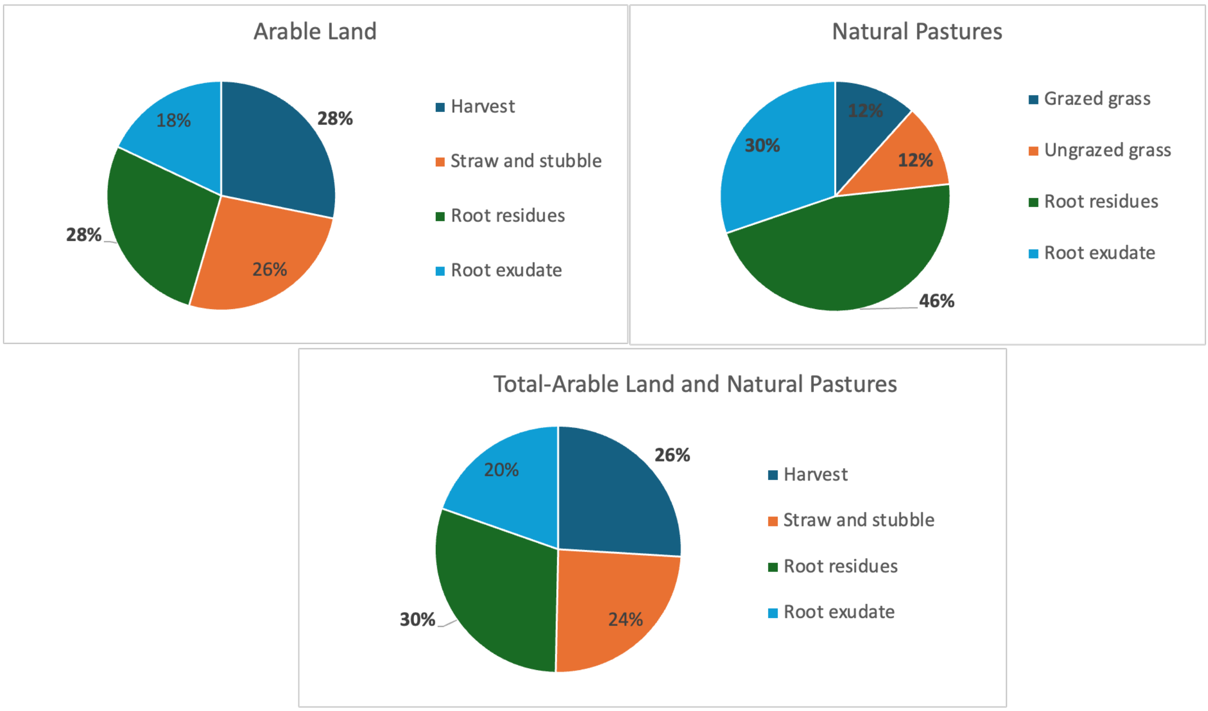

Figure 2. Distribution of carbon across arable land, natural pastures, and overall agricultural areas, categorized by different plant components

After accounting for carbon removed through harvesting and other agricultural activities, the net addition of carbon to arable land amounts to approximately 9.6 million tonnes each year. In addition, approximately 1.7 million tonnes of carbon is recycled back to the soil in the form of manure and various other residues, which significantly contributes to the organic composition of the soil. However, this report does not delve into a detailed examination of these soil carbon flows, nor does it evaluate the specific amounts of net carbon sequestration or loss in the soil itself.

A significant portion of the carbon captured through photosynthesis on arable land, a total of 15.8 million tonnes. 20% of this carbon input, approximately 3.2 million tonnes, which constitutes more than half of the carbon utilised, is directly linked to animal husbandry. This significant contribution highlights the crucial role of livestock in the agricultural carbon cycle, as animals consume a large part of the biomass produced. Approximately 17% of the carbon removed from photosynthesis is recycled back to the fields. This includes seeds planted for the next crop cycle and crop residues such as stubble and roots left after harvest. These practices are essential for maintaining soil organic matter and fertility, and highlight the cyclical nature of carbon in farming systems.

The feed and food industries uses 7% and 9% of total carbon respectively. This allocation reflects the important role these sectors play in transforming primary agricultural products into consumables, thereby linking farming practices directly to consumer markets. Similarly, the bioenergy sector accounts for a further 7% of carbon used, underscoring the growing importance of sustainable energy sources derived from agricultural products and by-products.

These activities result in approximately 11.3 million tonnes of carbon being emitted to the atmosphere, released into waterways or sequestered in soil each year, highlighting a significant interaction between farming practices and wider environmental impacts. This report does not delve deeply into the complexity of soil carbon dynamics. It does not quantify the exact degree of carbon sequestration or identify potential losses in the soil system, which is crucial for understanding the full environmental impact of these farming practices. The lack of a detailed analysis highlights the need for further research to properly map these flows and their implications for sustainable agriculture and climate change mitigation. Of the total carbon input of 2.47 million tonnes to natural grasslands, approximately 0.3 million tonnes is allocated to livestock farming, with a similar amount returned to grasslands through fertilization. A large proportion of the carbon, approximately 2.1 million tonnes, leaves grasslands through grazing and carbon dioxide emissions.

Comparisons per hectare of grass and cereals:

Calculated per hectare, the carbon input through photosynthesis from arable land (both crops and pasture) through crop cultivation is on average 6.07 tonnes of carbon per year. In specific agricultural methods, such as cereal production – which is dominant in Sweden alongside pasture cultivation – the average carbon input per hectare is 5.32 tonnes C. For mowed pasture, a higher proportion of 7.44 tonnes of carbon per hectare is noted. In addition, manure and residues from the food industry and waste management contribute 0.66 tonnes of carbon per hectare. For natural pasture, the carbon input is 5.86 tonnes per hectare. In terms of carbon extraction, the scenario shows that an average of 2 tonnes of carbon per hectare is removed annually from arable land, reflecting the effects of agricultural crops and other processes that extract carbon from the soil. In contrast, natural pastures see a lower carbon sequestration rate, with only 0.65 tonnes of carbon removed per hectare. This delineates a clear difference in carbon dynamics between cultivated land and natural pastures, underscoring the different approaches to carbon management within different types of land use.

A comparison of winter wheat and grass cultivation - the mainstay of Swedish agriculture - shows that both have similar estimated average primary production rates of 6.8–7.45 tonnes of carbon per hectare. Grasses, especially in permanent pastures, engage in continuous growth and develop extensive root systems that significantly enhance soil carbon sequestration. This advantage is largely due to the perennial nature of grasses, which allows for year-round photosynthesis and deeper deposition of organic matter, unlike wheat, which as an annual crop has a shorter growth period and a relatively shallower root system. This limits wheat's carbon sequestration to its above-ground biomass and root residues remaining after harvest.

In grasslands, most carbon is allocated below the surface, increasing long-term soil carbon storage. In contrast, wheat predominantly channels its carbon to cereal production, with only post-harvest residue contributing to soil carbon unless specific residue management practices are used. Grassland farming benefits from reduced soil disturbance and can be optimized with rotational grazing practices that help maintain soil structure and carbon levels. However, wheat farming often involves greater land interruption from annual tillage, although adopting no-till practices and strategic residue management can improve its carbon storage capacity. The integration of crop production with livestock farming presents a robust model for maximizing soil carbon storage. For example, both ryegrass and wheat show similar primary production rates per hectare, but ryegrass has the potential to sequester more carbon due to continuous photosynthesis and less intensive cultivation on marginal lands. Wheat can also be effective if straw removal is minimized and supplemented with fertilizer application, which promotes better soil carbon retention. However, the effectiveness of these methods varies, and much of the carbon eventually returns to the atmosphere, highlighting the need for improved management strategies to optimize long-term carbon sequestration in Swedish agricultural systems.

2.2. Animal Husbandry

The total carbon input from agricultural sources to livestock is estimated at around 4.5 million tonnes annually, illustrating the significant flow of resources within the agricultural sector. Notably, a significant proportion, around 70%, of this carbon comes directly from feed and straw provided by farms. A further 20% comes from the feed industry, which processes various agricultural products into specialised feeds, improving the nutritional value available to livestock. The remaining 10% of the carbon input comes from natural pastures and waste and by-products from the bioenergy and food industries. These interventions not only recycle waste but also contribute to the circular economy by reintegrating agricultural by-products back into the production cycle. Figure 3 shows the distribution of carbon input in animal husbandry.

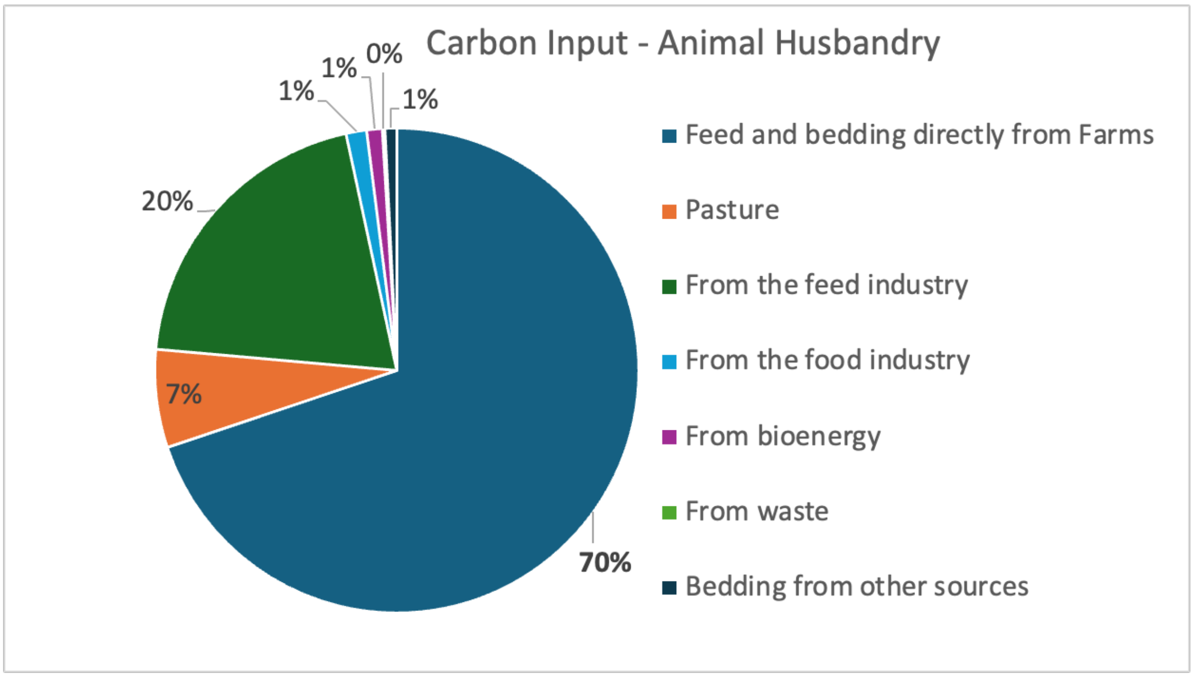

Figure 3. Distribution of carbon input in animal husbandry

Of the total carbon input received by livestock, the largest proportion – around 34% – returns to arable land. This recirculation of carbon in the form of organic manure enriches the soil and improves its fertility and structure, which is essential for maintaining crop production. Approximately 35% of carbon is released to the atmosphere and water resources. This includes animal respiration, methane emissions from manure, and carbon losses during manure storage and handling. The food industry uses approximately 10% of total carbon from animal husbandry, indicating its role in converting livestock production into consumer products. In addition, approximately 5% of carbon returns to natural pastures, supporting the regeneration of these ecosystems and contributing to sustainable grazing practices. The remaining 16% of carbon is used for heat production and biomass growth in animals, essential for maintaining healthy and productive livestock. This use of carbon for metabolic and growth processes is crucial for the viability of livestock as part of agricultural productivity.

Tracing the flow of nutrients in livestock farming is a critical and complex task, especially in light of the notable gaps observed in existing data reports. Our results reveal a significant discrepancy, approximately 10% or 0.4 million tonnes, between the reported feed supply to livestock and their actual consumption. This gap is exacerbated by data uncertainties, particularly for smaller livestock such as sheep, goats and pigs, with no data available for poultry. In addition, inefficiencies such as feed waste and overfeeding contribute to the gap between supply and use, compounding the challenges of accurately measuring feed flows. This highlights the urgent need for improved data collection and analysis methods to ensure that all livestock receive adequate and appropriate nutrition. Accurate and reliable feed data are important not only for animal health and welfare but also for the overall sustainability of agriculture. Ensuring accurate feed tracking and management is essential to address these discrepancies and support the sustainability of farming practices.

The dietary habits of different livestock species in Sweden differ significantly, not only in the amount of feed they consume but also in the type of feed they require. Cattle represent the largest single group of feed consumers and account for approximately half of the total feed consumed in terms of carbon content. A substantial 60% of their diet consists of feed from grassland and pasture, underlining their dependence on grass-based feed. Horses are the second largest consumer of feed and consume more than the combined total feed intake of pigs and sheep, which constitutes 15% of the total carbon-based feed consumption. This highlights the significant role of horses in the carbon dynamics of agriculture, especially given their dietary needs that differ from ruminants such as cattle and sheep. Poultry ranks third, accounting for 8% of feed consumption by carbon content. When analyzing the composition of the feed itself, hay and pasture dominate, accounting for 50% of the total carbon intake among all livestock. This is followed by cereals, which account for 23% and are a crucial component of the diet, especially for non-ruminants. Green fodder contributes another 7%, and protein-rich seeds, such as legumes, account for 6% of dietary carbon intake. The remaining 15% comes mainly from industrial by-products, which are often reused as feed ingredients, demonstrating recycling in the agricultural sector.

This variation in feed consumption patterns between different animal species highlights the complexity of managing agricultural resources and optimising feed use to reduce environmental impact while supporting different farming practices. The significant reliance on pasture and hay also highlights the importance of sustainable grazing and land management practices that support soil health and carbon sequestration. Figure 4 presents the distribution of carbon utilization in animal husbandry based on the; composition of animal feed (Figure 4a) and feed utilization across various types of livestock (Figure 4b).

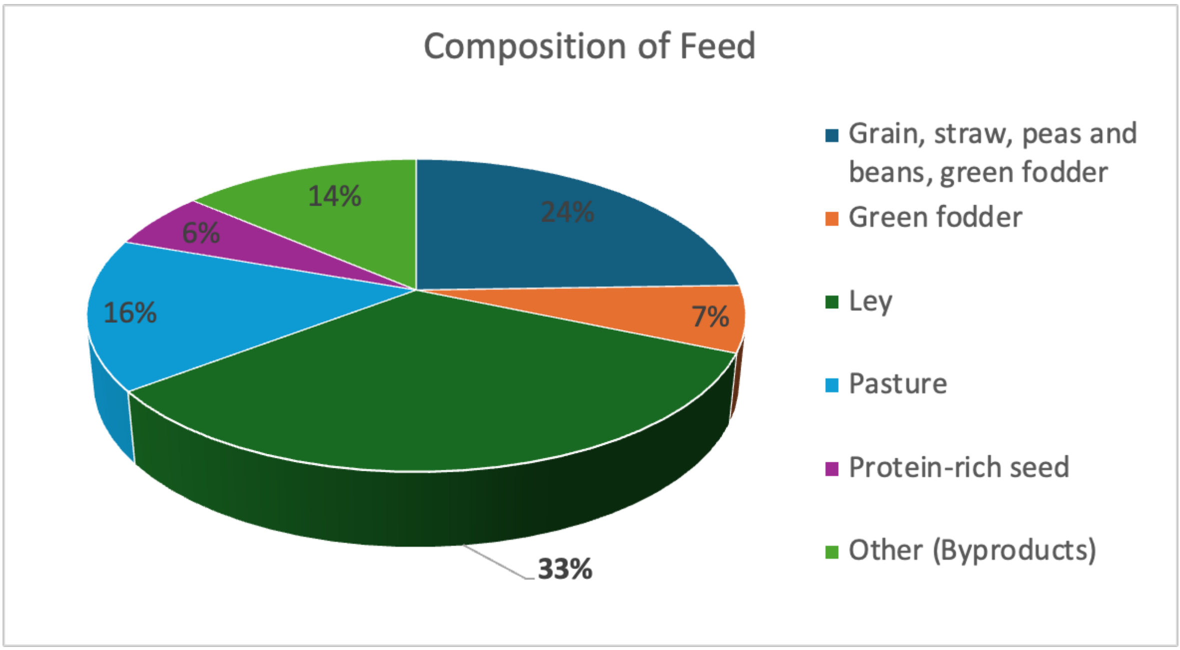

Figure 4a. Distribution of carbon utilization in animal husbandry based on the composition of animal feed

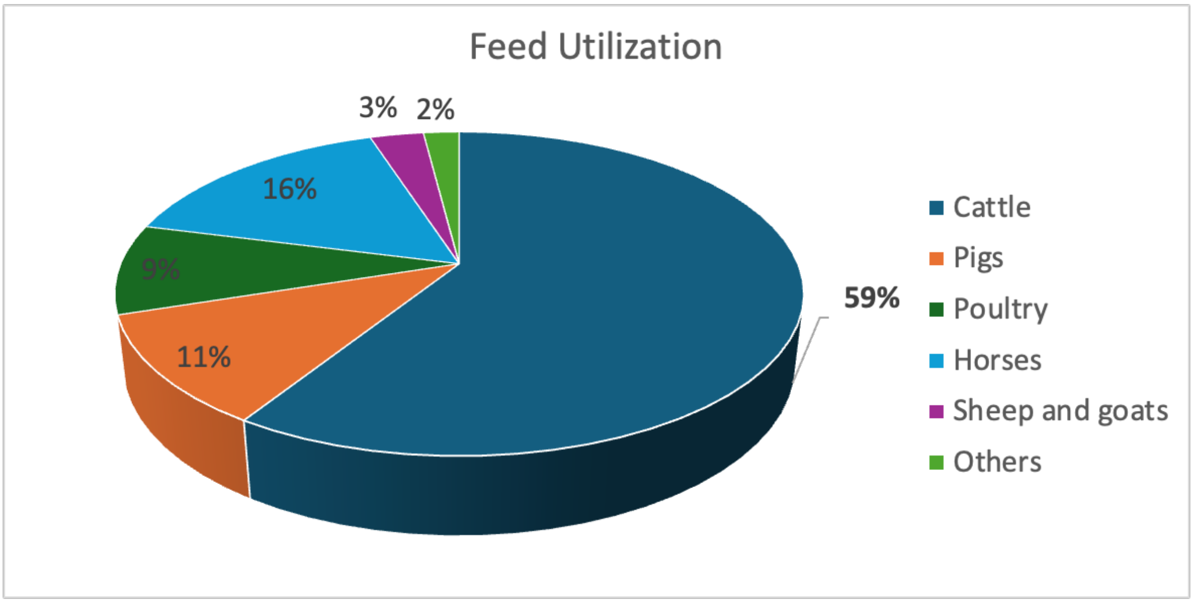

Figure 4b. Distribution of carbon utilization based on the feed utilization across various types of livestock

2.3. Food and Feed Industries

The Swedish food industry processes approximately 1.465 million tonnes of carbon annually. Figure 5 shows the distribution of the sources of carbon input to the food industry. This figure reflects the links between agriculture and food production, underlining the crucial role of crop production, which contributes 40% of the total carbon input. Within this agricultural contribution, wheat stands out, comprising 34% of the carbon from crops, highlighting its importance not only as a staple crop but also as a primary raw material in food processing. Sugar beet, another contributor at 27%, together with barley and oats, which contribute 17% and 8% respectively, further diversify the sources of carbon input to the food industry. Animal products make up 32% of the carbon input. This indicates the integral role that animal products play in the food chain, reflecting both consumption patterns and agricultural practices in Sweden. Furthermore, the dependence on imports, which provide 26% of total carbon, with fresh, chilled or frozen fish constituting 40% of these imports, highlights Sweden's integration into global food markets and its dependence on international sources to supplement domestic production.

Approximately 0.4 million tonnes of carbon from the food industry is directed to human consumption, corresponding to 33% of the total carbon usage in this sector. This figure covers domestic consumption, excluding exports, with animal products dominating at 60%. This proportion underlines the preference for animal-based foods in the Swedish diet. Bakeries and the sugar industry also have significant contributions, accounting for 30% and 10% of domestic carbon consumption, respectively. These sectors illustrate the diverse applications of carbon sources, from basic commodities to more highly valued goods. In addition, the food industry directs a portion of its carbon input to international markets, with 0.49 million tonnes of carbon channelled into exported products, representing 41% of the total carbon use in this sector. This highlights the global reach of Sweden's food products and the importance of export markets to the economic health of the industry. The feed industry, which consumes around 10% of the total carbon of the food industry, and animal husbandry, which uses around 5%, reflect further pathways through which carbon flows within the agriculture and food sectors. These percentages illustrate the cyclical nature of carbon use in agriculture, where outputs from one process act as inputs for another, contributing to the overall sustainability and efficiency of the sector. Figure 6 illustrates for the distribution of the carbon utilization on the food sector.

This analysis of carbon consumption patterns reveals an important detail: of the 17.5 million tonnes of carbon sequestered by photosynthesis in our fields and pastures, only 1 million tonnes ultimately contributes to human food. This small fraction highlights the extensive journey of carbon through the agricultural system before it reaches our plates. Within these 1 million tonnes, 40% comes from the domestic food industry, underscoring the role of local production in our food supply. However, the larger proportion of 60% comes from imported food. The continuation of the carbon cycle through human consumption is equally remarkable. Almost all the carbon we ingest from food is returned to the environment through respiration and waste. This cycle illustrates not only the biological processes of carbon but also the environmental impact of our food consumption. These insights are crucial for understanding the flow of carbon within our agricultural and food systems and for identifying potential areas for improving carbon efficiency and reducing the environmental footprint of our dietary choices.

The feed industry accounts for 0.98 million tonnes of carbon input annually. 43% of the carbon input to the feed industry comes directly from farms, indicating the fundamental role of primary agriculture in feed production. Wheat emerges as the dominant crop in this context, underlining its central importance in Swedish feed production. After wheat, barley contributes 21%, highlighting its significant but smaller role compared to wheat. Oilseeds contribute a further 18%, reflecting their importance in diversified crop rotations and as a source of both feed and industrial raw materials. The oil and bioenergy sectors provide 24% of the carbon input to the feed industry. Within this category, the vegetable oil and biofuel industry is the most important, contributing 65% to this segment. This significant figure points to the growing influence of bioenergy on agricultural carbon flows, in line with global trends towards more sustainable energy sources. The ethanol industry adds 34%, indicating its role in both energy production and as a by-product feeder for the feed industry. Mills, contributing 23%, demonstrate their continued relevance in processing agricultural products into usable forms for both food and feed. Imported feed, which accounts for around 20% of the feed industry's carbon supply, consists mainly of oilcakes and other solid residues. These imports, which constitute 70% of total imported carbon, reflect the global dependence of the Swedish feed industry and the need to supplement domestic production with foreign sources to meet demand. The food industry contributes 13% to the feed industry's carbon supply, mainly via mills. This relationship underlines the cyclical use of resources where by-products from food processing become inputs for animal feed, increasing resource efficiency and reducing waste. Figure 7 shows the distribution of carbon input to the feed industry according to the source of input.

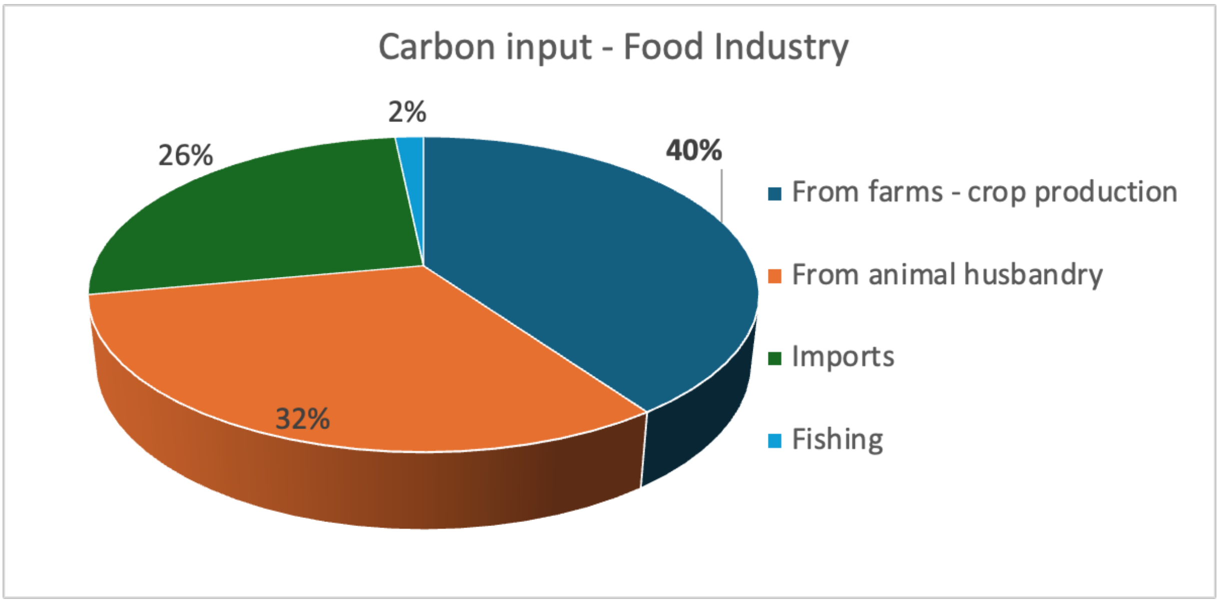

Figure 5. Distribution of the sources of carbon input to the food industry

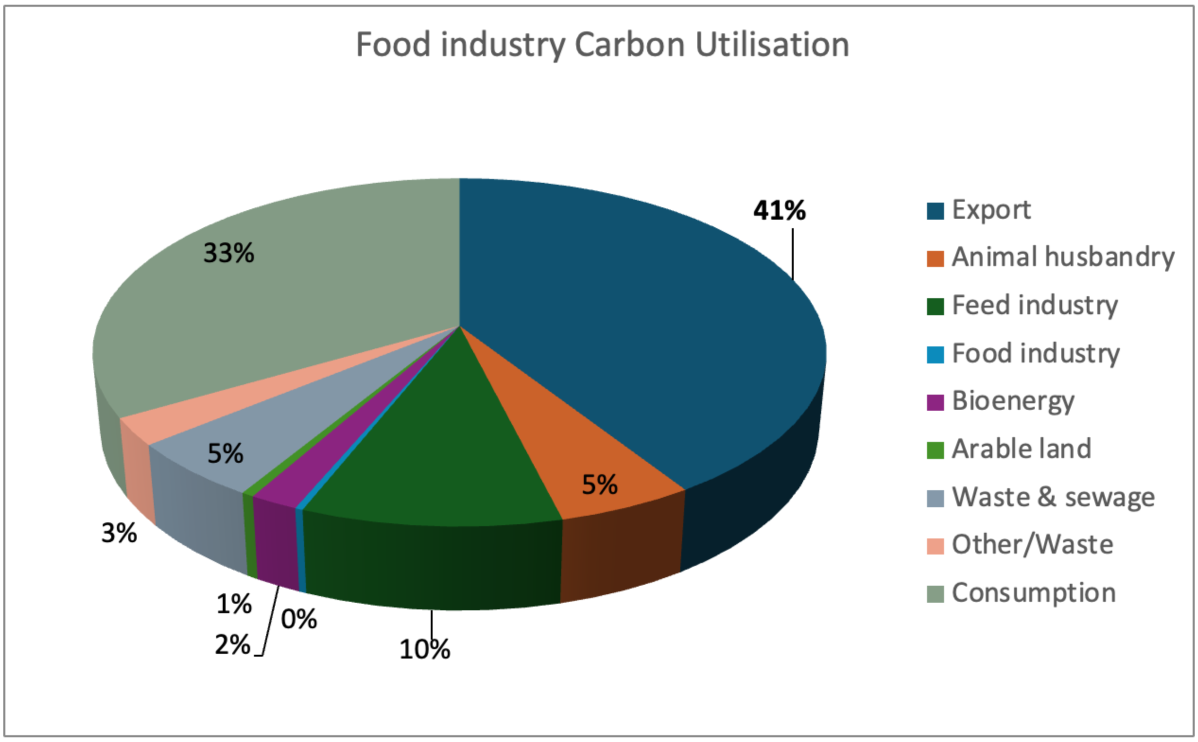

Figure 6. Distribution of the carbon utilization on the food industry

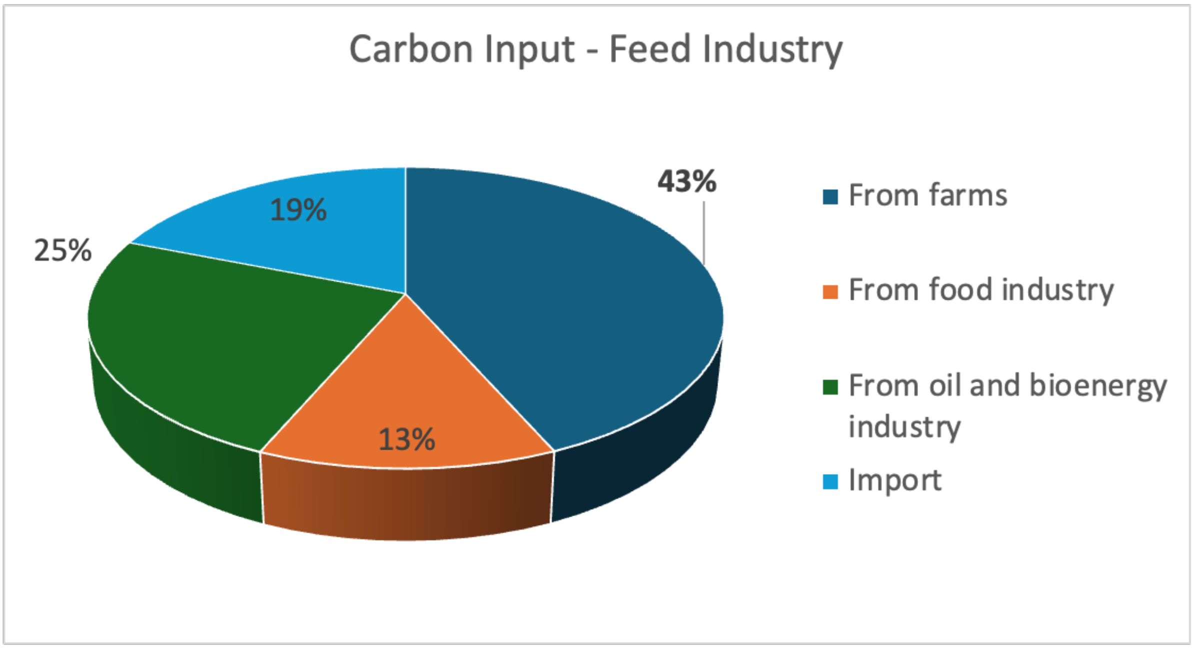

Figure 7. Distribution of carbon input to the feed industry according to the source of input

2.4. Bioenergy Industry

The bioenergy and oil industry in Sweden primarily obtains its carbon input from imports, with a strong emphasis on rapeseed oil and palm oil, alongside oilseeds such as rapeseed and oilcake used for feed purposes. Imports account for around 60% of the total carbon input to these sectors, underlining Sweden's dependence on external sources for these critical raw materials. This high share of imports highlights the global interconnectedness of the bioenergy and oil industry and reflects Sweden's position in the international trade in bioenergy resources. In addition, 26% of the carbon input comes from domestically grown crops, illustrating the integral role of Swedish agriculture in supporting the bioenergy and oil industry. This contribution from local agriculture not only helps to reduce dependence on imports but also supports the country's sustainability goals by using domestic resources. The biofuel and ethanol industry contributes a further 15% to the carbon input. Of the total carbon processed by these industries, 18% is destined for export.

Within the domestic market, 18% of the carbon is utilized by the feed industry, of which approximately 60% comes from vegetable oil and biofuels and 30% from waste by-products of the ethanol industry. This utilization demonstrates the circular nature of the industry, where by-products from one process serve as valuable inputs for another, improving the overall efficiency and sustainability of resource use. In addition, 15% of the carbon is consumed within the bioenergy sector itself. This internal consumption reflects the industry's self-sufficient practices and its role in contributing to Sweden's energy independence and sustainability goals.

The carbon dynamics in Sweden's waste management, biogas production and wastewater treatment sectors show a carbon input of approximately 0.38 million tonnes. This sector plays a central role in the sustainable processing of waste materials, with biogas production accounting for almost half of this carbon input, illustrating its significant contribution to renewable energy resources. Biogas production, mainly from wastewater, organic residues and other biodegradable streams, demonstrates an efficient utilisation of organic carbon.

Typically, biogas contains 50–65% methane (CH_4) and 35–50% carbon dioxide (CO_2). Methane is a renewable and clean energy source, especially when purified to biomethane for use as a vehicle fuel or grid injection. The CO_2 by-product requires careful management and can often be captured and used for industrial applications, increasing the overall environmental benefits of biogas production. This carbon management is consistent with Sweden's environmental strategies by reducing greenhouse gas emissions, in particular through the capture and efficient use of methane from biogas production. To further enhance biogas's role as a clean energy source, it is important to develop technologies to manage and reuse carbon dioxide as a by-product of the biogas process. By using carbon dioxide for industrial purposes, such as in greenhouses or the food industry, the climate benefit of biogas can be maximized and its emissions to the atmosphere minimized. Understanding these processes and opportunities is crucial for decision-makers and stakeholders to optimize the contribution of the waste and biogas sector to national and global sustainability goals.

3. Sankey Diagrams

The Sankey diagrams provide a visual representation of the results from Chapter 2, offering both a holistic overview of the agricultural system and detailed insights into specific sectors. The thickness of the arrows represents the magnitude of the flows, meaning smaller individual flows may not be visible and are therefore not included. As a result, some discrepancies may appear compared to the textual data in Chapter 2. Additionally, due to statistical limitations, calculations, and assumptions, a perfect balance of all flows is not always possible. In cases of differences, the figures in Chapter 2 should be considered authoritative.

Key Concepts in the Diagrams

Industry: Encompasses processing activities within food, feed, and bioenergy sectors, where products from arable land, animal husbandry, and imports are transformed.

Consumption: Includes household and service sectors (trade, restaurants, and catering), representing the final useof agricultural and industrial products.

Animal Husbandry: Covers cattle, pigs, chickens (for egg production), broiler chickens, and horses.

Other: Accounts for smaller flows such as pet feed (dogs, cats, wild birds), animals raised for consumption (rabbits, ducks, geese), farmed and wild-caught fish, game meat, mink farming, and associated industrial products. Also includes bedding materials from peat and wood shavings.

Diagram Structure and Focus Areas

- Figure 8 presents an overview of carbon flows across the system. However, as noted in Chapter 2, carbon emissions from land to the atmosphere are not included due to a lack of reliable data.
- To highlight specific smaller flows, Figures 9, 10, and 11 focus on distinct sub-areas from Figure 8:
  - Figure 9: Examines arable land and pasture, emphasizing their role as carbon sinks.
  - Figure 10: Highlights industry-related flows.
  - Figure 11: Details carbon flows within animal husbandry.

- In these sub-area diagrams, some larger flows are omitted to provide a clearer focus on smaller, significant flows. Since these represent partial system views, balance calculations are not included, as they would not be meaningful with incomplete data.

By structuring the data visually, these diagrams enhance understanding of the complex interactions within the agricultural system and its carbon dynamics.

3.1. The Overall System

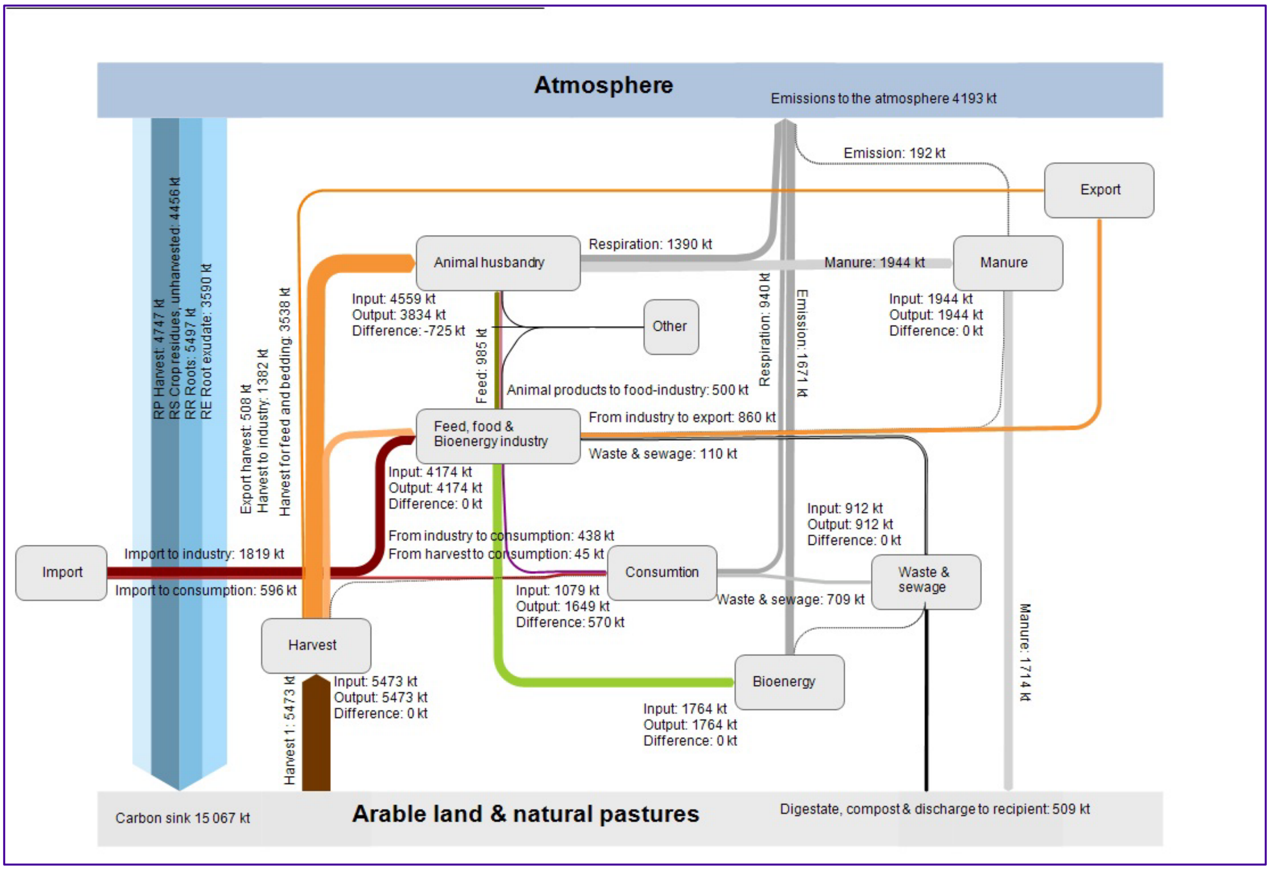

Figure 8. Overview carbon flows of the overall agricultural system

In the agricultural system, feed flows from the feed industry to animal husbandry, while animal products such as meat, eggs, and milk move from animal husbandry to the food industry. However, these flows are difficult to distinguish visually in the diagram due to their complexity. A portion of manure, waste, and sewage from the food and feed industries, as well as consumption, is directed to the bioenergy sector, where it is converted into bioenergy through combustion or biogas production. The digestate from biogas production is then returned to waste management and primarily applied to arable land as fertilizer.

It is important to note the carbon dynamics within this system:

- Carbon enters the soil through CO_2 absorption from the atmosphere and is reintroduced via manure and organic waste.
- At the same time, carbon is released back into the atmosphere through livestock respiration, consumption-related emissions, and bioenergy processes.
- The interconnections of carbon emissions from various sources illustrate the interplay between biological and industrial processes in the carbon cycle.

These interactions highlight the circular nature of carbon flows and the balance between inputs and emissions within the overall agricultural and bioenergy system.

3.2. Atmosphere and Arable Land and Natural Pastures as carbon sink

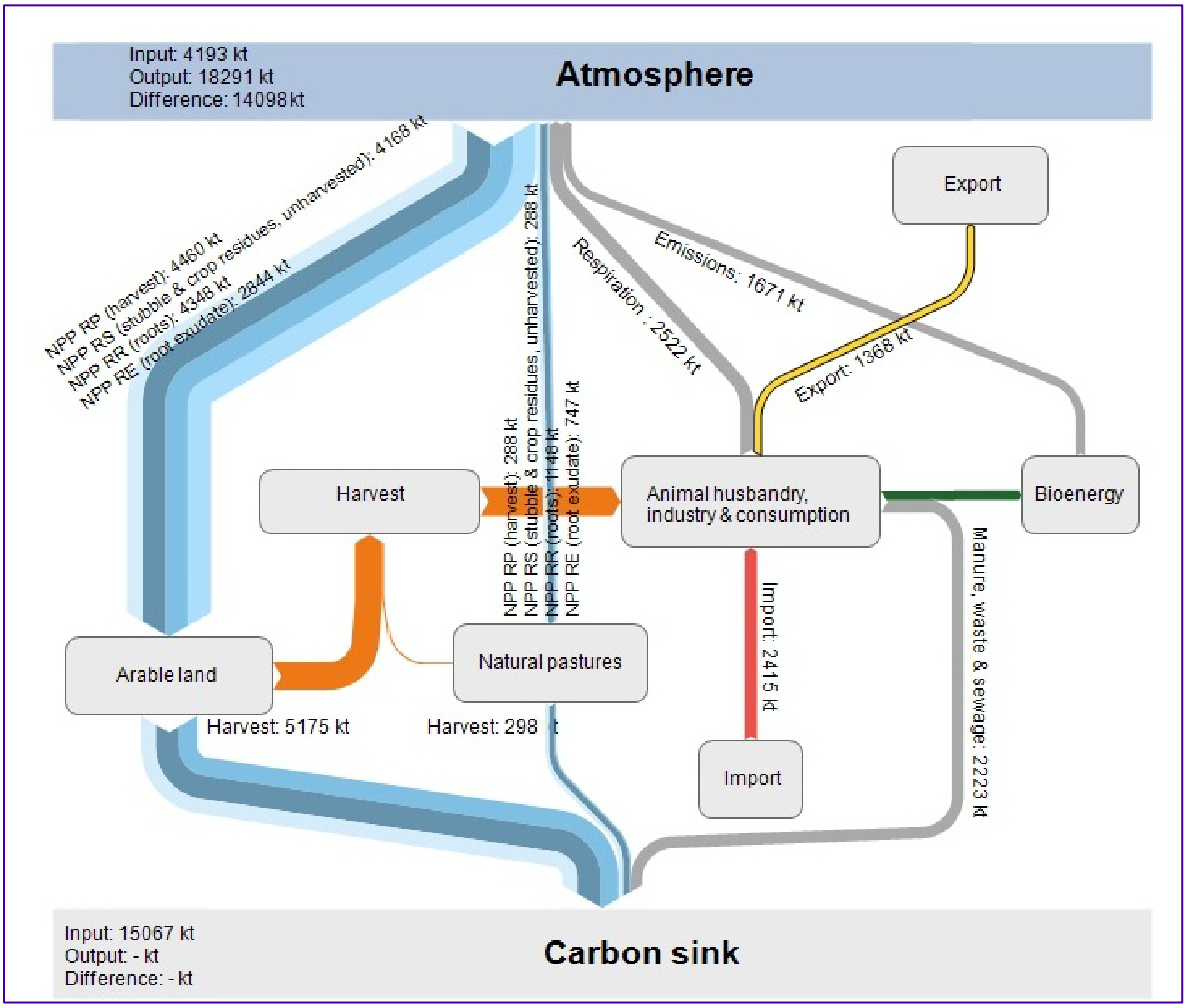

Figure 9. Arable land and natural pastures

Figure 9 illustrates the role of cropland and pasture in harvest production and their combined contribution to carbon accumulation in the soil. To highlight the significance of carbon sequestration, an additional level has been introduced in the diagram to distinguish the carbon sink.

For clarity, the flow of waste from consumption—which should ideally be distributed between cropland and pastures—has been simplified and aggregated into the carbon sink. This adjustment ensures a clearer representation of how carbon is retained within the system.

3.3. Food, Feed and Bioenergy Industries

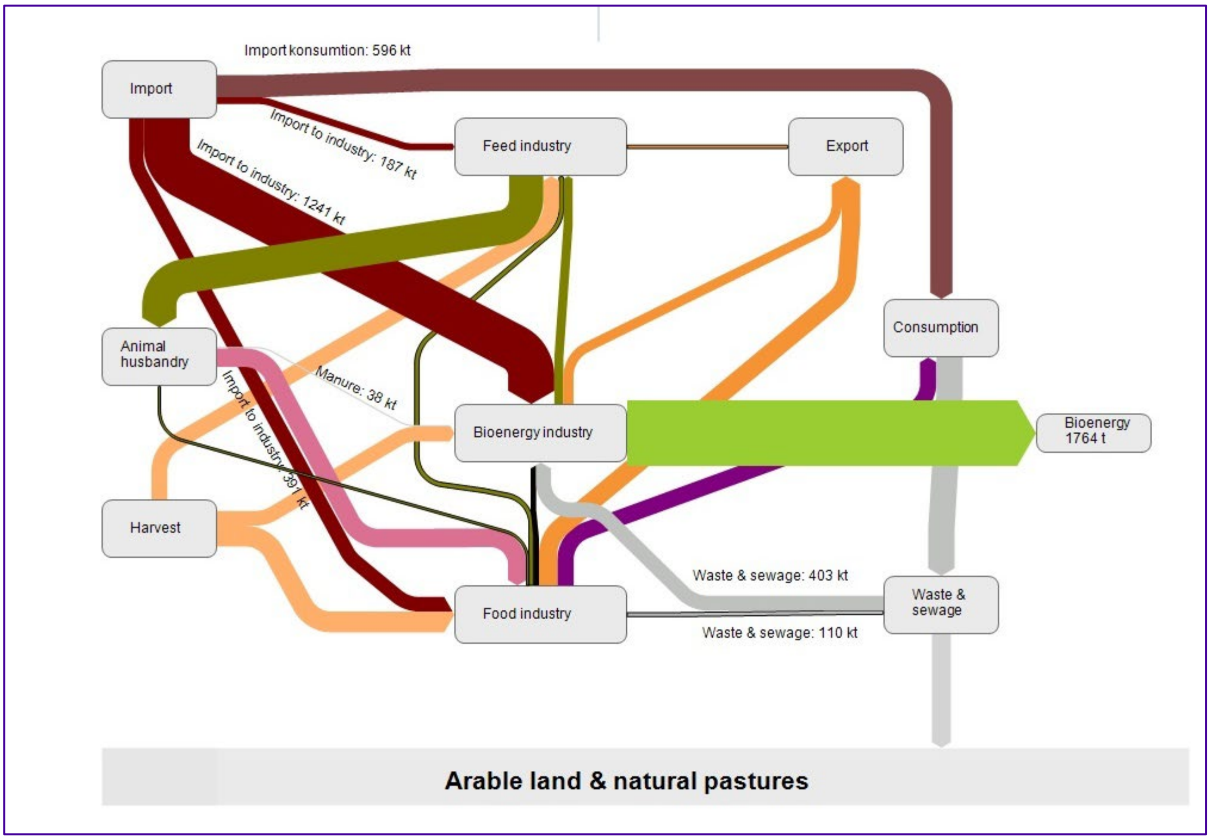

Figure 10. Food, Feed and bioenergy industries

Figure 10 highlights the flows between different industries, with less emphasis on exchanges with the atmosphere and land, which have been omitted for clarity. While flows from imports and animal husbandry into industries are based on relatively reliable data, it is more difficult to quantify flows between the feed, food, and bioenergy sectors. Additionally, returns from trade (within the consumption sector) back to food or bioenergy lack reliable data and have therefore been excluded.

The feed, food, and bioenergy industries are highly interconnected, making it challenging to distinguish certain flows. For example:

- A grain mill may produce feed entirely or split its output into flour (food) and bran (feed), while chaff can be burned for bioenergy.
- Oilseeds (e.g., rapeseed) yield oil for food or bioenergy (RME, FAME, HVO) while the press cake serves as feed or protein extraction for food.

- Fat from slaughterhouses can be used in food, feed, or fuel (HVO).
- Imports for bioenergy are primarily oilseeds, but data on how much of Sweden's domestic oilseed production becomes biofuel or food is uncertain.
- Residual products from one industry may support another industry's processes or return to farms as feed or soil inputs.

Given these complexities, Figure 10 does not present balances or precise flow quantities where uncertainties exist. However, it clearly illustrates key industry interactions, including:

- A significant share of waste products from industries is reused as animal feed.
- The food industry supplies nearly equal flows to domestic consumption and exports.
- A large portion of imports is allocated to bioenergy production, particularly for fuel manufacturing.

3.4. Animal Husbandry

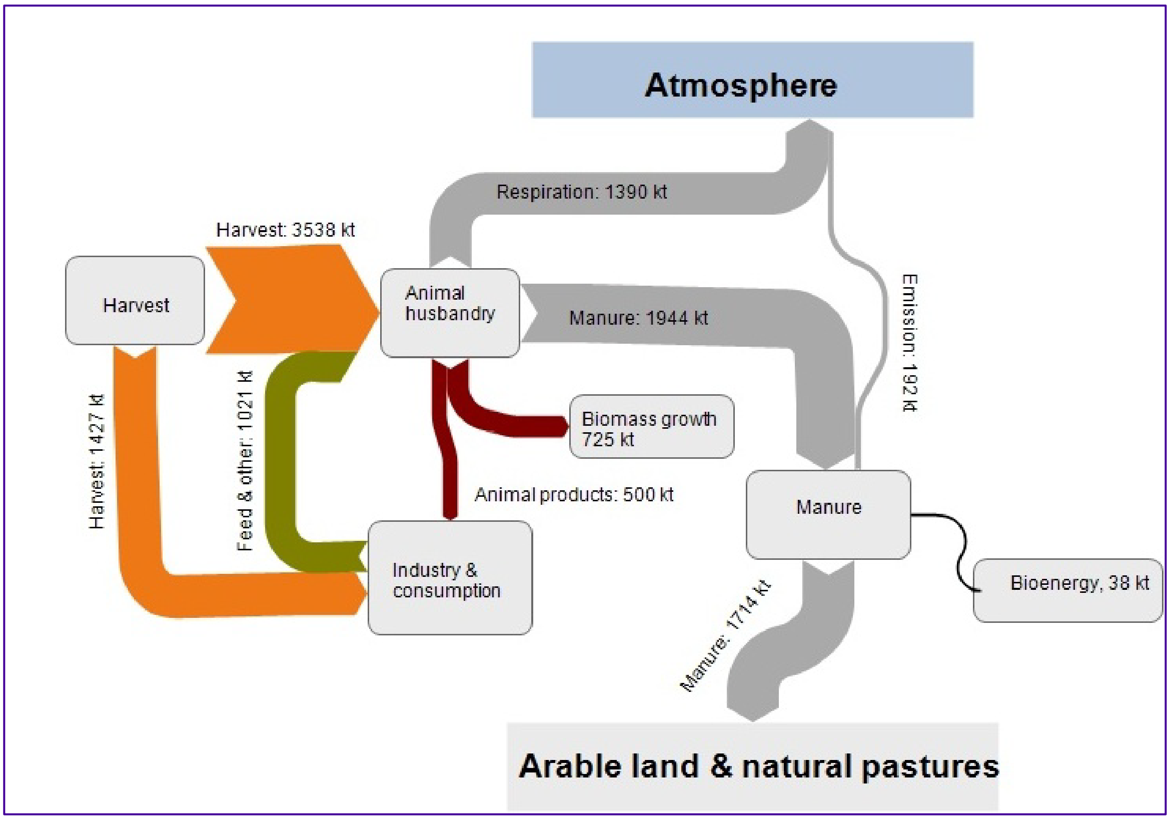

Figure 11. Animal Husbandry

Figure 11 illustrates the flows to and from animal husbandry, omitting interactions with the atmosphere, soil, and harvest for clarity and to better highlight the intended flows.

A significant portion of the total harvest is directed to animal husbandry, with over 70% of non-pasture feedconsisting of green fodder (grassland and fodder crops). Grassland, as a perennial crop, plays a crucial role in crop rotation, contributing to soil carbon content (humus). This has multiple benefits:

- Enhances water retention in the soil.
- Supports soil microorganisms and worms, which metabolize plant nutrients.
- Promotes carbon sequestration through root exudation (see Figure 8).
- Prevents soil compaction through deep-rooted grass systems.
- Provides natural fertilizer, further benefiting soil organisms.

Many crops used as feed fail to meet quality standards for human consumption, while animal husbandry also absorbs large residual flows from the food industry. This recycling of by-products prevents them from being disposed of directly into the soil or bioenergy sector, instead reintegrating them into food production.

Figure 8 presents a negative balance of 725 kt for animal husbandry, which is interpreted as an increase in biomasswithin the animal population. Since only a fraction of animals are slaughtered annually, this figure reflects carbon accumulation in living animals. Different species have varied lifespans before slaughter:

- Slaughter pigs and broilers have turnover periods of one year or less.
- Parent animals (e.g., dairy cows, beef cattle, and steers) live several years before slaughter.
- Recruitment animals (future parent stock) also contribute to population growth.

This increase in animal biomass, depicted as carbon production, highlights the role of livestock in carbon cyclingwithin the agricultural system.

4. Insights from interviews

This section presents a summary of findings from interviews conducted to complement the quantitative data and provide practical insights. A total of 12 interviews were carried out with experts from various agriculture-related sectors, offering a broad perspective on the challenges and opportunities in the field.

4.1. Holistic approach to value chains and innovation

The insights gathered from the interviews underline the importance of a strategic and comprehensive approach to managing value chains, by examining each phase from primary production to the final consumer touchpoints. This holistic approach has enabled a clearer mapping of bottlenecks and areas for improvement within different segments of the chain. By identifying specific needs and challenges, decision-makers have a better basis for prioritizing efforts and allocating resources more efficiently.

For example, the recent data from the Swedish Board of Agriculture has provided a detailed picture of the actual volumes flowing through the value chains, which has made it possible to:

• Locate over- or under-utilized resources.

• Identify opportunities to reduce waste and improve logistics flows.

• Optimize resource allocation to increase productivity and efficiency in the agricultural and food sectors.

Through this type of data-driven insight, the sector's operational efficiency has been strengthened and strategic decisions have been made to better meet both economic and sustainability-related goals. By understanding the intricacies of these volume flows, stakeholders are better positioned to address inefficiencies and streamline operations, leading to significant improvements in how resources are managed and used. This approach not only supports sustainable practices, but also improves the overall efficiency of the supply chain, ensuring that every step from farm to fork is carried out with optimal precision and minimal waste. Adopting this holistic view has proven to be crucial in advancing the sectors' capacity for sustainable management and responsible production, in line with broader environmental and economic goals.

4.2. Improving efficiency through digitalization

Interviewees highlighted the crucial role of digitalization in transforming the food industry. By incorporating advanced digital technologies, stakeholders can achieve highly accurate forecasts that allow them to synchronize production schedules with actual market demands more effectively. This alignment helps drastically reduce waste by ensuring that production volumes are aligned with consumer needs. The integration of these technological tools streamlines the management of production processes, improving overall business efficiency.

In addition, digitalization plays a key role in resource management within the industry, allowing companies to use their resources more wisely and sustainably. By leveraging data and digital analytics, companies can optimize their supply chains, reduce excess production, and minimize the environmental impact of their operations. This approach not only supports sustainability initiatives, but also contributes to cost reductions and improves the industry's adaptability to changing market conditions.

4.3. Collaboration for industrial symbiosis

Throughout the interviews, there was a strong focus on the necessity of collaboration to enable industrial symbiosis. By establishing networks that support the exchange and reuse of resources across industries, companies can significantly increase their sustainability and improve their operational efficiency. This collaborative approach not only helps companies reduce waste but also increases resource use by finding innovative ways to reuse by-products and residual materials.

Participants highlighted the importance of obtaining support from funders, noting that financial support is crucial to fostering research and innovation in industrial symbiosis. Such support is essential for exploring new ways to integrate sustainability into everyday business practices and for developing new technologies and methods that facilitate more efficient resource use. This support helps drive the progress needed to transition to more sustainable industrial operations, which is beneficial not only for individual companies but for the wider economy and environment.

4.4. Addressing environmental and regulatory challenges

Discussions frequently revisited the topic of the environmental impact of agricultural practices, particularly around the application of biochar and how the management of crop residues is shaped by environmental laws. Unlike Denmark and Norway, which have set definitive targets for incorporating biochar into agricultural processes, Sweden faces obstacles. These challenges stem from vague regulations and uncertainty among farmers about the economic and environmental benefits of biochar. The limited knowledge about possible economic incentives or tangible benefits makes it difficult to justify the wider adoption of biochar within Sweden's farming communities. There is a need for further research and demonstrations that clearly demonstrate how biochar can contribute to increased profitability and sustainability in practice.

In addition, the discussions deepened the possibilities for developing new business models that more deeply connect agriculture with biogas production. Such models would not only help to recycle agricultural waste into valuable energy resources, but also to reduce the carbon footprint of agricultural practices. However, participants noted that current government policies and regulations often constrain these innovative approaches, posing significant barriers to their implementation. Despite these barriers, there was consensus on the potential of these models to promote more sustainable agricultural practices, highlighting a significant opportunity for policy reform and industry adaptation to promote greener and more efficient agricultural practices.

4.5. Strategic sustainability work in large companies

Central sustainability teams play a crucial role in ensuring that purchasing decisions are aligned with broader climate impact goals. These teams guide the company's practices towards deforestation-free agricultural practices to significantly reduce carbon emissions. In addition, they are highly focused on the effective management of waste generated during food production and processing. To address this, various strategies are used, such as donating unsold food to charities or offering it at discounted prices to consumers. This not only helps reduce waste but also supports the well-being of society. Such initiatives reflect a deep commitment to sustainability that goes beyond simply meeting legal requirements and demonstrates a proactive approach to environmental stewardship. This broader, company-wide commitment to sustainability emphasizes responsible business behavior while engaging with community needs and environmental stewardship efforts.

4.6. Advocacy for supportive agricultural policies

The interviews highlighted a proactive approach to engaging with regulators, aiming to shape policies that directly impact farming practices. This advocacy work is focused on ensuring that legislation promotes sector growth while maintaining its sustainability and economic viability. Participants expressed a strong desire for regulations that are sensible, based on sound scientific research and economically feasible. This stance reflects a broad recognition of the need for policies that not only support current farming practices but also encourage innovation and flexibility. Such policies are crucial to enabling farmers to adapt to new challenges and opportunities in a rapidly changing market and environmental landscape. This advocacy for better regulation is seen as crucial to the long-term health and profitability of the agricultural sector, ensuring that it can continue to thrive while meeting the demands of sustainability and environmental stewardship.

4.7. Comprehensive carbon and nutrient management

The discussions also explored the complexities of managing carbon flows within the agricultural value chain, highlighting the importance of developing a comprehensive approach to effectively monitor these flows to enhance sustainability efforts. Managing carbon in agriculture is multifaceted; it requires not only the initial capture of carbon through methods such as photosynthesis and biochar integration, but also careful control of its subsequent release into the atmosphere. This involves a thorough understanding of the entire life cycle of carbon within agricultural systems, from its absorption in crops to its final release through processes such as decomposition, livestock respiration and organic waste management. The discussions highlighted that improved carbon management practices are crucial to reducing the overall carbon footprint of agriculture and involve a detailed assessment of how carbon is used and stored at different stages of the agricultural process.

4.8. Future research directions and recommendations

During the discussions, a strong need for concrete measures to improve sustainable practices in the agricultural and food sectors in Sweden emerged. Proposals included introducing economic incentives, such as reduced VAT rates on environmentally friendly products, as well as a potential meat tax to reduce emissions and encourage more sustainable consumption choices. At the same time, the importance of strengthening regulatory frameworks to promote carbon sequestration and reduce carbon losses in agricultural land through improved management of crop residues and increased use of biochar was emphasized, with a particular focus on changing the carbon balance of arable land.

The insights from interviews highlight key areas for intervention:

- Crop residue optimization: More efficient return of crop residues to arable land can reduce carbon losses and improve long-term carbon sequestration. Guidelines and incentives are needed to prevent residues from being removed or burned.
- Increased carbon allocation to roots and underground storage: Developing methods for perennial crops and improved crop rotations can maximise the contribution of root biomass to carbon storage.
- Improved resource use in animal husbandry: Measures to optimise feed use and manure management can reduce carbon losses and methane emissions, in particular through improved biogas recovery technologies.
- Circular value chains for agricultural waste: Converting organic residues from agriculture and food production into bioenergy or bio-based products can close the carbon cycle.

- Policy reforms and economic incentives: To overcome current obstacles, the need for clearer rules and stronger laws that can promote sustainable practices was highlighted. Examples from Denmark and Norway show that concrete targets and economic incentives are crucial for success. Proposed action is to implement reduced VAT rates on environmentally friendly products, support for biochar production and a potential meat tax to reduce emissions and encourage sustainable consumption choices.
- Strengthened innovation climate and regulatory frameworks: Participants called for supportive policies that create an environment for innovation and technological development. Better regulatory frameworks could facilitate the adoption of innovative agricultural technologies and ensure the long-term sustainability of the sector. The proposed action is to develop legislation that supports technological advances in agriculture, such as precision agriculture and digital platforms for resource optimization.
- Strengthened data flows and digitalization: An improved understanding of carbon flows requires high-quality data and integrated systems for monitoring carbon inputs and removals in agriculture. The proposed action is to develop digital platforms that enable accurate tracking of carbon flows and provide farmers with tools to optimize their practices, reduce waste and align production with sustainability goals.

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