METABOLIC

CIRCULAR AGRIFOOD

Potential of Circular Economy Actions to reduce Greenhouse Gas Emissions

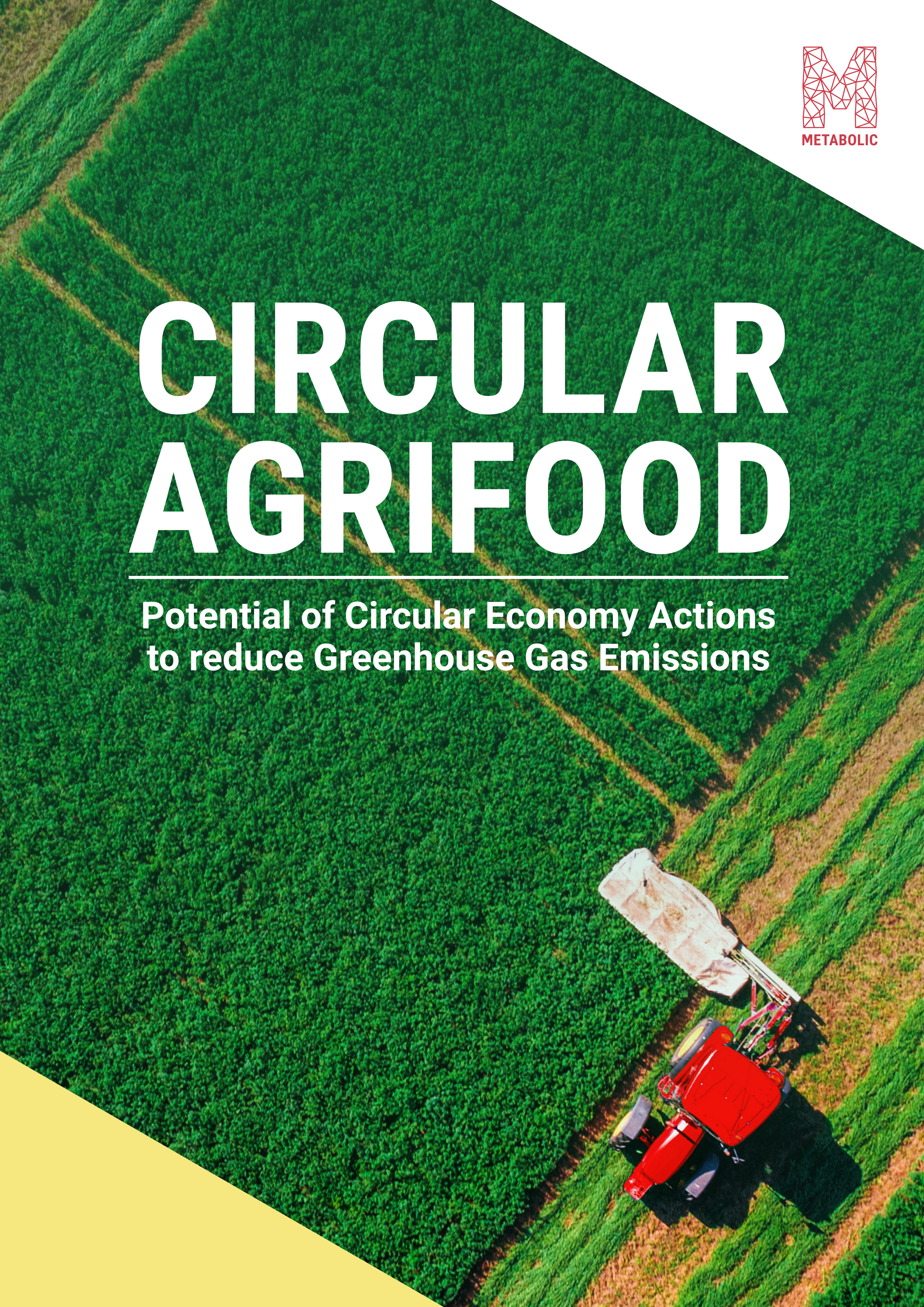


TABLE OF CONTENTS

EXECUTIVE SUMMARY

BACKGROUND

In recent years, the European Union and its Member States have increasingly put the circular economy (CE) at the forefront of environmental action. The 8th Environmental Action Programme, the Circular Economy Action Plan, and the European Green Deal are already working towards enhanced circular economies and their links with climate change mitigation efforts. However, there is still relatively little known about how much the circular economy can do to reduce emissions in specific sectors.

Pursuing a more circular agrifood sector provides us with a variety of opportunities for reaching climate targets. This study shows (based on Exiobase data) that the consumption of agrifood products in Europe alone results in an average greenhouse gas (GHG) emissions of roughly 0.75 tonnes of CO_2e per person each year. By 2050, in order to remain below 1.5 °C temperature rise, the total per capita greenhouse gas emissions need to be brought down to 1.5 tonnes CO_2e (IPCC, 2018), so the consumption of agrifood products is a considerable part of that total budget. Without making significant agrifood emission cuts, that goal will be challenging to reach.

The main purpose of this report is to explore the possibilities to reduce agrifood greenhouse gas emissions by exploring circular economy (CE) solutions. During the research for this report, around 80 CE actions were evaluated. Over a dozen of those actions have a higher potential in terms of feasibility and impact, compared to a 2016 baseline, and were selected to study further. These actions were assessed in terms of physical and technological feasible emissions reduction potential - both for actions on their own (ignoring overlap, e.g., between waste reduction and using waste) and in combined storylines that take interconnections between the actions into account.

Defining what a circular action is for the agrifood sector

The term circularity is well known in terms of technological materials and cycles, e.g. metals and electronics. However, there is still some work to do in defining what the term circular economy means for biological cycles and sectors like agrifood, as these rely on natural environments. In this report, we use a broad definition of the circular economy to decide which actions can be considered within the scope of our analysis. We therefore present actions in three “layers”, ranging from the narrowest definition of circularity to the widest definition. These are described briefly here:

Layer 1

Most narrow definition of the circular economy - Actions focused on closing material and product cycles

Layer 2

Circular economy in a limited system - Actions to reduce consumption in order to be in line with regeneration rates (includes re-evaluating the balance between livestock and crop production)

Layer 3

Molecular circularity in production systems - Actions that address molecular circularity of carbon, nitrogen, and phosphorus cycles

Results of the greenhouse gas reduction assessment for selected circular economy actions

Europe’s agrifood sector has the potential to serve as a net carbon sink through actions designed to reduce or return more carbon to land and vegetation than is emitted. This study shows that between 360,000 and 2.1 million kT CO_2e emissions could be avoided or sequestered. However, reaching these numbers requires a major shift in not only people’s diets, but also production-systems and the way we try to avoid and handle waste. This effectively means changing the face of the agricultural system, as well as the types of products that are available to consumers. There are serious challenges regarding the technical, social, and economic implications and feasibility of such changes. For example, substantially reducing the production and consumption of animal products or greatly reducing food waste will be major undertakings.

If we look at actions that can potentially reduce greenhouse gas emissions, the total avoided CO_2e will be around 300,000 kT, two-thirds of the current agrifood system’s emissions. Actions that sequester carbon in soil and vegetation show high potential (around 900,000 kT), nearly twice the annual emissions of the agrifood system. However, these actions also come with the highest uncertainty. The outcomes depend on how and where they are applied. Actions designed to return carbon to soil and vegetation are also limited in time as there is a maximum amount of carbon that can be stored this way. After just a few decades the maximum potential of these actions would be reached.

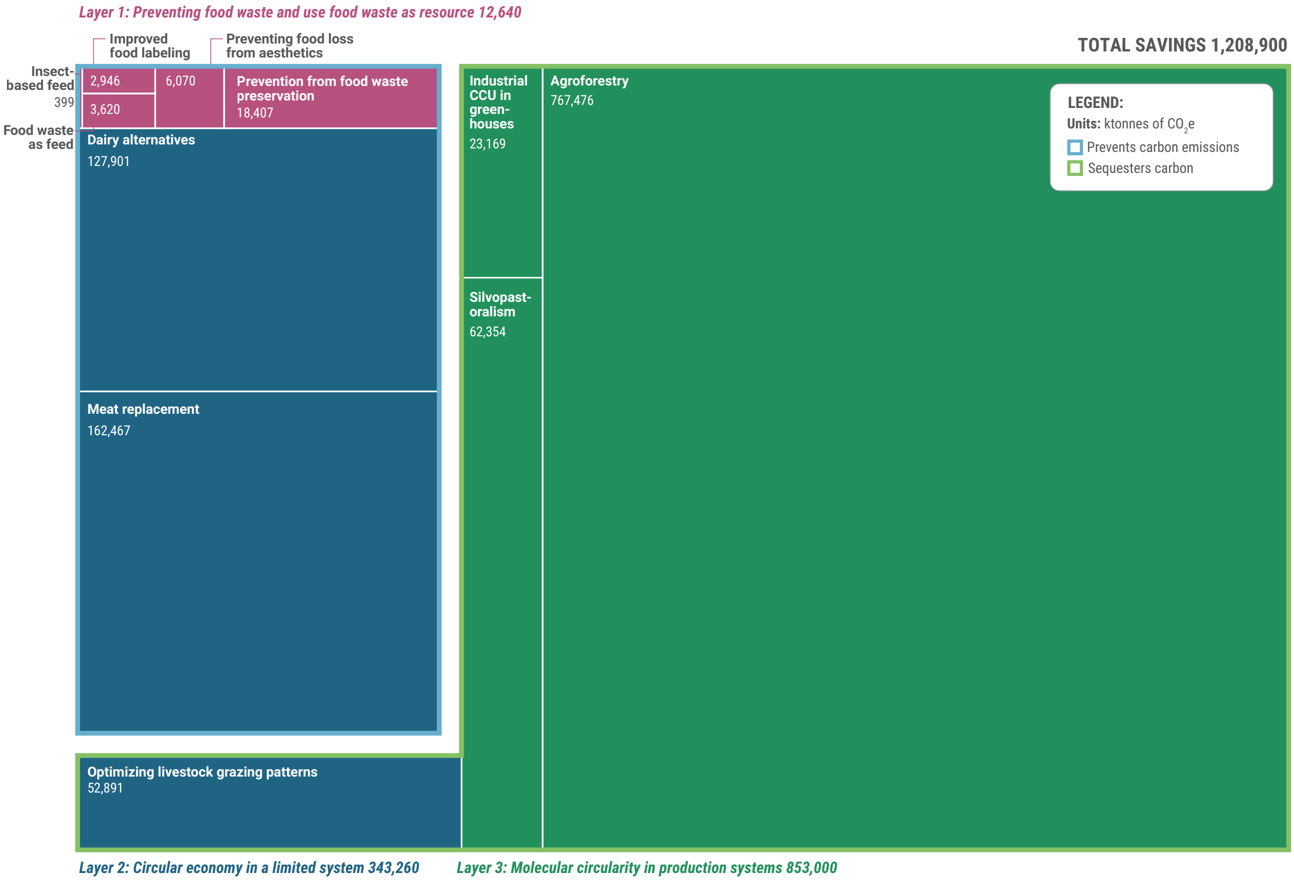


Figure 1 *Total impact reduction of all actions, broken down by layer and action.*

Understanding the possible uncertainties of mitigating climate change with CE actions

Looking at the most conservative outcome from our calculations, the total net greenhouse gas emissions reduction potential amounts to 356,000 ktonnes annually (66% of the entire sector's annual emissions). The higher, more optimistic result, results in a potential of 2.1 million ktonnes of CO_2e (more than half of all European emissions, not just the agrifood sector). These numbers mean that even with the most conservative estimations, that, if universally adopted, circular economy actions can potentially lead to a neutral or even net-negative emissions agrifood sector in Europe. It should be noted however, that around 74% of the net emissions savings are due to carbon sequestering, rather than carbon mitigating actions.

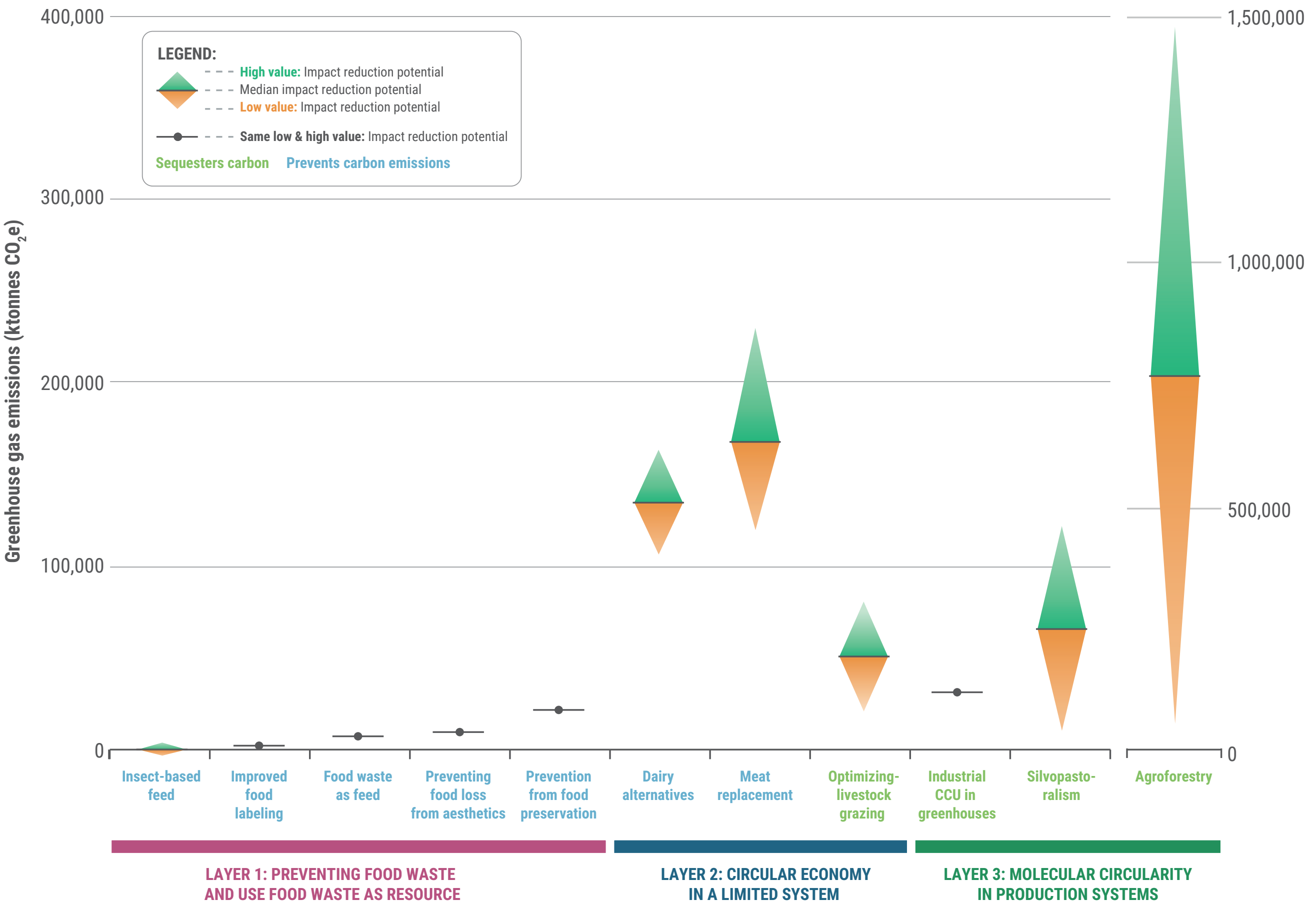


Figure 2 *Sensitivity of total impact reduction across the CE actions of each storyline.*

Considerations on feasibility and co-benefits

There are many questions about whether these CE actions would be accepted by the public as food and landscapes are very personal topics. The European Green Deal, Farm to Fork Strategy, and forthcoming Action Plans for example should therefore not only integrate production and consumption interventions, but also situate these actions in a broader social and cultural narrative in order to achieve transformation. This research is mainly focused on reducing greenhouse gases and not so much the social impact of the implementation of such actions. Social implications come with a completely different set of challenges.

Further application of the approach

This study demonstrates more broadly the value of a previously defined methodology (originally designed by le Den et al., 2020 and applied to the building sector). At the same time, it works to identify further potential adaptations described in the "Reflection on the Methodology" supplementary report. This report highlights the importance of including elements such as time and space in the assessment of CE actions. It also identifies the need for more stakeholder engagement and review of the assessment during the process. The methodology reflections, as well as the results of this study, will be shared with experts on climate mitigation and circular economy in the EU and EEA member countries. The methodology outlined in this report can be applied to national contexts as well. It is also relevant to consider application of this generic methodology to a third sector, besides the building and agrifood sectors, but plans for that have not yet been set up.

01 INTRODUCTION

PURPOSE

Globally, the agriculture and food (agrifood) value chain is responsible for between 25 - 30% of global greenhouse gas emissions (IPCC, 2014; Bajželj et al, 2013). After the energy and transport sectors, it is Europe's largest contributor to climate change (European Union, 2018). The agrifood sector is unique in a sense because it has the potential to store large amounts of carbon in soil and vegetation, to the extent that environmental impact from other sectors can be compensated for (Kay et al., 2019. However, currently, the opposite trend is visible: land-use change and agricultural production practices, driven by unsustainable production and consumption patterns and waste, result in carbon being released. Since the start of the industrial revolution, an estimated 214 Pg of carbon has been emitted from land-use change and the depletion of soil organic carbon, compared to the 270 Pg from the combustion of fossil fuels (Zomer et al., 2017). The agricultural system also results in significant N2O emissions and methane from mineral fertilisers and compost.

In order to meet the Paris Climate Agreement targets and keep the rise of global temperature below 1.5 °C, a major transformation needs to take place in all sectors including the agrifood sector (Clark et al., 2020). A more circular economy is seen as a means to reduce greenhouse gas emissions. Achieving a circular economy does not correspond directly to the reduction of emissions, however, and circular economy ambitions are covered separately in policy. This report aims to reconcile ideas about circularity and climate change mitigation by exploring the two concepts simultaneously. The main purpose of the report is therefore to evaluate the potential of circular economy actions in the agrifoods sector to achieve Europe's net-zero emissions target.

The circular economy (CE) is defined by the Ellen MacArthur Foundation as "an economy that is "restorative or regenerative by design and aims to keep products, components, and materials at their highest utility and value at all times, distinguishing between technical and biological cycles." The European Environment Agency (EEA) defines the circular economy as "a circular economy seeks to increase the proportion of renewable or recyclable resources and reduce the consumption of raw materials and energy in the economy, while, at the same time, protecting the environment through cutting emissions and minimising material losses" (EEA, 2018).

In recent years, the European Union as well as individual Member States have increasingly put the circular economy at the forefront of environmental action. The 8th Environmental Action Programme, the Circular Economy Action Plan, and the European Green Deal are already focussing on the integration of circular economy and climate mitigation efforts. However, there is still relatively little known about how much the circular economy can assist in climate mitigation within specific sectors.

Focusing on high-emission sectors such as agrifood provides an opportunity to dig deeper into the specific ways circular economy processes can influence climate mitigation efforts. This is necessary on multiple levels. On a European level, it will enable clearer connections and coordination between the Circular Economy Action Plan, the European Green Deal, the Climate Law, and the Farm to Fork Strategy. Strategies considered in this study could help achieve multiple policy goals simultaneously. At the same time, sector level insights can help Member States in setting up more coherent, targeted, and effective strategies for climate change mitigation throughout the agrifood value chain.

Establishing a circular agrifood sector provides us with a variety of opportunities to reach our climate targets. By 2050, in order to remain below 1.5 °C global temperature rise, the total per capita greenhouse gas emissions need to be cut down to 1.5 tonnes CO_2e (IPCC, 2018). This study shows (based on Exiobase data) that the consumption of agrifood products in Europe alone results in an average greenhouse gas (GHG) emission of roughly 0.75 tonnes CO_2e per person per year, which is a considerable part of the total emissions budget. Without making significant cuts to agrifood emissions, this goal will be challenging to reach. However, the primary purpose of the circular economy is to conserve and preserve materials and creating a more circular economy does not always reduce greenhouse gas emissions. It is in fact not common to measure the success of circular economy strategies this way.

The main purpose of this report is to explore the potential to reduce greenhouse gas emissions in the agrifoods sector using circular economy actions. This is done in two parts:

- **A snapshot of the baseline situation**

  What were the main sources of GHG emissions associated with agrifood sector in 2016 (the most recent year data was available for)? How do materials and embedded impacts flow between segments of the agrifood sector and between Europe and other regions?

- **Circular Economy actions that can prevent climate change**

  Around 80 CE actions were analysed, and more than a dozen with a high potential in terms of feasibility and impact were selected to evaluate further. These actions were deemed to have a higher potential based on physical and technological feasible emissions reduction potential, Actions were evaluated individually and in combination (e.g. taking into account the interactions between actions).

CONTEXT OF THE EUROPEAN AGRIFOOD SYSTEM

Europe benefits from an agrifood system that produces world-renowned gastronomies and food cultures, but those come with a hefty price. First of all, the agrifood system is causing significant damage to ecosystems and biodiversity in Europe (Crenna, Sinkko & Sala, 2019; European Environment Agency, 2020b), which in the long run will reduce the ability to produce food. For example, recent insect monitoring schemes and long-term European studies reveal a drastic decline in insect numbers, distributions, or collective weight (biomass) (Almond, Grooten, & Petersen, 2020). Without insect pollination, agricultural production in Europe would be reduced by 25-32%. It is therefore surprising that due to incentives supporting destructive practices it is the agrifood sector that is one of the main contributors to insect declines (Zulian, Maes, & Paracchini, 2013).

Secondly, the European agrifood sector remains highly wasteful. The Food Loss Index shows that European losses from post-harvest to distribution are among the highest in the world. During this stage over 15% of food was wasted in 2016 (Almond, Grooten, & Petersen, 2020). Inefficiencies such as these are obvious areas to begin with when considering the road ahead for the European agrifood sector.

Waste is, in a high-impact and resource-intensive sector, an important issue to solve. Europe has earned its place as a world leader in technologies, trade, and value-added products in the agrifood sector, however, there is still a significant gap between the current situation and Europe's ambitions of creating a circular and carbon-neutral economy. While Europeans account for less than 10% of the global population, their food consumption is responsible for 45% of global pesticide use (De, Bose, Kumar, Mozumdar, 2014). Also, roughly one third of the land needed to feed the European population is located outside the EU, therefore pushing some of the associated environmental impacts onto other regions (Steen-Olsen et al., 2012). Europe should consider the role it plays in damaging the environment globally.

Even beyond the impacts embedded in imported products, there is also the economic might of Europe to consider in global food production systems and markets. Organisations in the European food system control a large share of global food markets and the region exports significant amounts of agricultural inputs, knowledge, and technologies. While this report focuses mainly on how the circular economy can potentially affect domestic greenhouse gas emissions, changes in consumption behaviors, practices, and technologies applied within the European agrifood sector could have a global impact indirectly.

Even beyond the impacts embedded in imported products, there is also the economic might of Europe to consider in global food production systems and markets. Organisations in the European food system control a large share of global food markets and the region exports significant amounts of agricultural inputs, knowledge, and technologies. While this report focuses mainly on how the circular economy can potentially affect domestic greenhouse gas emissions, changes in consumption behaviors, practices, and technologies applied within the European agrifood sector could have a global impact indirectly.

APPROACH

Part of the mission of the European Environment Agency (EEA) is to support policymaking with targeted and actionable knowledge. The EU and its Member States are formulating policies to dramatically reduce greenhouse gas emissions and achieve greater sustainability. Identification of the most impactful measures to increase the circularity of the agrifood system while simultaneously reducing the sector's contributions to climate change is an important contribution to these efforts.

In order to do this, the EEA therefore initiated a project to:

- Create a comprehensive quantitative baseline understanding of the agrifood system in the EU-27 which can be used to identify the most high-impact CE actions (following the approach developed by the EEA together with Rambøll Management Consulting A/S). See Table 1 for an overview of this methodology.
- Select and evaluate a number of CE actions that can potentially result in a significant reduction of greenhouse gas emissions without undesirable trade-offs.
- Evaluate the uncertainty associated with the approach, data, and assumptions used to draw key conclusions on how reliable the outcomes of the work are.
- Collaborate with Eionet's National Reference Centres and transfer knowledge.

To achieve these goals, the approach developed by the EEA and Rambøll Management Consulting A/S, which was previously applied to the construction sector of Europe (The Decarbonisation Benefits of Sectoral Circular Economy Actions), was applied. Some adjustments were made to this approach, due to recommendations that came out of that study, as well as adjustments that seemed to make more sense when applied to the agrifood system in particular. For more details on the methodology, please refer to the supplementary report "Reflection on the Methodology".

Table 1: Greenhouse gas reduction potential of CE actions in agrifood sector, approach, step by step

STEP	DESCRIPTION OF ACTIVITIES
Step 1: Scoping	• Scoping of the sector, materials and products • Interviews with agrifood experts to check assumptions on scoping and focus
Step 2: Baseline assessment	• Evaluating the main sources of emissions using multi-regional input-output (MRIO) data • Baseline material flow analysis
Step 3: Identification of CE actions	• Long list of CE actions and rapid assessment of their impact and feasibility • Shortlist of most promising CE action
Step 4: Quantification of CE actions' impacts on greenhouse gas emissions	• Assessment of greenhouse gas reduction of shortlisted CE actions (based on LCA and other data) • Interviews to collect data and verify assumption
Step 5: Developing a storyline to calculate the impact of combined actions	• Evaluation of a combined storyline of the shortlisted actions in terms of combined impact
Step 6: Linking of results to the existing reporting categories (UNFCCC CRF and ETS)	• Allocation of emissions to UNFCCC categories and to ETS or non-ETS sectors

Reflections on each step of the methodology and the results for the agrifoods sector are presented in the following chapters.

02

BASELINE ASSESSMENT FOR 2016

SCOPING

The scope of this assessment has been mainly based on what is relevant from a policy perspective and for circular economy actions. The geographic scope of the assessment on the potential of circular economy actions is the EU-27. Trade flows into and out of the EU-27 (as well as their embodied impacts) are also quantified in the baseline assessment. This report focuses on greenhouse gas emissions (in CO_2e) as the only indicator of environmental impact, though other environmental impacts are considered briefly in a qualitative assessment in terms of co-benefits and (negative) side effects.

There were several iterations to determine the scope of sectors, products, and steps in the agrifood value chain that would be taken into the assessment of greenhouse gas emissions and material flows. The scoping process included discussions with the EEA, other key experts and stakeholders, and an internal scoping session with our agrifood team to map out the value chain and discuss which elements should be included in the scope. After careful consideration the scope included the following (illustrated in Figure 1):

Production of food products

- Food and feed crop production (production, imports, and exports)
- Animal husbandry and animal products (production, imports, and exports)
- Food additives (production, imports, and exports) - including ingredients such as salt and chemical products used in food manufacturing

Production of supplementary, non-food products

- Packaging (production, imports, and exports) related to the agrifood sector
- Agrochemicals and fertilisers (production, imports, and exports)

Food value chain emissions and waste

- Food processing
- Point of sale (e.g. retail, wholesale)
- Restaurants
- Households (only considering food waste, not the impact of food preparation at home)

Waste treatment

- Food and other organic waste treatment (related to the agrifood sector)
- Human and animal waste (e.g. manure, faeces)

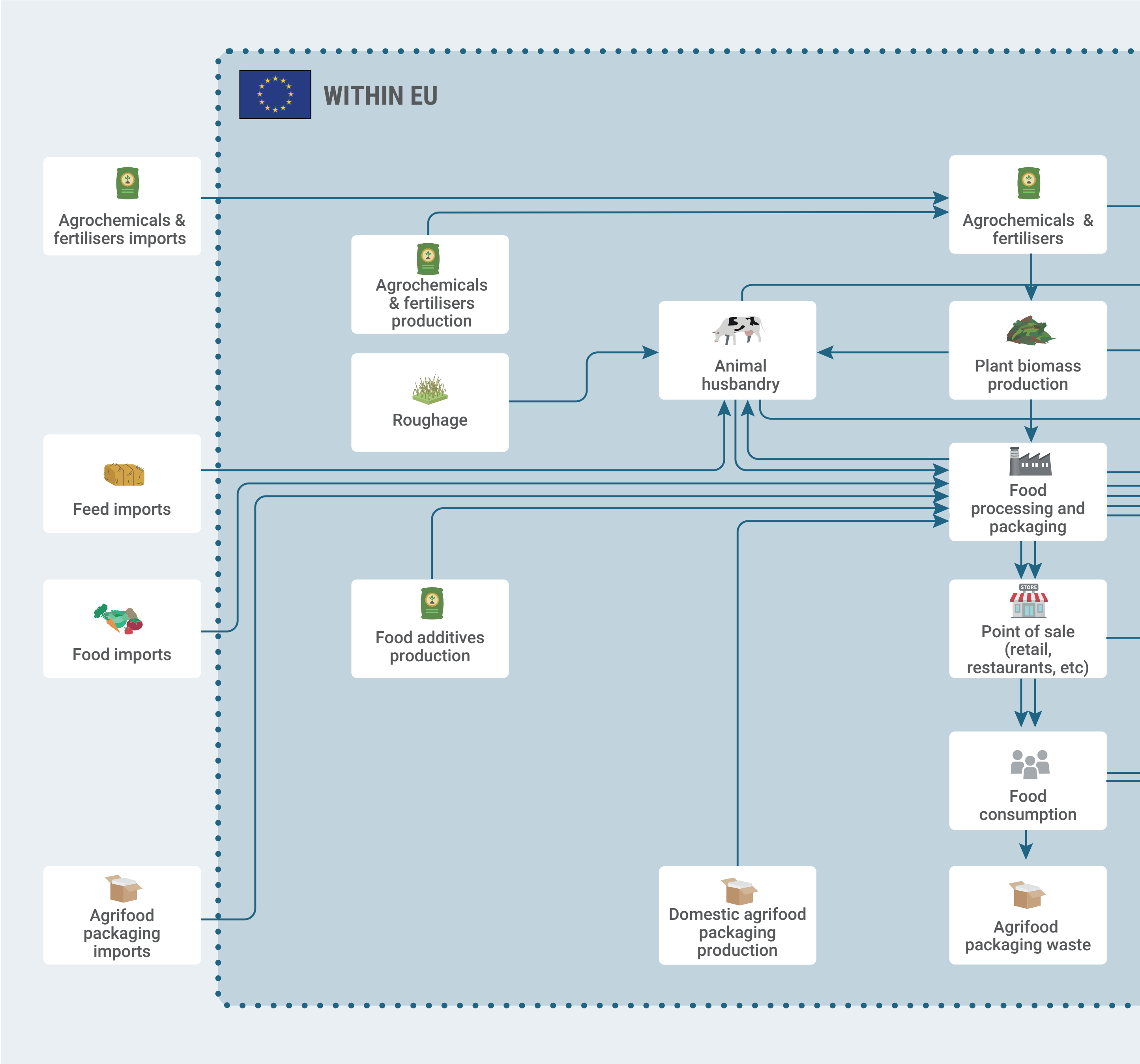
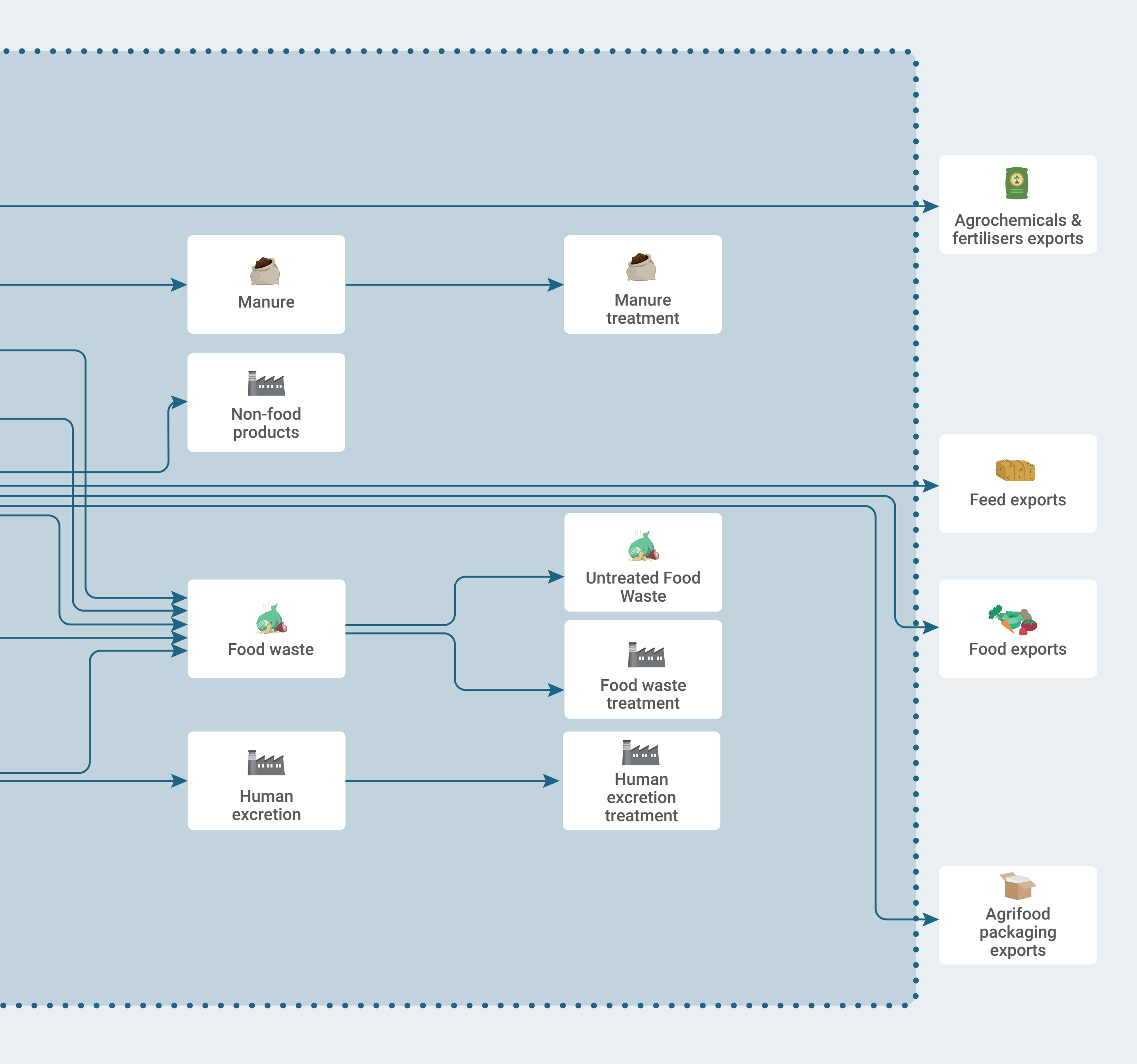


Figure 3 *Full agrifood sector scope in term of this assessment, inside as well as outside of the EU.*



The scope does not include:

- Fisheries, aquaculture, and related seafood sectors (part of the reason for exclusion is the political separation between land-based and marine food systems)
- Biomass production for non-food and non-feed uses (e.g. fuel, textiles, ingredients for personal care products, bioplastics, etc). These types of products are also covered under other policy frameworks, plust the focus of this report is agricultural products used in food.
- Other agricultural inputs other than fertilisers and agrochemicals (such as agri-plastics, machinery)
- Other capital goods in other parts of the agrifood chain, such as processing equipment.

BASELINE ASSESSMENT

After the scoping part of the research, a baseline assessment was done for 2016. This assessment includes an Environmentally-Extended Multi-Regional Input-Output (EE-MRIO) analysis and a Material Flow Analysis (MFA). Together, these two analyses provide a high-level overview of priority areas in the agrifood sector - where to focus effort for the greatest impact, based on the areas in which most of the losses or impacts are currently occurring.

The values from the EE-MRIO assessment were used as a starting point in calculating the savings associated with actions. Mass flows from the MFA were used as intermediate values to calculate the potential greenhouse gas emissions savings (for example to evaluate the potential associated with preventing food waste in a certain point of the value chain). On a few occasions, the two analyses (outlined below) were combined to arrive at factors for emissions per mass, which were used in further assessment of actions.

For the baseline assessment, the year 2016 was chosen because this was the most recent year input-output data is available for.

A brief description of the two previously mentioned analyses:

Environmentally-Extended Multi-Region Input-Output (EE-MRIO) analysis is a method that uses trade data and translates monetary value into a wide range of environmental impact categories. This type of assessment allows looking at environmental impacts related to sectors and products from a production-based perspective as well as a consumption-based perspective. The EE-MRIO analysis provides the baseline for greenhouse gas emissions in different parts of the agrifood sector.

- Exiobase 3.7 was used for the MRIO assessment
- Exiobase includes greenhouse gas emissions (CO_2, CH_4, N_2O, etc) as a weighted aggregate in tonnes CO_2e per year
- More recent date was used for sector-to-sector (2016, vs 2011 for product-to-product flows)
- The data was processed using Python programming and Pymrio Python library
- Subselection and data aggregation was done for the scope of this report

Material Flow Analysis (MFA), is a method used to show inputs, outputs, and throughput within or between regions and sectors. MFA provides a high-level view of the size of different material flows, giving insight into the level of significance of different parts of a sector and the material flows between them. In the MFA, flows into and out of different parts of the agrifood sector within Europe are quantified (e.g. livestock production, crop production, food processing). Trade flows into and out of Europe are also shown.

- The sources used to quantify material flows include Easy Comext trade data, Prodcom European production data, Eurostat waste data, and data from FAOstat on agricultural production and trade, supplemented where necessary with other sources.
- The data was processed to fit the scope and where necessary aggregated or reclassified to align with the categories in the MRIO assessment.
- Mass balances were calculated and compared with other assessments and reference data to check for imbalances, which is crucial when combining different data sets that might be inconsistent.

For more information on the baseline assessment, please refer to the supplementary report "Reflection on the Methodology".

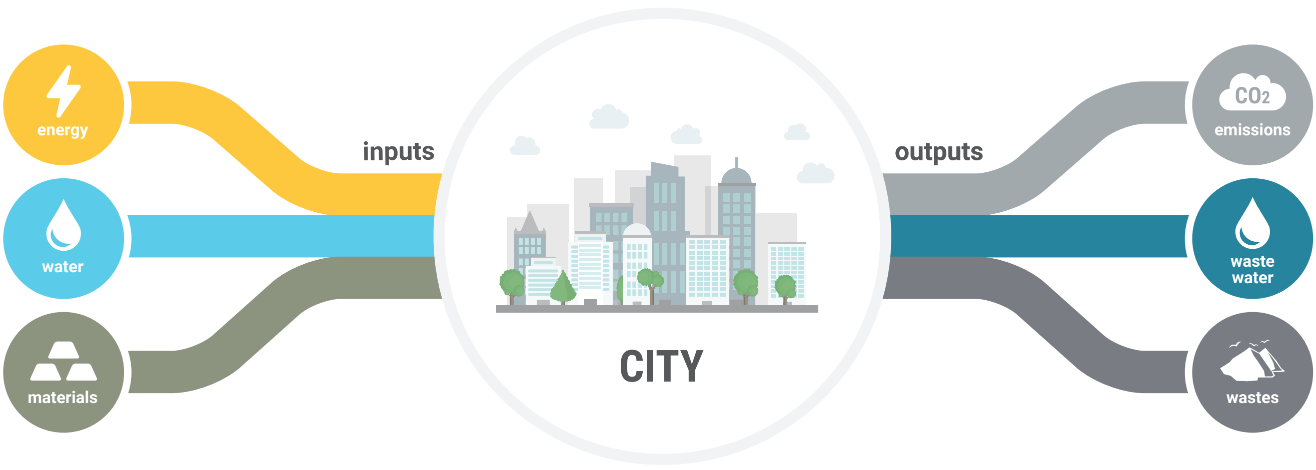


Figure 4 *High-level overview of a Material Flow Analysis (MFA).*

AGRIFOOD GREENHOUSE GAS EMISSIONS IN THE EU (EE-MRIO)

The image below shows the domestic emissions of the EU-27 agrifood sector, reflecting the domestic, production-based emissions in the EU in 2016. The image includes the direct impact each part of the sector has on the environment, regardless of whether that impact comes from products consumed in the EU-27. The image does not include emissions embedded in imported food, feed, fertilisers and pesticides.

In total, the agrifood sectors collectively produced 492,000 ktonnes of CO_2e in 2016. There are some clear outliers - cattle farming and dairy farming account for the largest share of domestic emissions: 44% of the total. Other areas of high emissions include the cultivation of cereals (due to high land and energy use) and waste management (food waste resulting in direct emissions during decomposition for example).

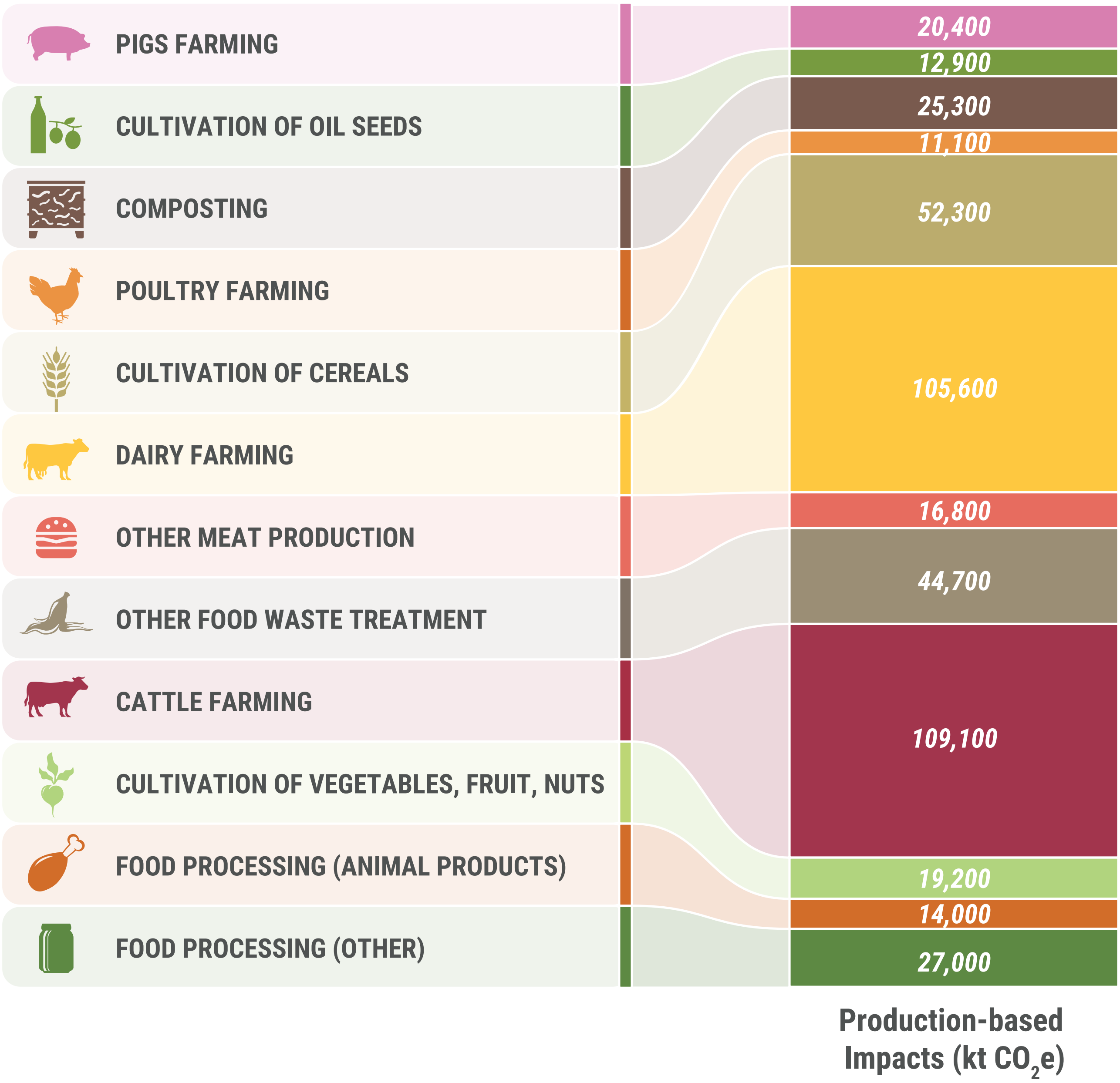
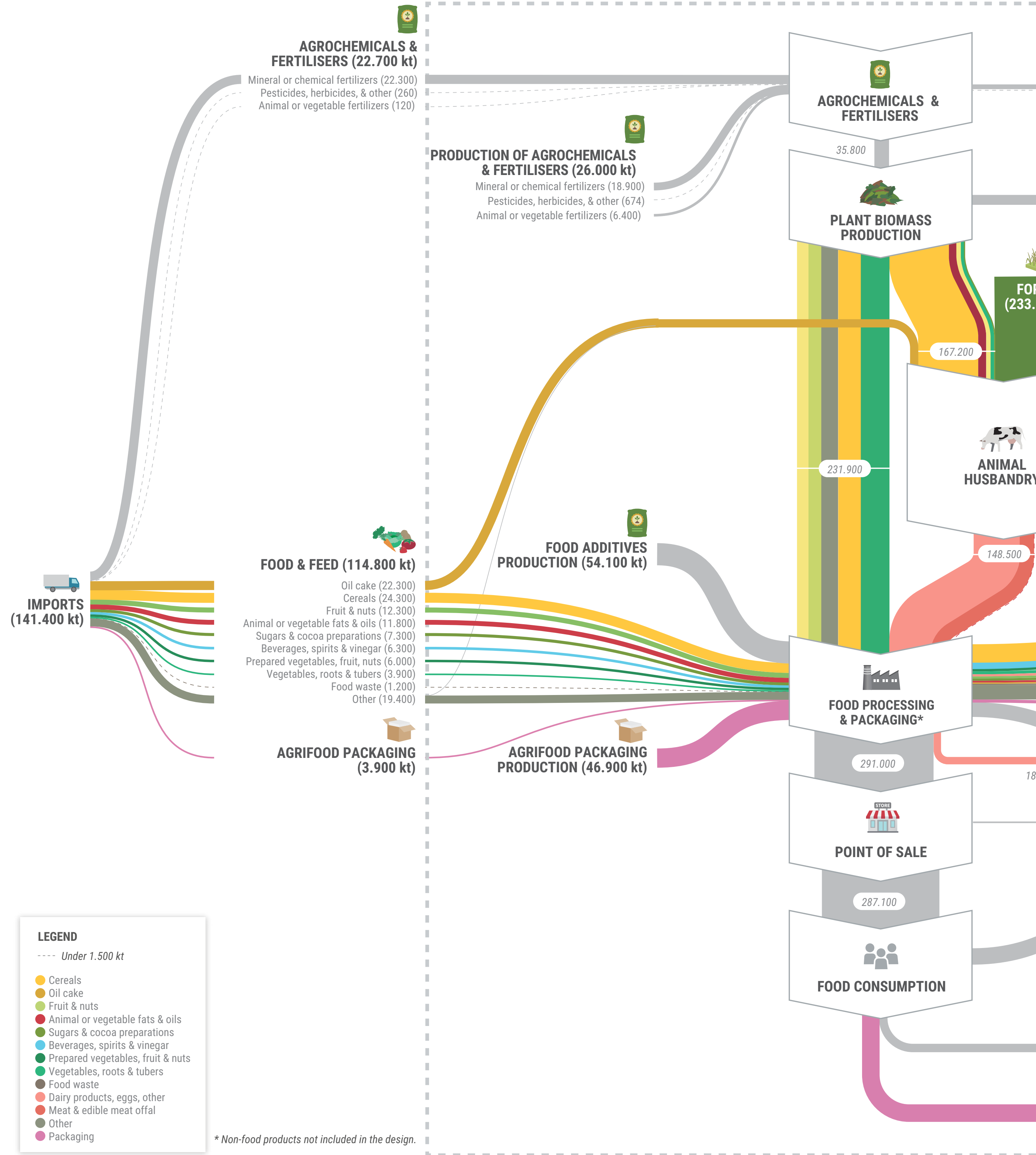


Figure 5 *Production-based / domestic emissions by selected agrifood sectors in 2016 (calculated by using Exiobase data).*



EUROPEAN AGRIFOOD MATERIAL FLOWS

The results of the material flow analysis of European agrifood sector flows are shown in the following figure. The left side (outside the border of the graph) shows the import flows coming into Europe from the rest of the world and the right side shows the export flows. Inside the borders of the image, from the top down, the domestic flows of materials for different sectors such as agricultural inputs to biomass are shown as they flow through different parts of the value chain.

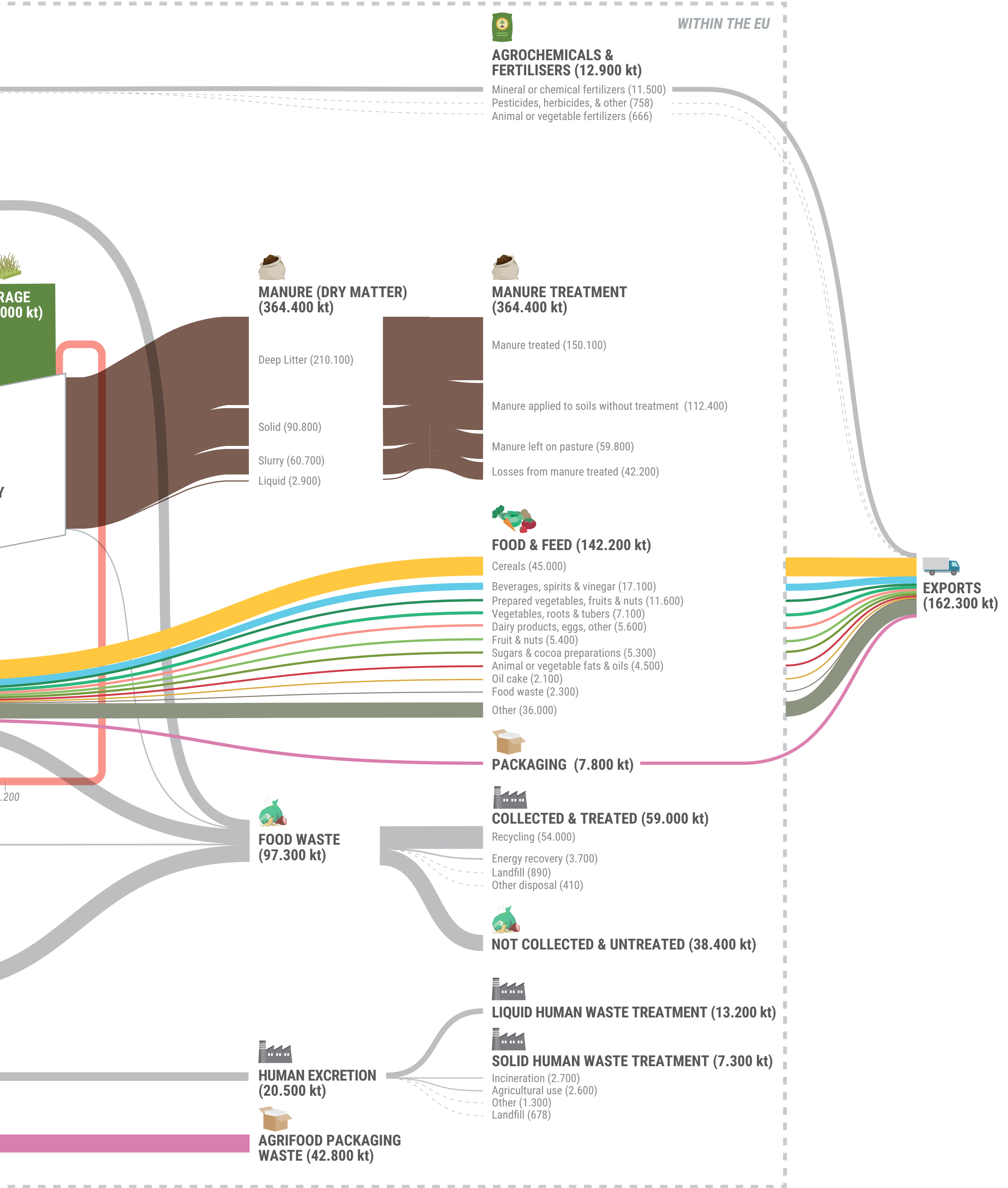


Figure 6 *Material Flow Analysis for the Agrifood System of the EU-27 in 2016 (all references used in compiling this MFA are described in the "Reflection on the Methodology" report).*

Key imports

Nearly half of the agrochemicals and fertilizers used in the EU-27 are imported and Europe is a net importer of these agricultural inputs. The largest share of these agrochemicals and fertilizers come from European countries outside of the EU-27 and Asia. The vast majority of livestock feed consumed in Europe is produced inside Europe, however there is some import and export as well. Overall, the EU-27 is a net importer of livestock feed (around 18,352 ktonnes of feed).

Livestock production and fertilisers

Europe's domestic livestock production is largely made up of meat, dairy and eggs production. The majority of commercial fertilisers used in agriculture are mineral or chemical fertilisers (~41,000 ktonnes vs <7,000 ktonnes from animal or vegetable sources). Around half of the total mass of manure is left on pastures or directly applied to arable land directly as fertiliser.

Around half of livestock feed comes from forage, while the other half comes from primary crops and processed feed products. From food processing, approximately 18,000 ktonnes of processed animal products are made up predominantly from dairy and eggs, as well as certain animal fats which are later recycled back as livestock feed.

Biomass consumption: In total, livestock in the EU-27 consume around 450,000 ktonnes of biomass, compared to less than 250.000 ktonnes consumed by people. Because of the higher amount of biomass consumed by livestock and because of the high-fibre nature of the biomass, human waste production pales in comparison to the overall mass of manure from livestock. Livestock manure is, in terms of mass, by far the most significant flow of materials in the EU agrifood system. There is a lot to be gained in terms of circularity from closing manure/nutrient cycles.

Food trade

The EU-27 has a net export of food, exporting nearly 45.000 ktonnes more food than is imported, dominated by the export of cereals. Despite having a net export of food, Europe is a large net importer of fruits, vegetables, and nuts while at the same time being a large net exporter of grains and beverages.

Packaging

The MFA is missing packaging entering the EU-27 on products processed and packaged outside of Europe as there is no data on these flows. The EU-27 is a large packaging producer itself, producing the majority of packaging used within Europe, and exporting more packaging than is imported. By mass, paper makes up the biggest amount of domestic agrifood packaging production (45%), followed by glass (30%), plastic (19%), and metal (6%). This distribution makes sense when considering the weight of different materials, and the fact that paper is commonly used as secondary and tertiary packaging in the food supply chain.

Food additives

Food additives also play an important role in the agrifood system. Salt represents two thirds of that total mass of food additives. One third of food additives are other inorganic chemicals such as sodium, potassium, and calcium products.

Other food product uses

A large amount of food ingredients are used in non-food and non-feed products - around 53.000 ktonnes. This product group includes items such as pet food, soaps and cosmetics, products for medical use, and crops for biofuels. The majority of products used for non-food purposes are wheat, maize, oils such as rapeseed, mustard, and palm oil, and milk products. Non-food and non-feed products are excluded from the scope of this MFA, but this type of use essentially results in an imbalance between the amount of mass going into processing versus what comes out as food.

Human waste

Just over a third of solid human waste from wastewater returns to the agricultural system - the majority however is incinerated.

Food waste

National statistics may underestimate food waste, so we used a different approach to estimate food waste. Besides inconsistencies in data collection approaches across regions, there is a lot of uncertainty in waste data as it is challenging to have representative sampling in data collection (European Commission, 2020). For the purpose of this report, the estimated food waste at different parts of the value chain was calculated using coefficients provided in a study from Caldeira et al. (2019). This study uses the following definition of food waste: “food and inedible parts of food removed from the food supply chain to be recovered or disposed” and excludes food waste that is directly used as animal feed. How food waste is treated is estimated using proportions to different treatment methods provided in Eurostat data. Nearly 100.000 ktonnes of food waste is estimated to be generated along the value chain. Almost half of any food waste consists of vegetables and fruits (46%), followed by cereals (12%) and smaller amounts of other food categories (Caldeira et al., 2019).

More than 90% of food is wasted at the farm level (~30%), during storage and food processing (~37%), and in households (~25%). A big part of farm-level food waste is left on fields or processed at the farm. Food waste generated during food processing is largely used either as animal feed, compost, or is put to good use in other ways. Around 61% of processing food waste is collected separately for treatment and used, however, around 10,000 ktonnes of collected food waste still ends up in the landfill.

The biggest problem area is the food wasted in households. Not only does household food waste form a massive part of the total food waste, but most of this waste is either not separately collected or not processed in any sort of valuable way. While estimates of how much waste this causes exist, it is difficult to quantify the amount exactly as different countries have different ways of reporting biowaste (EEA, 2020).

Text box: The role of trade – domestic and footprint emissions

Agrifood greenhouse gas emissions can be analysed from two different perspectives: either from a domestic (regional production-based) point of view, or from a footprint (consumption-based) point of view.

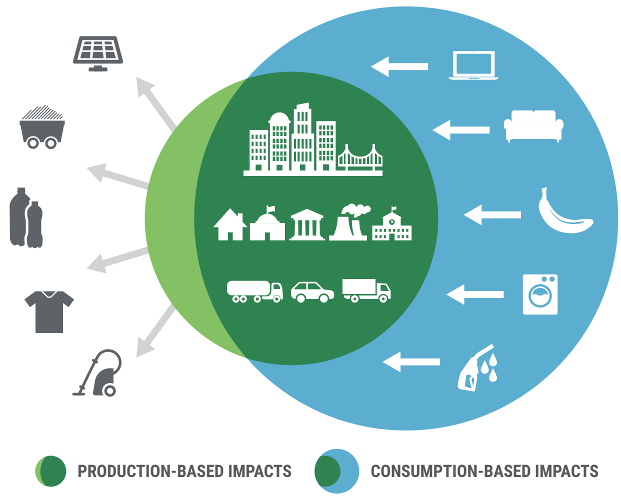


Figure 7 *Production- versus consumption-based impacts. The impacts in green are domestic production-based impacts produced within a certain region. Some of the impact of this production however is exported to other regions. There is an import of "embedded impact" as well, which is added to the consumption-based impacts.*

This report uses the perspective of domestic emissions, which is in line with the accounting principles of the UNFCCC, i.e., it accounts for all emissions generated by the agrifood sectors within the EU-27, regardless of where the food is consumed. This perspective was chosen as the purpose of the report is to show the potential of circular economy actions to reduce domestic greenhouse gas emissions as a contribution to meet the EU's (territorial-based) net zero emission target.

However, the EU increasingly recognises that emissions embedded in trade need attention, not only domestic impacts. This is indicated by the discussion of a carbon border adjustment mechanism and the recent proposal for an EU regulation (European commission, 2021) to curb EU-driven deforestation and forest degradation outside of the EU (especially related to the import of palm oil, beef, soy, coffee, cocoa, and wood). These regulations aim to reduce both biodiversity loss and GHG emissions related to imports of these commodities into the EU.

The analysis of footprint emissions (consumption perspective), assesses the GHG emissions caused by the total amount of food consumed within the EU-27, including emissions embedded in imports, and deducting the emissions embedded in food exports. The footprint or consumption perspective is a valuable complementary analytical approach, given that the EU is both importing and exporting large amounts of food, feed, fertilisers etc., and because changes in the agrifoods sector in Europe can also contribute to the reduction of emissions outside of Europe.

JRC's publication Consumer and Consumption Footprint: assessing the environmental impacts of consumption in the EU (Sala, 2019) and the EEA and FOEN's report Is Europe living within the limits of our planet? (EEA & FOEN, 2020) both focus on the contribution of consumption to global impacts, each highlighting the increasing importance of food in consumption-based footprints. For example, the JRC study found that GHG emissions caused by food consumption of an average EU citizen increased between 2010 and 2015. The role of consumption and trade is an important area for additional research in the future.

The following figure below shows the GHG emissions from both a domestic emissions perspective and from a footprint perspective of EU-27 agrifood sectors, as well as the share of emissions that are either embedded in imported or exported products and raw materials. The consumption-based emissions are shown in green, with the top (lighter, hatched) part of the bar showing how much of those embedded emissions are imported from outside of Europe. The domestic emissions are shown in pink, with the portion that is ultimately exported displayed in the top part of the bar.

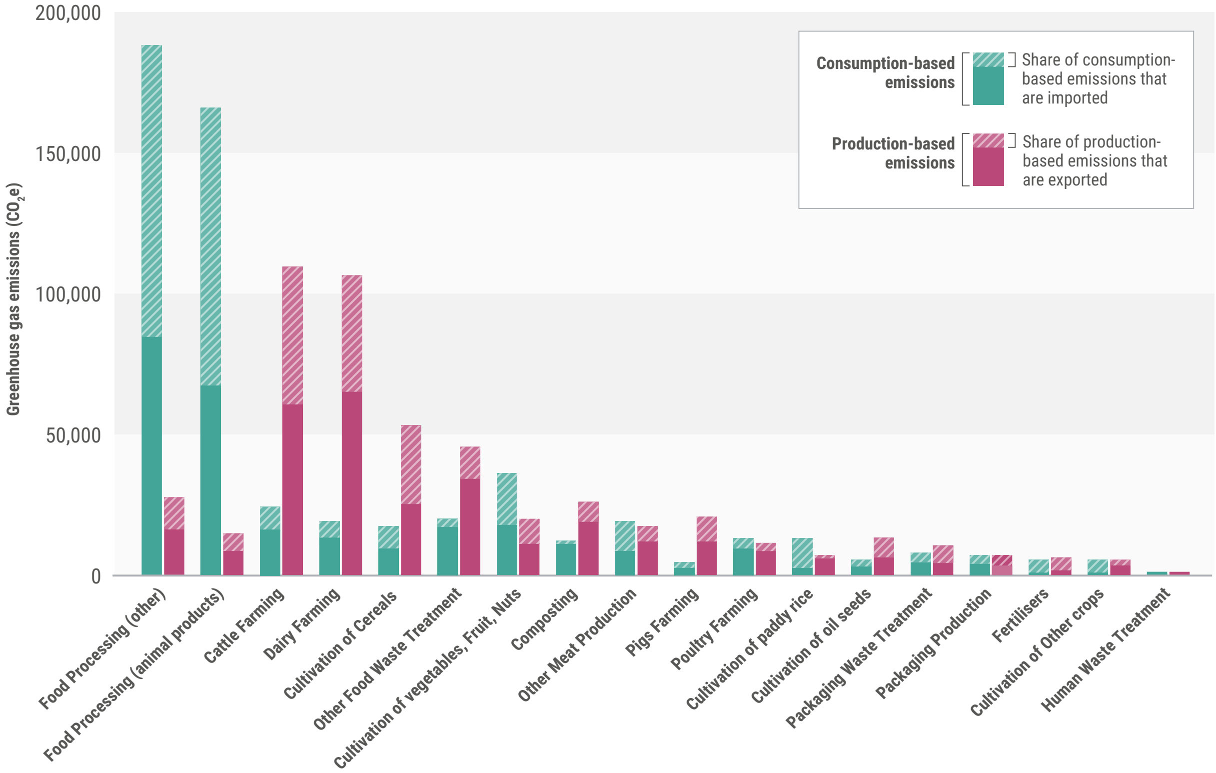


Figure 8 *Domestic- vs footprint-based emissions with the share of impact from imports and exports across selected agrifood sectors in 2016 (calculated using Exiobase).*

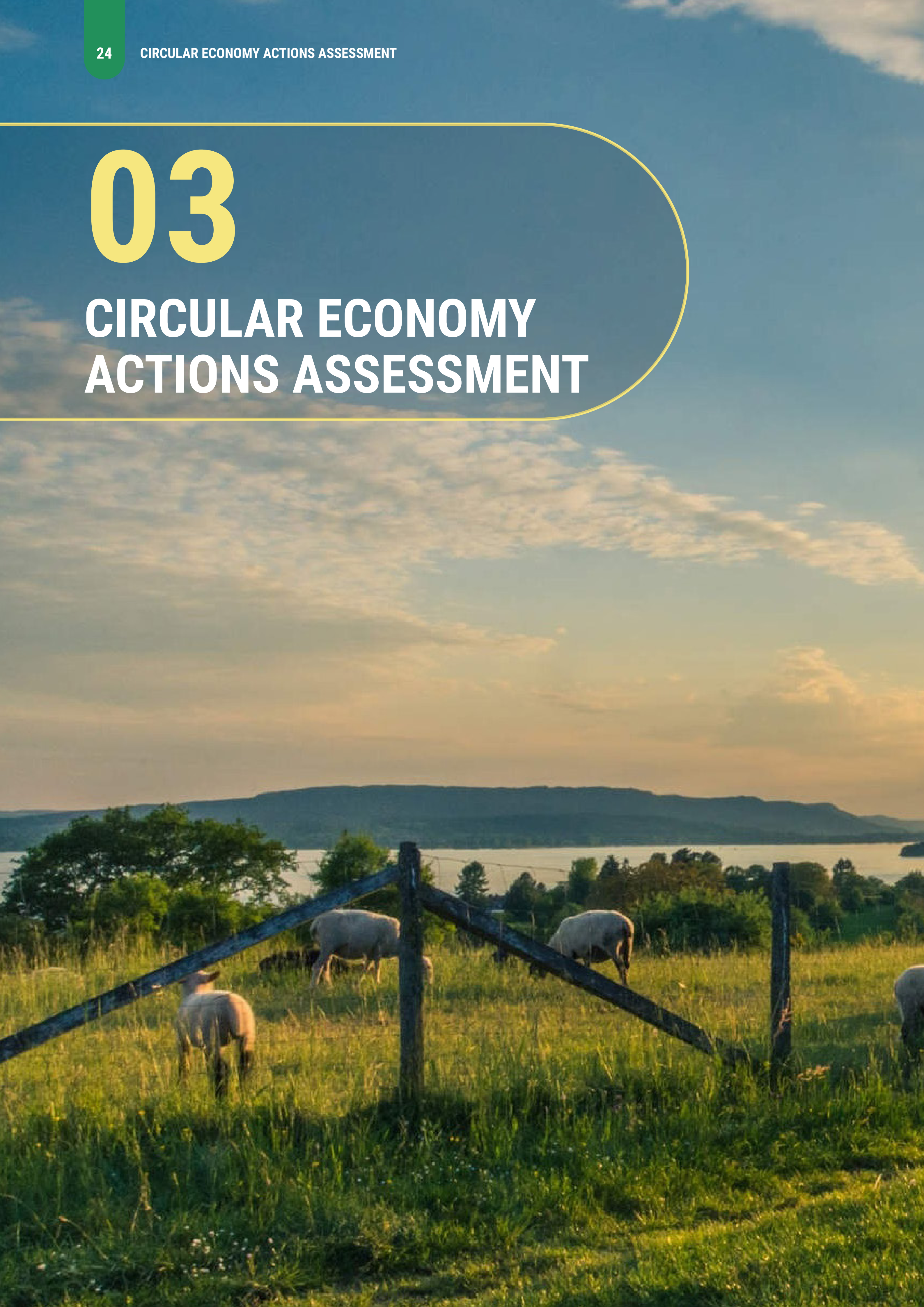
Some interesting points related to trade:

- The total emissions of the agrifood sectors from the consumption-based footprint perspective (553,000 ktonnes) are higher than from the domestic emissions perspective (492,000 ktonnes).
- The reason why the consumption-based emissions for food processing sectors are so high is that this is also where imported processed food products are captured. Unfortunately, more details about this consumption category are unavailable.
- Most domestic emissions are caused by the production of animal products. A large part of domestic impacts due to cattle farming and dairy are embedded in meat and dairy products that are eventually exported, although the majority is still consumed within Europe. Consumption-based impacts for these animal production is due mainly to livestock feed inputs for the sector. Using a production-based approach, feed largely falls under crop production categories instead.
- Within the waste treatment categories, the domestic impacts are, as expected, higher than the consumption-based impacts, although the total impact of both is quite small.
- The production-based emissions of fertilizers and packaging are extremely low in comparison to the other categories. However, when considering the emissions from fertilizer use (rather than production), those impacts would show up under the production-based impacts of crop production sectors.

Systemic changes to the European food system as analysed in this report will have impacts on the global food system. However, we only consider how actions affect national greenhouse gas emissions accounting. It is assumed that emissions reductions related to CE actions described in the following chapter take place on domestic impacts, although we recognize that both a domestic and a consumption-based footprint approach are necessary. For example, if Europe were to halt the production of livestock (which is a major contributor to domestic emissions), without addressing consumption, those impacts would just be transferred to other regions.

03

CIRCULAR ECONOMY ACTIONS ASSESSMENT



POTENTIAL CE ACTIONS

Defining circular economy actions for the agrifood sector

The definition of the circular economy is well defined for technological materials and cycles, for example for metals and electronics. However, the definition of the circular economy in terms of biological cycles and nature-dependent sectors like agrifood, is less clear. In this report, we use a broad definition of the circular economy to decide which actions to consider for the scope of this analysis, being aware that this approach might stretch beyond some existing definitions of the circular economy. As in this report a broad definition is used, the actions will be presented in three "layers", ranging from the most narrow definition of circularity to the broadest.

Layer 1:

Most limited definition of the circular economy

When imagining circular economy actions in the agrifood sector, the first things that come to mind are actions that result in extending the lifespan of products and closing material and product cycles - specifically material flows such as (waste) biomass, human and animal waste, and packaging materials, as well as reducing food waste.

Layer 2:

Circular economy in a limited system

There are some characteristics of biological systems that necessitate a broader definition of the circular economy. For one, since biological systems include renewable resources, they are frequently viewed as unlimited. Resources like soil and water are technically renewable, but on timescales that necessitate they be treated as non-renewable. Even plant matter, such as wood, can easily be extracted at rates far faster than regeneration rates. For these reasons, a slightly broader definition of the circular economy for agrifood systems should consider the limits of the system. Actions to reduce consumption to be in line with regeneration rates would fall under this second definition. A large part of this includes re-evaluating the level of animal-based products possible to sustainably produce in line with this principle. Livestock and crop production systems need to be brought in balance - neither one can be fully circular without the other.

Layer 3:

Molecular circularity in production systems

Another key characteristic of biological systems is that they are built on a different set of molecules compared to technological cycles. Instead of metals and minerals, the key building blocks are carbon, nitrogen, and phosphorus, so molecular circularity of these building blocks is also needed in a definition of the circular economy for agrifood. One of the most pressing environmental problems from a circularity standpoint is closing nutrient cycles and fixing imbalances in regional nutrient systems for elements like nitrogen and phosphorus. The European Commission acknowledges this pressing need in the Circular Economy Action Plan, which names Food, Water, and Nutrients as one of seven crucial supply chains requiring "urgent, comprehensive and coordinated actions," in particular with regard to ensuring the sustainable recovery and application of nutrients (European Commission, 2020).

Less attention is paid to carbon circularity, although carbon storage and removals are a part of the Circular Economy Action Plan. The intersection of climate change and the circular economy is an interesting topic for the agrifood sector, as the most relevant component of the agrifood system is carbon. Our economic system results in global land conversion and deforestation. The amount of carbon removed from land systems is far greater than the amount added to it, which has historically been a major driver of climate change. Due to linear production processes that depend on the imports of fodder and fertilisers, regional nutrient and carbon balances have become increasingly distorted. However, there is the opportunity to reverse these trends and use agricultural systems to their full potential as a place to store carbon. If done well, regenerative agricultural practices that restore carbon and nutrient cycles also come with additional benefits for long-term economic value (through soil quality preservation) as well as for biodiversity.

The definition of the circular economy for agrifood used for this report results in a broad set of sustainability actions. However, not every action that could be considered "sustainable" is included in the definition of circularity used here. The following types of actions are excluded:

- Efficiency measures for utilities (e.g., energy and water), for example more efficient tractors, ships, or manufacturing equipment
- The use of renewable energy in agrifood sectors more broadly, beyond that from agri-food waste products
- Actions to reduce downstream impacts of agrifood systems like agricultural runoff, the impacts of pesticides on biodiversity, etc

Identifying and evaluating actions

A list of nearly 80 circular economy actions was compiled to evaluate in a light assessment (described below). This assessment led to a short list of actions for a more detailed assessment. The long list of actions was drafted by reviewing hundreds of circular economy case studies involving agriculture and food. This began with the database compiled in the Circular Economy Mapping Week and case studies were grouped into similar actions. Additional actions were added to the list from other circular economy strategies and additional ideas from the researchers and those who were interviewed.

The following information was collected for each circular economy action:

- **Description:** A definition of the action
- **Assumptions:** Any details on assumptions made in the light assessment
- **Quantifiability:** Possibility to quantify the potential impact of the action on the environment with any certainty. To quantify the potential impact, it is important to establish if real data exists, how reliable estimates are, or if data that is available is representative enough to apply across Europe.
- **Applicability:** An indication of whether it is possible to apply the action across Europe, or if there are key barriers preventing implementation of the action across an entire sector or region.

Each of the actions on the long list were ranked, based on the average score between impact and feasibility:

Impact

Each action was ranked based on the potential greenhouse gas emissions reduction. When possible (e.g. when the actions link directly to sectors we have information on emissions for), the ranking was done by using the outcomes of the baseline assessment of emissions. For actions that did not link well to the baseline assessment, additional references were sought to place the actions in categories for impact potential.

The following ranking was used:

- **5: Very high potential** - greater than 10% of the total sector emissions
- **4: High potential** - 5-10% of the total sector emissions
- **3: Medium potential** - 1-5% sector emissions reduction potential
- **2: Low potential** - 0.5-1% of the total sector emissions
- **1: Very low potential** - less than 0.5% of the total sector emissions

Feasibility

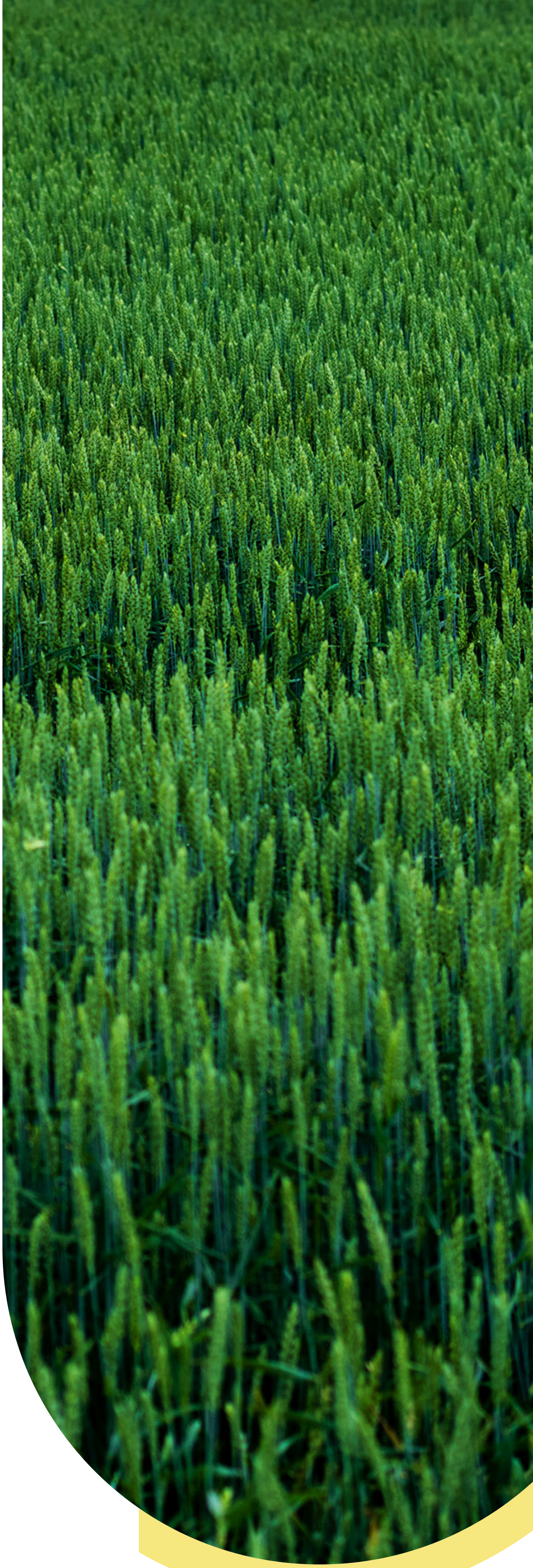
A scale of 1-5 was adopted to represent the feasibility of an action (1 = nearly impossible, 5 = no feasibility issues) across given dimensions. The average feasibility across all dimensions was then used for the total ranking. The feasibility assessment is a qualitative assessment, based on the research team's expertise, quick research, and information from initial interviews. Some feasibility aspects (e.g. social and political feasibility) are challenging to assess, but the purpose was to ensure that actions in the assessment could be filtered out if they would be infeasible.

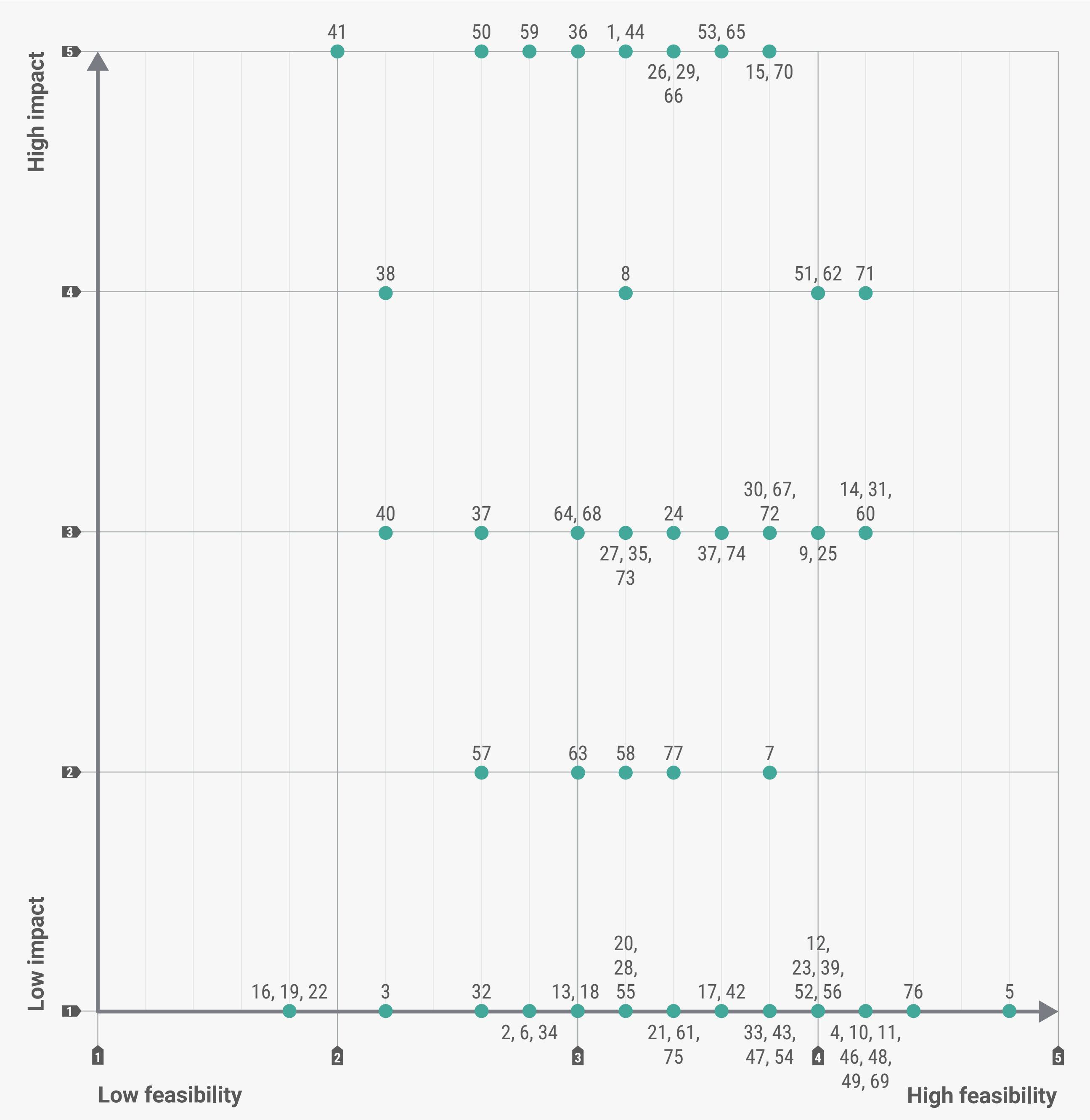
The five dimensions included in the light assessment were:

- **Social feasibility**, e.g. cultural or psychological barriers that would hinder implementation
- **Economic feasibility,** e.g. costs of implementation, economic incentive frameworks such as subsidies
- **Practical feasibility**, e.g. logist or spatial restrictions, or barriers due to the number of people needed to implement the action
- **Political feasibility**, e.g. legal or political restrictions based on (political) appeal of the action
- **Technical feasibility**, e.g. lack of suitable technologies or knowledge

One more nuance was added to the assessment - an evaluation of environmental trade-offs and co-benefits beyond climate change. These were evaluated for water use, land use, biodiversity, nutrient cycles, and other emissions (e.g. pesticides, plastics and air pollutants). These trade-offs or co-benefits were used to get a second, ***"adjusted"*** average score. Both the original as well as the adjusted ranking position of each action were considered in translating the long list to a short list.

The full list of CE actions used to conduct the rapid assessment is provided in Appendix I. The following figure shows the results of the rapid assessment for the long list of actions in terms of potential effectiveness (impact) and feasibility.





CE Actions

1 Agroforestry
2 Algae-based feed
3 Algae-based food
4 Alternative pesticides
5 Animal byproduct composting
6 Aquaponics
7 Biogas for heating greenhouses
8 Biogas production from manure
9 Cellulosic waste packaging
10 Coffee grounds based substrate
11 Compostable packaging
12 Conservation tillage
13 Crop genetic optimization
14 Crop rotation
15 Dairy alternatives
16 Edible packaging
17 Equipment sharing
18 Farming automation
19 Fertilizers from faeces
20 Fertilizers from food waste
21 Fertilizers from processed manure
22 Fertilizers from urine
23 First gen bioplastics
24 Food loss prevention: on farm
25 Food manufacturing efficiency
26 Food preservation
27 Food waste composting
28 Food waste prevention: food processing
29 Food waste prevention: home
30 Food waste prevention: restaurants/catering
31 Food waste prevention: retail
32 Green and gray water utilization
33 Green waste composting
34 Hydroponics
35 Improved food labeling
36 Industrial CCU in greenhouses
37 Insect-based feed
38 Insect-based protein
39 Integrated pest management strategies
40 Lab-grown protein/precision fermentation
41 Livestock CCU
42 Livestock genetic optimization
43 Local food
44 Low-impact diets
45 Low-impact freight
46 Low-impact irrigation
47 Manual weeding
48 Manure composting
49 Manure-based substrate
50 Meat replacement
51 Methane capture from waste treatment
52 More efficient cold chain
53 Optimizing livestock grazing patterns
54 Organic production
55 Organics recycling into non-agrifood products
56 Packaging downcycling
57 Packaging prevention
58 Packaging recycling
59 Plant-based diets
60 Polyculture
61 Precision agriculture
62 Precision feeding of livestock
63 Recyclable packaging
64 Reduced cold chain
65 Reduced dairy consumption
66 Reduced ruminant meat consumption
67 Renewable greenhouse heating
68 Reusable packaging
69 Seasonal diets
70 Silvopastoralism
71 Sustainable procurement
72 Urban agriculture
73 Vertical farming
74 Waste heat for heating greenhouses
75 Waste ingredients / byproduct utilization
76 Waste-based feed
77 Yield growth

Figure 9 *CE Actions Feasibility and Impacts (scores and notes are provided in Appendix I).*

From the rapid assessment of the long list of actions, the highest average score for impact and feasibility was established for the original score as well as the adjusted score. Both sets of ranked actions are shown in the table below.

Table 2: Top 10 ranked circular economy actions, with and without co-benefits and trade-offs - full list and ranking values are provided in Appendix I.

RANK	RANKING WITHOUT CO-BENEFITS AND TRADE-OFFS	RANKING WITH CO-BENEFITS AND TRADE-OFFS
1	**Dairy alternatives**	**Dairy alternatives**
2	**Silvopastoralism**	**Reduced dairy consumption**
3	**Optimising livestock grazing patterns**	**Food waste prevention: home**
4	**Reduced dairy consumption**	**Reduced ruminant meat consumption**
5	**Food preservation**	**Sustainable procurement**
6	**Food waste prevention: home**	**Precision feeding of livestock**
7	**Reduced ruminant meat consumption**	**Silvopastoralism**
8	**Agroforestry**	**Meat replacement**

Actions that made it into one or both of the top 10 lists, as well as some additional high-ranking actions from the long list that were connected with the other actions were put on the short list. Several actions were excluded from the detailed assessment as the calculations would have been nearly identical (e.g., reduced dairy consumption and plant-based dairy alternatives) or the actions were deemed too hard to define (e.g. sustainable procurement, low-impact diets).

Selected actions for detailed assessment

After the rapid assessment, 17 actions were included in a more detailed assessment. The final short list is shown below, including a description of each action and the assumptions used in the calculation of each action's "maximum potential". Note that some of the actions were taken off the list, merged, or changed to account for interactions when the actions were combined into a storyline.

Table 3: Final short list of CE actions taken into the detailed assessment

LAYER	CE ACTION	DESCRIPTION AND ASSUMPTIONS FOR MAXIMUM INDIVIDUAL ACTIONS
Layer 1: Most limited definition of the circular economy	Food waste prevention: restaurants/catering	All food waste from restaurants/catering is prevented in Europe (1,076 kT).
	Food loss prevention: on farm	All food waste from farms (also called food loss) is prevented in Europe (27,856 kT).
	Food waste prevention: home	All food waste from households is prevented in Europe (28,817 kT).
	Food waste prevention: manufacturing	All food waste from food processing / manufacturing is prevented in Europe (35,993 kT).
	Food waste prevention: retail	All food waste from retail stores is prevented in Europe (3,879 kT).
	Improved food labelling	All food waste in Europe from restaurants and households caused by date labelling is prevented (3,443 kT). Impacts due to food waste treatment and production are eliminated.
	Prevention from food preservation	Best practices are applied to food in order to extend the shelf life of products. This can be done by improving packaging, and thereby preventing food waste in European households. Impacts due to food waste treatment and production of the prevented household food waste are eliminated (22,865 kT). The impacts of additional packaging is added.
	Preventing food loss from aesthetics	Wasted food at farm level due to aesthetics requirements from buyers is entirely prevented in Europe (7,097 kT). Therefore, impacts due to food waste treatment and production are eliminated.
	Food waste as feed	All food waste from food processing, retail, and food services in the EU is used to serve as pig feed, preventing the embedded emissions of pig feed production.
	Insect-based feed	Insect-based feed can be produced from food waste, replacing feed as much as possible, considering nutritional limitations. Insects can eat food waste from crop production, animal husbandry, manufacturing, point-of-sale, and food service. The impacts of feed production are reduced by the amount that is replaced by insect-based feed.
Layer 2: Circular economy in a limited system	Dairy alternatives	All dairy produced in Europe is replaced with plant-based alternatives. Impacts from dairy cows and dairy processing are thereby eliminated, but there are also impacts added from the production of the dairy alternatives.
	Meat replacement	All meat produced in Europe is replaced with plant-based alternatives. The impacts from meat production are thereby eliminated, however there are new impacts from crop production to produce the alternatives.
	Precision feeding of livestock	All livestock in Europe are fed using precision feeding - which entails careful control of the amount and type of feed that cattle consume. This results in less direct emissions from livestock from enteric fermentation and manure and less embedded feed impacts.
	Optimising livestock grazing patterns	Optimising cattle grazing patterns consists of cautious use of grazing pattern rotations to optimize biomass output of the land and carbon storage from manure into soils This action takes into account the increased long-term storage of carbon in European soil.
Layer 3: Molecular circularity in production systems	Agroforestry	All arable land in Europe is converted to agroforestry. This is a combined system of growing crops as well as trees together in a single land-use system. In agroforestry, the trees typically provide forestry co-products in addition to the crops. There is some debate on whether agroforestry reduces yields.This is highly dependent on the combination of the types of trees and crops. Overall, total biomass yields will increase, but yields for a single product in the same area of land could decrease. This tradeoff has significant implications for how production systems are arranged, because many farmers currently focus on one product. Agroforestry systems have the ability to store far more carbon in soil and vegetation in the long term than crop production alone (which tends to result in loss of soil carbon).

	Silvopastoralism	Silvopastoralism is a diverse pasture system that combines pasture with vegetation such as shrubs and trees. It is in essence a subcategory of agroforestry for pasture systems. Like agroforestry, silvopastoralism stores far more carbon in Europe's soil and vegetation in the long term. For the calculation of the individual action's potential, all of Europe's pasture lands are considered to have adopted silvopastoralism.
	Industrial Carbon Capture and Utilization (CCU) in greenhouses	Greenhouse CO_2 inputs and heat are typically provided by combined heat and power systems (CHP) which use natural gas. In this action, it is assumed that all existing greenhouses in the EU use CO_2 inputs from industry emissions and electrical heat, rather than using natural gas.

For a full list of references and assumptions, please refer to Appendix II.

THE POTENTIAL IMPACT OF INDIVIDUAL CE ACTIONS

fter compiling the short list, the expected changes that come with each action were listed, and the total potential impact for each action was calculated based on these changes. For example:

WASTE-BASED FEED	SILVOPASTORALISM
Maximum impact assumption: • All feed that can be replaced with food waste is replaced **Mechanisms:** • Embedded emissions for the feed replaced is subtracted • Emissions associated with the impacts of food waste treatment are subtracted	**Maximum impact assumption:** • All pasture used for grazing livestock will use silvopastoralism **Mechanisms:** • Less direct emissions per unit of livestock • Better carbon storage per area of pastureland

For each of the actions, it is assumed that the actions are taking place within Europe, even where they affect elements like livestock feed that are traded internationally. The impact of each action was calculated using either a top-down approach (from a share of the total impact) or a bottom-up approach (e.g. Life Cycle Assessment (LCA) impacts per unit of a material flow or land area). Where multiple data sources or ranges of values were available for the same parameter, the median value of the information available was used. The ranges of parameter values were also used in a sensitivity analysis.

For further information, please refer to Appendix II: Assumptions and References for Shortlisted Actions.

More context on the agroforestry calculations

Agroforestry (including silvopastoralism) is a challenging action to define assumptions for because there is such a large range in the amount of carbon sequestered per hectare of land. These values depend on spatial considerations (e.g. climate, soil) as well as characteristics of the type of agroforestry applied and the rate of wood harvest (if any).

The value used for carbon sequestered per hectare was the median value of a range provided by Kay et al. (2019). The median value may be too high for the spatial context of Europe and other possible assumptions for this value were explored. However, the value from Kay et al. (2019) only includes carbon sequestered in biomass and excludes soil organic carbon, which is a significant part of the carbon sequestered. For this reason, the median value was used here despite some questions around the validity for the European context.

An additional consideration is that these values are average values of carbon sequestered across a certain time period (typically 20-40 years). It therefore needs to be considered that in a certain year, the potential sequestration might be significantly higher or lower than the average value. It will take several years to reach the average annual sequestration potential, in the middle years more carbon will be sequestered than the average. Eventually, the maximum potential of this action will be reached and little additional carbon will be sequestered annually. Given the vast cumulative size of carbon removals from land and soil (Zomer et al., 2017), it will be many decades before this potential is fully realized. However, it is important to note that this is different from actions that reduce emissions of greenhouse gases, as these actions could continue net reductions in perpetuity.

Finally, there is an additional challenge in determining whether agroforestry when applied to crop production systems could result in reduced yield and therefore result in shifting production elsewhere. There is no clear answer on whether yields are decreased in general (it depends on the system), However, there may be a critical tradeoff to consider between the carbon sequestration potential and food and biomass harvests of different systems. Harvesting a lot of biomass means that less carbon will be stored in vegetation.

The following figure shows the total maximum greenhouse gas emissions reduction for each of the shortlisted CE actions. This initial assessment of actions does not yet take into account that some of these actions are interdependent (e.g., food waste prevention and use).

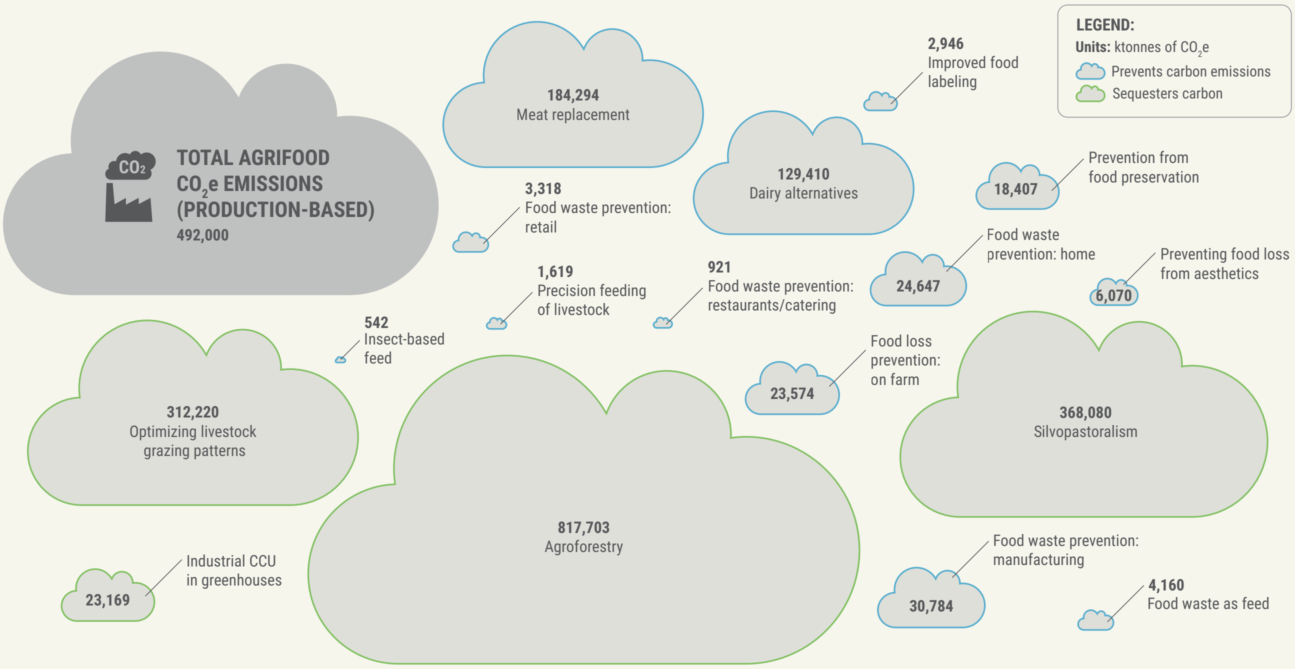


Figure 10 *Visualization of the potential reduction impact size for each action individually, compared to the total agrifood emissions in 2016.*

Collectively, the actions show the potential to reduce or sequester more emissions annually than the total agrifood currently emits. Actions that prevent food waste along the supply chain are estimated to collectively prevent nearly 17% of the total sector emissions.

Replacing animal-based products (meat and dairy) have the second biggest impact reduction potential - up to 64% of the production-based greenhouse gas emissions if plant-based alternatives would replace all animal products currently produced in Europe. While significant, the opportunity is far lower than the carbon-sequestering actions.

The big outlier is agroforestry. The median emissions sequestration potential for agroforestry is nearly double the greenhouse gas emissions of the agrifood sector as a whole. While converting all arable land in Europe to agroforestry systems is infeasible for a number of reasons, it does highlight that exploring the agrifood systems as a carbon sink is promising. Other actions, such as silvopastoralism, or optimising grazing patterns (which have the effect of storing more carbon in pasture systems), also show enormous potential. These can collectively sequester up to 75% of EU agrifood production emissions. This echoes some of the findings in the World Resources Institute's report on Sustainable Food Futures in terms of the opportunities these types of actions can provide (Searchinger et al., 2019).

Considering impacts along the lifecycle of food products

The actions were grouped into lifecycle stages: Design - Production - Use - End of Life. Translating terms to agrifood, “Design” is considered to include dietary choices and product design, to include actions such as food preservation and dairy alternatives. “Production” includes actions that involve the production of food. “Use” includes actions that result in food waste, and “End of life” includes actions that use food waste.

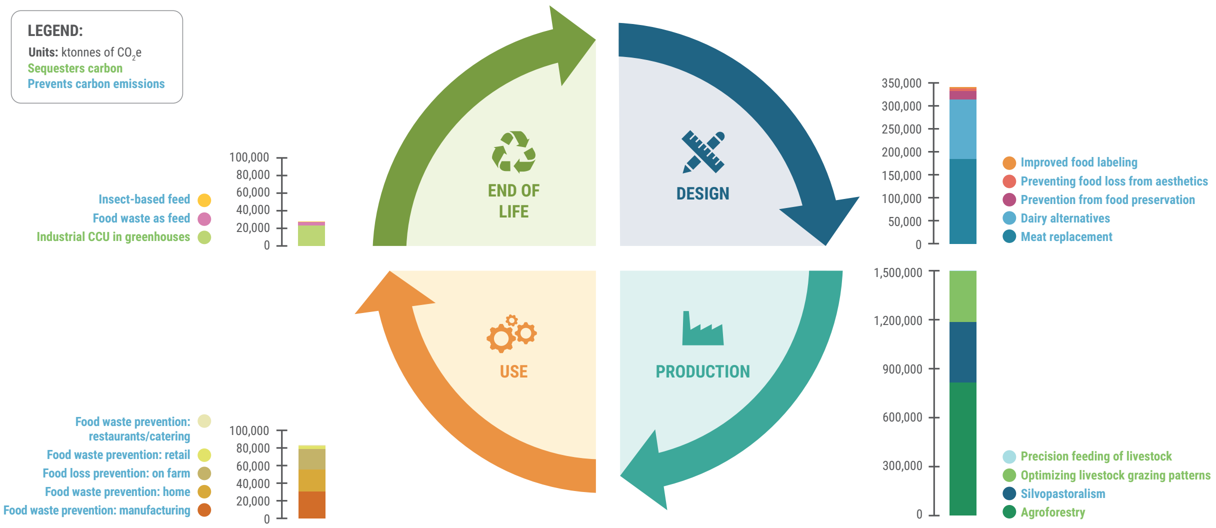


Figure 11 *Emissions reductions from CE Agrifood actions, by lifecycle stage (references used for calculations provided in Appendix II).*

When CE actions are placed into different stages of the life cycle, it is clear that the Production stage far outweighs the other stages. The reason for this is, again, the enormous potential of the agrifood system as a carbon sink through sequestration. The second highest stage is “Design”. Design includes the composition of our food products, how they are processed, packaged, etc. Such factors play a big role in the type of land systems that are developed as well as the amount of produced waste.

A large share of all food, and therefore the embedded impacts of food production, are wasted. In addition to the impacts from producing food that is never consumed, food waste treatment results in additional impacts. Overall, food waste accounts for around 10-15% of EU’s agrifood emissions. Preventing waste should therefore be included in any decarbonisation plan for the sector, even if it is overshadowed by the potential of dietary or production systems changes.

Substituting food waste for other products (e.g. animal feed) at the End of life stage can also prevent significant upstream impacts. In fact, collected and processed in the right way, food waste is essentially the same as a post-industrial waste (comparable to fabric cuttings in an apparel factory) rather than a post-consumer waste (like a used pair of shoes), even when the waste is generated by households. If it can be collected in a timely manner without contamination, it could still serve an important purpose in the agrifood system.

THE POTENTIAL IMPACT OF AN INTEGRATED CE STORYLINE

The outcomes described on the previous pages show the potential of individual actions, but simply adding the outcomes together to calculate the total impact potential is not possible. Some actions affect others or use the same resources (e.g., food waste or land). That is why an integrated CE storyline was developed. The potential maximum impact was calculated taking into account the limitations mentioned in the previous sentences. Only the technical and physical feasibility are considered in the calculations (not the economic, social, or political implications). The storyline has been organized based on three different definitions of the circular economy, the so-called "layers" introduced in the previous chapter. The three storyline layers are:

Layer 1:

Most limited definition of the circular economy - only the circularity of products and the waste treatment of those products form part of this strict definition of the circular economy. It therefore only covers the prevention and treatment of packaging and food waste.

The actions included in the storyline are:

CE ACTION	DESCRIPTION AND ASSUMPTIONS FOR STORYLINE
Food waste as feed	15,9% of processed food waste from manufacturing, retail & food services that is left over after food waste prevention actions replaces pig feed, preventing the embedded emissions of feed production for pork. The percentage of 15.9% is based on what part of the waste is considered feasible to be used as a direct feed source (Luyckx et al., 2019).
Insect-based feed	Insect-based feed produced using food waste (from crop production, animal husbandry, manufacturing, point-of-sale, food services) replaces as much feed for pigs and poultry as possible, after accounting for food waste prevented or used directly as feed.
Improved food labelling	Any food wasted in Europe from restaurants and households because of expiry date labelling is prevented (3,443 kT). Impacts due to production and treatment of the wasted food are eliminated.
Prevention from food preservation	Best practices are applied to food to extend the shelf life of products by improving packaging, ultimately preventing food waste in Europe. Impacts due to production and treatment of the wasted food are eliminated (for 22,865 kT of food waste). Impacts from additional packaging are accounted for.
Preventing food loss from aesthetics	It is assumed that all food lost at the farm level due to aesthetics requirements from consumers will entirely be prevented in Europe (7,097 kT). Impacts due to production and treatment of the wasted food are eliminated.

It is important to note that the combined storyline assumes that food waste that can be prevented (through food labelling, better preservation, and eliminating aesthetic requirements) happens first. The remaining food waste is then assumed to be cascaded directly into feed or the production of insects.

Layer 2:

Circular economy in a limited system - As a truly circular system can only be created if it can be supported with the limited resources available, consumption patterns and other pathways to reduce resource consumption are included. In this layer the focus lies on livestock systems, which can put a particularly high pressure on resources when produced on a large scale. To calculate the potential of livestock actions, a "circular carrying capacity" for livestock was defined, which includes livestock that can be produced on marginal land or waste and waste-based products (e.g. insects). This amounts to about 14% of the current production of animal productions. This means the production of animal products is reduced by 86% in the calculations. Beyond the circular carrying capacity, it is assumed that animal products are replaced with plant-based alternatives.

The actions included in the storyline are:

CE ACTION	DESCRIPTION AND ASSUMPTIONS FOR STORYLINE
Dairy alternatives	All dairy produced inside Europe beyond the circular carrying capacity is replaced with plant-based alternatives. Impacts from dairy cows and dairy processing are eliminated for the dairy production that is reduced. There are some negative impacts associated with the production of plant-based alternatives that are added.
Meat replacement	All meat produced in Europe beyond the circular carrying capacity is replaced with plant-based alternatives. Impacts from meat production are eliminated for the meat production that is reduced, but there are new impacts from crop production used for the production of plant-based alternatives.
Optimizing livestock grazing patterns	Optimising cattle grazing patterns can result in less direct emissions from livestock and better carbon storage in the soil. This action takes into account the increased long-term storage of carbon in the soil in Europe. This storyline assumes that grazing pattern optimization occurs on all remaining (marginal) land currently used for grazing.

Livestock are one of the largest drivers of climate change. The consumption of animal products will need to be drastically reduced to meet existing climate targets. However, livestock also plays an important role in a circular food system. Livestock can graze on land unsuitable for other uses and they can make use of food waste and other products from waste, such as insects. Hence why the "circular carrying capacity" for livestock has been defined as the amount of livestock that can be produced sustainably from grazing on marginal land, or consuming food waste and insects. This calculation was done by calculating the food waste left over after the prevention measures are put in place and what is possible to use directly as feed or use to produce insects. For this storyline, it was also assumed that livestock grazing patterns are optimized and silvopastoralism is implemented (which is included in the third layer). Precision feeding is excluded from the combined storyline calculations as it is assumed that no primary crops are used in livestock feeding.

Layer 3:

Molecular circularity in production systems - the last layer includes not only the circular production systems but also molecules in circular cycles - from water, to nutrients and carbon in soils. The actions that ended up in the short list however were ones focused on carbon sequestration in land systems.

The actions included in the storyline are:

CE ACTION	DESCRIPTION AND ASSUMPTIONS FOR STORYLINE
Agroforestry	Arable land that is technically suitable for agroforestry in Europe (according to Aertsens et al. 2013: 90 Mha, compared to 96 Mha estimated by EURAF) is converted to agroforestry. Agroforestry is a combined system of growing both crops and trees together and stores far more carbon in the soil and vegetation in the long term than crop production alone. Crop production alone tends to actually release carbon from the soil. It is estimated that each hectare of land converted to agroforestry can sequester 2.3 tonnes of carbon per year (Kay et al., 2019).
Silvopastoralism	All marginal land (assumed to be used for livestock grazing in this storyline) will apply silvopastoralism. The amount of marginal land within Europe is 11.35 Mha (Strapasson et al, 2020). Silvopastoralism is a diverse pasture system that combines pasture with shrubs and trees. Like agroforestry, silvopastoralism stores far more carbon in Europe's soil and vegetation in the longer term than current land systems. It is assumed that each hectare of land converted to silvopastoralism can sequester 1.5 tonnes of carbon per year (Kay et al., 2019).
Industrial Carbon Capture and Utilization (CCU) in greenhouses	Greenhouse CO_2 inputs and heat are typically provided by combined heat and power systems (CHP) which use natural gas. In this action, it is assumed that all existing greenhouses in the EU use CO_2 inputs from industry emissions and electrical heat, rather than using natural gas.

Agroforestry and silvopastoralism in the combined storyline are subjected to stricter limitations. Silvopastoralism is assumed to be applied only to marginal land (which also defines the limit of sustainable/ circular livestock production). Instead of assuming that agroforestry is applied to all arable land, it is assumed that 90 Mha of land would be converted to agroforestry. This is the amount estimated by Aertsens et al. (2013) to be suitable for this land system.

Looking at the outcomes of the storyline (see figure below), it becomes clear that the third layer (molecular circularity) has the highest potential for climate change mitigation, followed by the second storyline (circular economy in a limited system). All actions offer a significant opportunity in terms of working towards climate goals, but significant gains require actions beyond the most limited definition of the circular economy.

Compared to outcomes of the individual CE actions, the impact reduction potential of dairy and meat alternatives in the combined storyline are nearly the same. This is because the amount of cattle that can be produced from food waste and marginal land using a silvopastoral system (the "circular carrying capacity") is far less than current production (14%). As the amount of food waste is minimised, the impact reduction potential from using that food waste as feed or for insect cultivation is also reduced. The agroforestry and silvopastoralism potential decreases because of the stricter definition for what type of land these systems are applied to. The potential for silvopastoralism decreases even further due to the assumption that is only applied to marginal land.

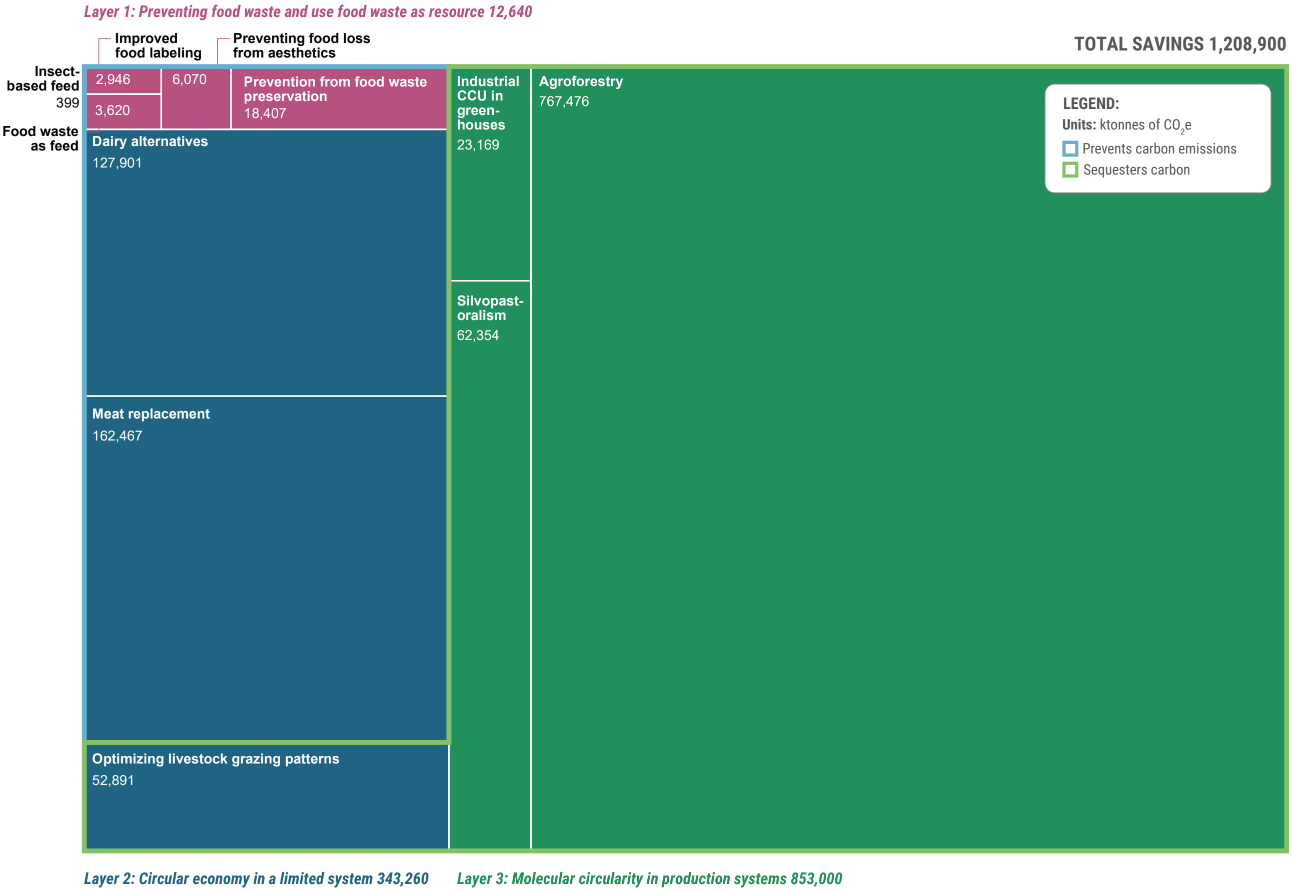


Figure 12 *Total impact reduction of all actions, broken down by layer and action.*

The potential of the agrifood sector as a net carbon sink looks extremely promising. The total emission reduction potential for this storyline is around one third of the total annual European greenhouse gas emissions, while the agrifood sector is only contributing around 10% the annual greenhouse gas emissions of Europe. However, it should be noted that these are merely estimations. For the purpose of this report, the median values of data sources were used in the calculations. Considering the range of potential values used in the calculations present a slightly more conservative view on the potential of these CE actions.

The lowest, most conservative numbers show a potential of the combined storyline of 356,000 ktonnes of CO_2e annually (66% of the entire sector's annual emissions). Applying the higher numbers the total impact reduction potential is 2.1 million ktonnes of CO_2e (more than half of all European emissions, not just those of agrifood sectors). The conclusion is that even with the most conservative estimations, if universally adopted, these circular economy actions can lead to a neutral or even net-negative emissions agrifood sector in Europe. It should be noted however, that around 74% of the net emissions savings are possible through carbon sequestering, rather than carbon mitigating actions.

All CE actions show emissions savings across their sensitivity ranges (see figure below), except for insect-based feed. Reports on insect-based feed present only marginal greenhouse gas emission savings, even with optimal production conditions. The highest potential savings from insect-based feed (close to 4,000 ktonnes) are only possible when renewable energy sources are used during the production of insects (Smetana et al., 2019). Insect-based feed production can even result in an increase of greenhouse gas emissions if implemented using fossil energy sources and other inefficient processes.

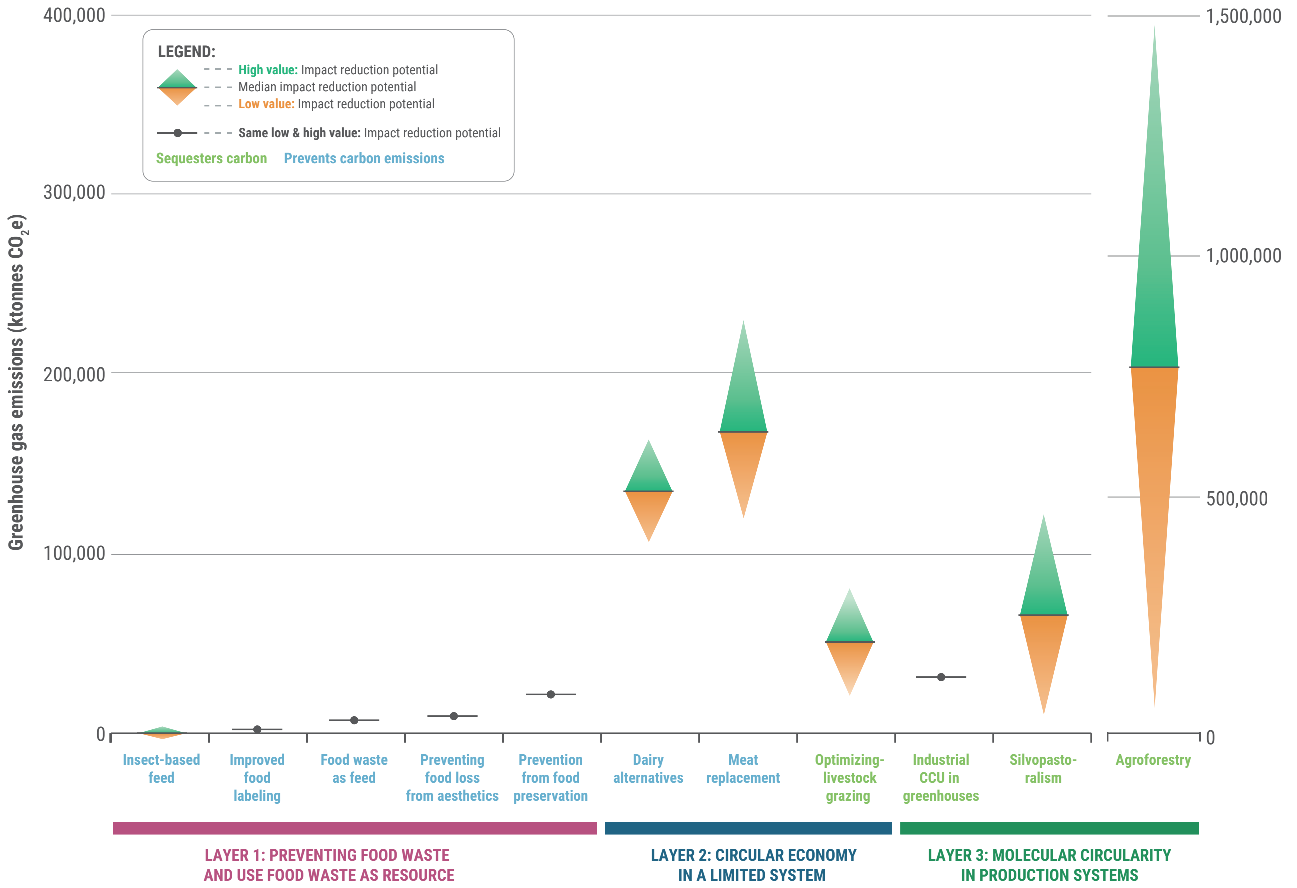


Figure 13 *Ranges of total impact reduction across the CE actions for each storyline (references used for calculations provided in Appendix II).*

A critical assumption of this work is that the actions could be adopted to the extent that is technically and physically feasible. However, there are also many legitimate non-technological challenges to implementation that go beyond any technological limits. Silvopastoralism would be difficult to implement in the Netherlands, for example, where open grassy fields and unobstructed horizons are a key part of the cultural identity. There has been resistance from farmers and communities to diversifying these open landscapes with trees. It will be difficult to change the minds of an entire population to accept silvopastoralism. Even if this system was adopted, some people might argue that it is not worth losing important cultural and historic value over.

Similar challenges can arise trying to replace meat and dairy with plant-based alternatives. The replacement could very well result in nearly halving the agrifood footprint, but dietary choices are also very personal and culturally significant.

This study does not take cultural, political, and economic considerations into account for the achievability of CE actions. However, to facilitate (the level of) implementation of the CE actions, this report has been complemented with an interactive dashboard. Users of the dashboard can remove certain actions or reduce their ambition levels if desired, to explore the final outcomes in different circumstances. The dashboard has been built using a system dynamics model, meaning that changing the ambition level of one action will change the outcome for all actions connected to the change.

ALLOCATION OF IMPACTS TO SECTORS

In the final step, the median greenhouse gas (GHG) emission savings of the individual circular economy actions in the storylines are allocated to UNFCCC (United Nations Framework Convention on Climate Change) Common Reporting Format (CRF) categories as well as to the ETS (European Trading system), non-ETS or LULUCF (land use, land-use change, and forestry) frameworks. This allocation provides a bit more insight into the policy relevance of the results of this study. Allocating actions can help EU Member States to identify how CE actions can help them reach targets set in the Climate Action Regulation (Regulation (EU) 2018/842), for example, and how the actions impact land use, land use change and forestry (LULUCF) regulated under Regulation (EU) 2018/841.

Implementing actions in the agrifood sector such as preventing food waste or lowering the impacts from meat production involves changes across many UNFCCC sectors, making this a challenging step. The process of allocating impacts to the UNFCCC sector categories does however provide more insights into where trade-offs may occur. For example, an action can reduce emissions in one UNFCCC category while increasing emissions in another category (e.g. additional packaging being used to prevent food waste).

Emission changes related to electricity, heat generation and industrial processes can be applied to the ETS non-ETS allocation framework. Where sufficient information regarding the emissions is available, emission reductions and increases were allocated to the ETS vs. non-ETS sectors, based on the Annex I of the ETS Directive (amended Directive 2003/87/EC).

Allocation of food waste reducing actions

The "Energy" categories in the UNFCCC framework include "Energy: Manufacturing Industries and Construction" (1.A.2) and subcategory "Food Processing, Beverages and Tobacco" (1.A.2.e). Changes in these categories are all associated with the actions related to food waste reduction. Less food waste means less food throughout the value chain, and therefore less emissions from processing food. However, to increase the shelf life of food, the emissions from manufacturing packaging rises. Emission category 1.A.2 (without the subcategory) therefore shows a net emission increase of 0.4 Mt CO_2e while the emissions of the category "Food processing (1.A.2.e) decrease by 3.4 Mt CO_2e.

In waste (category 5), the reduction of food waste directly reduces the emissions from waste processing by 6.8 Mt CO_2e. The highest emission reduction (77%) takes place in "Biological Treatment of Solid Waste" (5.B), which is the category where the majority of the separately collected organic waste and 13% of the food waste from mixed municipal wastes is processed.

Allocation of actions that affect agriculture, forestry, and land-use categories

The carbon-sequestering actions with the largest emission changes are allocated to the Agriculture, Forestry and Other Land Use (AFOLU) categories (UNFCCC category 3 and 4). Within AFOLU, the main change in net emissions comes from increased forest land (4.A.2) (62% of the total AFOLU reductions). While agroforestry was allocated to increased forest land, it could have also been allocated to cropland. The choice of category depends on whether the land is predominantly considered forest or cropland following implementation of agroforestry.

Next, is the category "grassland remaining grassland" (4.C.1) where optimised livestock grazing patterns ensures the emission reduction. After this category, the majority of changes in emissions are due to actions that are impossible to allocate to detailed categories. For example, the impacts of food waste take place across all of the categories. For this reason, the reduction is allocated to the more general category of Agriculture and LULUCF (3/4). An increase in net emissions (roughly 146 Mt CO_2e) happens in the "land converted to cropland" category (4.B.2) because dairy and meat alternatives require the production of crops.

Actions that affect industrial emissions

Outside of the AFOLU categories, several CE actions result in big changes in "Energy" (UNFCCC category 1), "Waste" (UNFCCC category 5), and "Process Emissions" (UNFCCC category 2). The largest single emission reduction of 18.4 Mt CO_2e is in the category "Energy: Agriculture/Forestry/Fishing" (1.A.4.c). This comes from industrial Carbon Capture and Utilization (CCU) in greenhouses which substitutes the onsite combustion of natural gas to provide CO_2 for the greenhouses. Some actions have negative side effects in the form of increased emissions for a particular category. For example, emissions increase in the "Public electricity and heat generation" category (1.A.1.a), due to electricity consumption of the industrial insect-based feed production.

Using industrial CCU in greenhouses reduces 4.7 Mt CO_2e from other manufacturing processes as it entails capturing CO_2e from industrial processes such as ammonia production or refinery processes, steel or cement production.

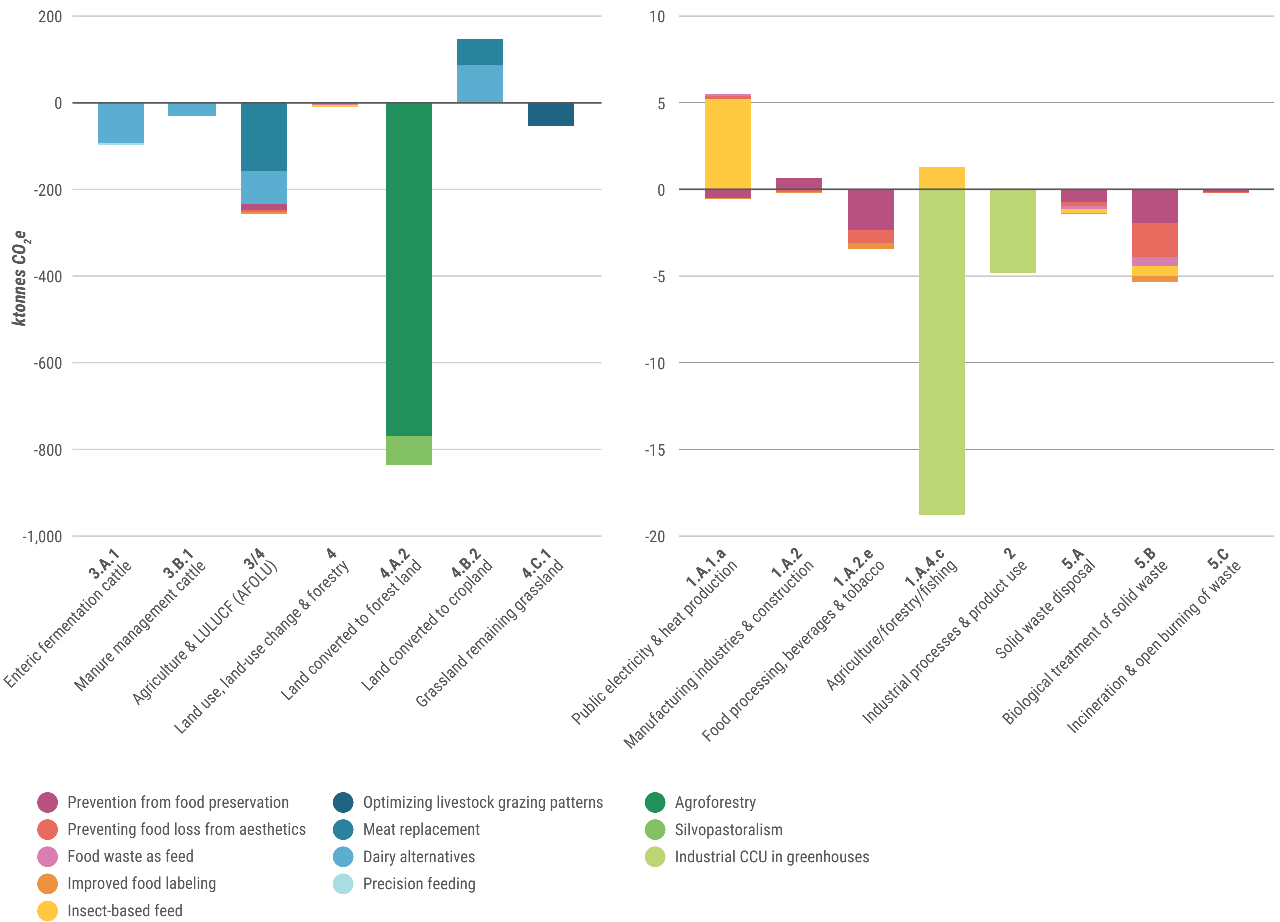


Figure 14 *Allocation of greenhouse gas emission changes in UNFCCC emission categories for AFOLU (right) as well as Energy, Process Emissions and Waste (left). Please note that this is curr ently split into two graphs as the scale is considerably different for AFOLU (emission category 3 and 4) and Energy, Process Emissions and Waste (emission categories 1, 2 and 5).*

Emission impact in the ETS, non-ETS and LULUCF policy areas

Many of the CE actions lead to emission reductions in LULUCF and agriculture. Neither of these sectors are part of the ETS, but non-CO_2 agricultural emissions are currently covered by the Effort Sharing Regulation instead (Regulation (EU) 2018/842) (referred to as "Non-ETS" in the next graph). CO_2 emissions and removals from land, land-use change, and forestry (LULUCF) are covered in the LULUCF Regulation (Regulation (EU) 2018/841). The emission impact from decreased or increased energy needs and the reduction of process emissions from industrial facilities fall under the ETS if the facilities meet the Annex 1 criteria. Most importantly, combustion activities are only included in the ETS categories if the total rated thermal input exceeds 20 MW. This means that the ETS does not cover small-scale onsite gas combustion for heat generation or for the generation of CO_2 in greenhouses, so these emissions are also excluded from ETS.

Therefore, only 0.2% of the net emission reduction of the actions can be included in the ETS. 70% of the total potential emissions reductions are LULUCF emissions and 11% in non-ETS emissions. The remaining 19% emission reduction is realised in non-ETS/LULUCF, as no allocation to agriculture and/or LULUCF is possible (see also description of limitations in the supplementary report **(Reflection on the Methodology)**.

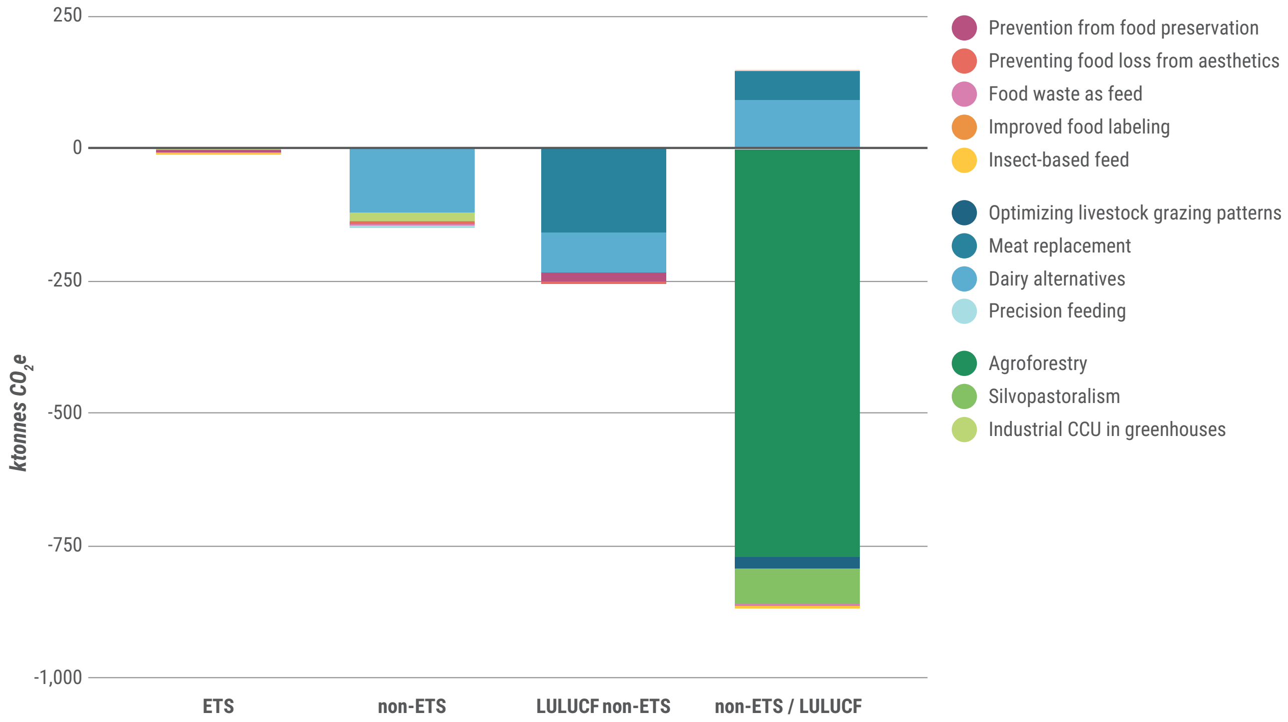


Figure 15 *GHG emission changes in the policy areas: ETS, non-ETS and LULUCF (calculations based on UNFCCC emission categories, Annex I of the ETS Directive, Climate Action Regulation and LULUCF Regulation). References used for the calculations are provided in Appendix II.*

04

REFLECTION ON THE SHORTCOMINGS OF THE APPROACH & SCOPE

The supplementary report "Reflection on the Methodology" outlines shortcomings related to the approach and scope of this report in more detail. For clarification purposes, some reflections on key assumptions and shortcomings will be briefly mentioned here:

- Co-benefits and risks are included in a qualitative assessment of the long list of potential circular economy actions, but these were not included in the detailed assessment. It is crucial to include additional impact considerations besides carbon to avoid burden shifting. In particular, biodiversity can be greatly affected by many of these actions. There are also social and ethical considerations that could be taken into account.
- A really important by-product of circular economy actions is the effect on nutrient flows, but these flows do not form part of this study. For example, changes to production systems or the consumption of animal products will have far-reaching implications for nutrient flows by affecting manure and food waste. Ideally, nutrient flow implications would be calculated alongside greenhouse gas emissions.
- This assessment focuses exclusively on actions related to the design of products, the application of technologies, and production practices. However, in order to achieve these "physical" changes, there are a number of enabling conditions that need to be put in place. This can include policies, education, research, etc. These types of enabling conditions were excluded from the scope of actions included in this report, but can be interesting to explore in terms of their contribution to the final outcomes.
- The method applied in this study excludes any analysis of costs (e.g., CO_2e cost abatement) related to the actions. Besides the costs of technologies or applying different practices, many actions may have macro-economic consequences in terms of how Europe is positioned in the global agrifood sector.
- Space and time are important factors to consider in an assessment about potential changes in land systems. This assessment excludes both of these factors for simplification purposes, but it is recognised that these factors could be included in a follow-up assessment, because:
    - Europe's agricultural land is very heterogeneous, with extreme differences between types of soil and climates between different parts of the continent. A much more detailed model including spatial heterogeneity can add additional value to an assessment on the potential of circular economy actions.
    - Time is a very critical factor in climate science. Different greenhouse gasses result in climate forcing for different lengths of time and some actions (for example carbon storage in soils) only have short term positive effects. This report only outlines the potential impact of actions at their peak potential in a single year. However, it is possible to build a much more robust model that estimates how the positive effects of CE actions evolve over time.
    - There are other critical elements of time that are excluded in the baseline assessment. Again, only the impact of the CE actions for 2016 are included in the report, but populations and consumption patterns continue to change over time. The reduction potential of CE actions related to changing factors will thus continue to evolve.

05
SYNTHESIS

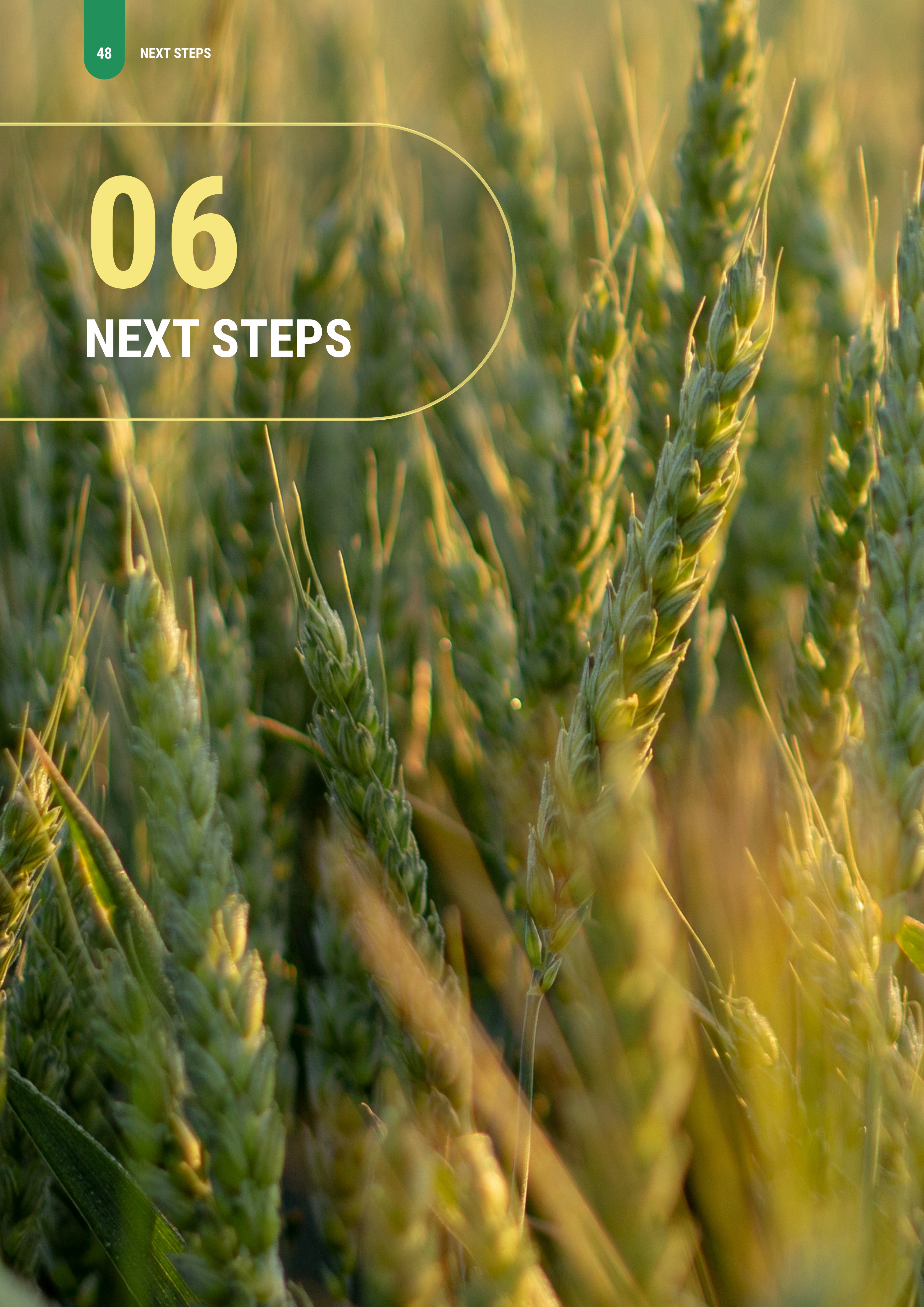
Europe's agrifood sector has the potential to serve as a net carbon sink through actions designed to reduce or return more carbon to land and vegetation than is emitted. This study shows that between 360,000 and 2.1 million kT CO_2e emissions could be avoided or sequestered. However, reaching these numbers requires a major shift in not only people's diets, but also production-systems and the way we try to avoid and handle waste. This effectively means changing the face of the agricultural system, as well as the types of products that are available to consumers. There are serious challenges regarding the technical, social, and economic implications and feasibility of such changes. For example, substantially reducing the production and consumption of animal products or greatly reducing food waste will be major undertakings.

If we look at actions that can potentially reduce greenhouse gas emissions, the total avoided CO_2e will be around 300,000 kT, two-thirds of the current agrifood system's emissions. Actions that sequester carbon in soil and vegetation show high potential (around 900,000 kT), nearly twice the annual emissions of the agrifood system. However, these actions also come with the highest uncertainty. The outcomes depend on how and where they are applied. Actions designed to return carbon to soil and vegetation are also limited in time as there is a maximum amount of carbon that can be stored this way. After just a few decades the maximum potential of these actions would be reached.

Policymakers should start by aligning economic incentives, land-use planning, and other policies in order to change patterns of behaviour at each stage of the current agrifood value chain. Looking at the end of life, it seems that a coherent approach to food waste reduction throughout Europe may be possible. Meanwhile, much more progress could be made in the Design and Production categories. The degree of regional specialisation across countries poses a significant challenge to European-level policies (e.g. the Farm to Fork Strategy). Regional specialties in food production means that interventions in land use and production systems may be best deployed by Member States, with guidance and support from the EU.

As mentioned, there are many social and cultural challenges attached to implementing certain CE actions, because food choices and a country's landscapes are socially and culturally determined. At the end of the day, policy is guided by social models and paradigms. The European Green Deal, Farm to Fork Strategy, and forthcoming Action Plans must therefore not only integrate production and consumption interventions into a cohesive strategy, but must also situate these actions in a broader social and cultural narrative if they hope to achieve real transformation. If the goal were extended further to include other environmental issues (e.g., nutrient pollution, biodiversity, etc), it is likely that similar actions would be identified and we would find ourselves facing the same barriers. To meet key societal goals requires figuring out how to change our policies, economy, and most importantly the paradigms informing how our food system is structured.

06
NEXT STEPS



This study has used a relatively simplistic approach to evaluate the potential reductions gains of CE actions to guide policy makers towards areas for further exploration. Steps that need to be taken to turn this report into action are:

1

First: figuring out which enabling conditions need to be put in place before physical interventions can be implemented. That means changing incentive structures, land-use planning, policies, consumer behaviour, etc. Additionally, an integrated approach to implementing a circular economy is necessary. As an example, both consumption and production patterns need to change simultaneously. If livestock production is reduced, without reducing consumption, then impacts will simply be shifted to another region while negatively impacting the European economy.

The EEA is currently working on several projects that work to help identify new climate mitigation and circular economy policies and measures. This study is an important input for identifying where to focus some of these efforts.

2

Second: recognizing that additional insights are needed to strengthen the findings of this study. There are major differences in terms of specialisation per region. Some countries are highly specialised in livestock production and a few countries have significant greenhouse horticulture, for example. This study has an EU-wide setup, but evaluating regional differences will be necessary to work further towards implementation.

Besides regional differentiation, there are other points of improvement that can be incorporated in follow-up research. This includes better capturing the context of time and space, especially when considering actions like agroforestry, which can differ drastically over time and space. Any additional research should also include evaluation of co-benefits and tradeoffs related to circular economy actions. In particular, the intersection of climate mitigation, resource use, and biodiversity is critical, and this is another area the EEA is working on in parallel.

This study demonstrates more broadly the value of the methodology originally designed by le Den et al., 2020 and applied to the building sector). At the same time, it works to identify further potential adaptations described in the “Reflection on the Methodology” supplementary report. The methodology reflections, as well as the results of this study, will be shared with experts on climate mitigation and circular economy in the EU and EEA member countries. The methodology outlined in this report can be applied to national contexts as well. It is also relevant to consider application of this generic methodology to a third sector, besides the building and agrifood sectors, but plans for that have not yet been set up.

BIBLIOGRAPHY

- Aertsens, J., De Nocker, L., & Gobin, A. (2013). Valuing the carbon sequestration potential for European agriculture. Land Use Policy, 31, 584–594. https://doi.org/10.1016/j.landusepol.2012.09.003
- Almond, R. E. A., Grooten, M., & Petersen, T. (2020). Living Planet Report 2020 - Bending the curve of biodiversity loss. Wwf. Retrieved from http://www.ecoguinea.org/papers-development.html
- Baroni, L., Cenci, L., Tettamanti, M., & Berati, M. (2007). Evaluating the environmental impact of various dietary patterns combined with different food production systems. European Journal of Clinical Nutrition, 61(2), 279–286. https://doi.org/10.1038/sj.ejcn.1602522
- Baroni, L., Cenci, L., Tettamanti, M., & Berati, M. (2007). Evaluating the environmental impact of various dietary patterns combined with different food production systems. European Journal of Clinical Nutrition, 61(2), 279–286. https://doi.org/10.1038/sj.ejcn.1602522
- Bartzanas, T., Amon, B., Calvet, S., Mele, M., Morgavi, D., Norton, T., … Vandongen, C. (2013). Reducing livestock emissions from Cattle farming Mini-paper – Precision Livestock Farming. EIP-AGRI Focus Group, 1–10.
- Behnke, G. D., Zuber, S. M., Pittelkow, C. M., Nafziger, E. D., & Villamil, M. B. (2018). Long-term crop rotation and tillage effects on soil greenhouse gas emissions and crop production in Illinois, USA. Agriculture, Ecosystems and Environment, 261(January), 62–70. https://doi.org/10.1016/j.agee.2018.03.007
- Bellarby, J., Tirado, R., Leip, A., Weiss, F., Lesschen, J. P., & Smith, P. (2013). Livestock greenhouse gas emissions and mitigation potential in Europe. Global Change Biology, 19(1), 3–18. https://doi.org/10.1111/j.1365-2486.2012.02786.x
- Benemann, J. (2013). Microalgae for biofuels and animal feeds. Energies, 6(11), 5869–5886. https://doi.org/10.3390/en6115869
- Benetti, C. (2018, May). Marginal Lands for Growing Industrial Crops: Turning a Burden into an Opportunity. Retrieved from http://www.besustainablemagazine.com/cms2/marginal-lands-for-growing-industrial-crops-turning-a-burden-into-an-opportunity/
- Beretta, C., Stoessel, F., Baier, U., & Hellweg, S. (2013). Quantifying food losses and the potential for reduction in Switzerland. Waste Management, 33(3), 764–773. https://doi.org/10.1016/j.wasman.2012.11.007
- Berg, N. (2016). The future of freight: More shipping, less emissions? Retrieved from https://www.greenbiz.com/article/future-freight-more-shipping-less-emissions
- Beylot, A., Secchi, M., Cerutti, A., Merciai, S., Schmidt, J., & Sala, S. (2019). Assessing the environmental impacts of EU consumption at macro-scale. Journal of Cleaner Production, 216, 382–393. https://doi.org/10.1016/j.jclepro.2019.01.134
- Bibbiani, C., Fantozzi, F., Gargari, C., Campiotti, C. A., Schettini, E., & Vox, G. (2016). Wood Biomass as Sustainable Energy for Greenhouses Heating in Italy. Agriculture and Agricultural Science Procedia, 8, 637–645. https://doi.org/10.1016/j.aaspro.2016.02.086
- Braun, S. (2019, September). Vegan meat: The future of planet-saving plant-based eating. Retrieved from https://www.dw.com/en/vegan-meat-the-future-of-planet-saving-plant-based-eating/a-51054861
- Brief, R. P., Ec, T., Economy, C., Plan, A., & Parliament, E. (2019). Avoiding food waste through feeding surplus food to omnivorous non-ruminant livestock Key Messages 1 Enacting policy to drive food waste reduction, (641933).
- Broekema, R., & van Paassen, M. (2017). Milieueffecten van vlees en vleesvervangers. Gouda. Retrieved from https://www.blonkconsultants.nl/wp-content/uploads/2017/11/Milieueffecten-van-vlees-en-vleesvervangers-3-8-2017-Eindrapport-v1.2.pdf
- Broocks, A., Andreini, E., Rolf, M., & Place, S. (2017). Carbon Footprint Comparison Between Grass- and Grain-finished Beef. Retrieved September 4, 2020, from https://extension.okstate.edu/fact-sheets/carbon-footprint-comparison-between-grass-and-grain-finished-beef.html#summary
- Brown, T., Hipps, N. A., Easteal, S., Parry, A., & Evans, J. A. (2014). Reducing domestic food waste by lowering home refrigerator temperatures. International Journal of Refrigeration, 40, 246–253. https://doi.org/10.1016/j.ijrefrig.2013.11.021
- Brown, T., Hipps, N. A., Easteal, S., Parry, A., & Evans, J. A. (2014). Reducing domestic food waste by freezing at home. International Journal of Refrigeration, 40, 362–369. https://doi.org/10.1016/j.ijrefrig.2013.12.009
- Brown, V. (2018). Can Responsible Grazing Make Beef Climate-Neutral? Retrieved from https://civileats.com/2018/04/10/can-responsible-grazing-make-beef-climate-neutral/

- Bruckner, M., Wood, R., Moran, D., Kuschnig, N., Wieland, H., Maus, V., & Börner, J. (2019). FABIO - The Construction of the Food and Agriculture Biomass Input-Output Model. Environmental Science and Technology, 53(19), 11302–11312. https://doi.org/10.1021/acs.est.9b03554
- Caldeira, C., De Laurentiis, V., Corrado, S., van Holsteijn, F., & Sala, S. (2019). Quantification of food waste per product group along the food supply chain in the European Union: a mass flow analysis. Resources, Conservation and Recycling, 149(August 2018), 479–488. https://doi.org/10.1016/j.resconrec.2019.06.011
- Campiotti, C., Viola, C., Alonzo, G., Bibbiani, C., Giagnacovo, G., Scoccianti, M., & Tumminelli, G. (2012). Sustainable greenhouse horticulture in Europe. Journal of Sustainable Energy, 3(3), 159–163.
- Capper, J. L. (2012). Is the Grass Always Greener? Comparing the Environmental Impact of Conventional, Natural and Grass-Fed Production Systems. Animals, 2(2), 127–143.
- Carrington, D. (2018). Avoiding meat and dairy is “single biggest way” to reduce your impact on Earth. Retrieved from https://www.theguardian.com/environment/2018/may/31/avoiding-meat-and-dairy-is-single-biggest-way-to-reduce-your-impact-on-earth
- Cederberg, C., & Berglund, M. (2009). Greenhouse Gas Emissions in Animal Feed Production, 28.
- Clark, M. A., Domingo, N. G., Colgan, K., Thakrar, S. K., Tilman, D., Lynch, J., ... & Hill, J. D. (2020). Global food system emissions could preclude achieving the 1.5° and 2° C climate change targets. Science, 370(6517), 705-708.
- Clark, M. A., Springmann, M., Hill, J., & Tilman, D. (2019). Multiple health and environmental impacts of foods. Proceedings of the National Academy of Sciences of the United States of America, 116(46), 23357–23362. https://doi.org/10.1073/pnas.1906908116
- Corrado, S., & Sala, S. (2018). Food waste accounting along global and European food supply chains: State of the art and outlook. Waste Management, 79, 120–131. https://doi.org/10.1016/j.wasman.2018.07.032
- Crenna, E., Sinkko, T., & Sala, S. (2019). Biodiversity impacts due to food consumption in Europe. Journal of Cleaner Production, 227, 378–391. https://doi.org/10.1016/j.jclepro.2019.04.054
- Crenna, E., Sinkko, T., & Sala, S. (2019). Biodiversity impacts due to food consumption in Europe. Journal of Cleaner Production, 227, 378–391. https://doi.org/10.1016/j.jclepro.2019.04.054
- Cuypers, D., Geerken, T., Gorissen, L., Lust, A., Peters, G., Karstensen, J., … Velthuizen, H. Van. (2013). The impact of EU consumption on deforestation: Comprehensive analysis of the impact of EU consumption on deforestation. Technical Report - 063 - European Commission. https://doi.org/10.2779/822269
- Darmawan, D. (2019). https://doi.org/10.1017/CBO9781107415324.004
- Date, P. (2016). feed ingredients in swine and poultry production : A life cycle assessment 1, 2664–2681. https://doi.org/10.2527/jas2015-9036
- De Boer, H. C., van Krimpen, M. M., Blonk, H., & Tyszler, M. (2014). Replacement of soybean meal in compound feed by European protein sources. Livestock Research Report 819, 47.
- De Wilde, B., Mortier, N., & Peuckert, J. (2014). Review on centralized composting, 32(0). Retrieved from www.biobasedeconomy.eu/app/uploads/sites/2/2017/07/centralized-composting.pdf
- de Wit, M., & van Ooijen, F. (2016). The circular dairy economy. FrieslandCampina, 20. Retrieved from https://www.circle-economy.com/wp-content/uploads/2016/10/the-circular-dairy-economy.pdf
- De, A., Bose, R., Kumar, A., & Mozumdar, S. (2014). Targeted Delivery of Pesticides Using Biodegradable Polymeric Nanoparticles. Fundamentals and Applications of Controlled Release Drug Delivery, 629–639. https://doi.org/10.1007/978-81-322-1689-6
- denkstatt GmbH. (2017). How Packaging Contributes to Food Waste Prevention: Specific examples from Austrian stakeholder projects, Consumers’ views of contributing to more sustainable environment All packaging materials cause footprint of. Retrieved from https://www.save-food.org/cgi-bin/md_interpack/lib/all/lob/return_download.cgi/3_Interpack_2017_denkstatt_Packaging_Food_Waste_Prevention_V1.0.pdf?ticket=g_u_e_s_t&bid=5684&no_mime_type=0
- Easy Comext. (n.d.). Easy Comext Data. Retrieved from http://epp.eurostat.ec.europa.eu/newxtweb/
- Easy Comext. (n.d.). FOCUS ON COMEXT. Retrieved from https://ec.europa.eu/eurostat/web/international-trade-in-goods/data/focus-on-comext
- Elbersen, B., van Eupen, M., Mantel, S., Alexopoulou, E., Zanghou, B., Boogaard, H., … Zanetti, F. (2018). Mapping Marginal land potentially available for industrial crops in Europe. European Biomass Conference and Exhibition (26th Edition EUBCE 2018), (May), 71.

- Ellen MacArthur Foundation. (2018). Cities and circular economy for food: Technical Appendix. Ellen Macarthur Foundation, 66. Retrieved from https://www.ellenmacarthurfoundation.org/assets/downloads/Cities-and-Circular-Economy-for-Food-Appendix.pdf
- Enzing, C., Ploeg, M., Barbosa, M., & Sijtsma, L. (2014). Microalgae-based products for the food and feed sector: an outlook for Europe. JRC Scientific and Policy Reports. European Comission. https://doi.org/10.2791/3339
- Eriksson, M., Strid, I., & Hansson, P. A. (2016). Food waste reduction in supermarkets - Net costs and benefits of reduced storage temperature. Resources, Conservation and Recycling, 107, 73–81. https://doi.org/10.1016/j.resconrec.2015.11.022
- Esposito, B., Sessa, M. R., & Sica, D. (2020). Towards Circular Economy in the Agri-Food Sector. A Systematic Literature Review.
- European Agroforestry Federation. (2020). Policy Briefing 2. Agroforestry in the EU Forest Strategy, 1–6.
- European Commission. (2018). EIP-AGRI Focus Group. Grazing for Carbon. Final Report, (September), 32. Retrieved from https://ec.europa.eu/eip/agriculture/sites/agri-eip/files/eip-agri_fg_grazing_for_carbon_final_report_2018_en.pdf
- European Commission. (2018). Market study on date marking and other information provided on food labels and food waste prevention. Retrieved from http://www.minagric.gr/images/stories/docs/politis/Trofima_Ygeia/spatali-trofimon/Market_study_date_marking_other_information_food_labels__Food_waste_prevention.pdf
- European Commission. (2018). Market study on date marking and other information provided on food labels and food waste prevention. Retrieved from https://ec.europa.eu/food/sites/food/files/safety/docs/fw_lib_srp_date-marking.pdf
- European Commission. (2020). Circular Economy Action Plan. Retrieved from: https://ec.europa.eu/environment/pdf/circular-economy/new_circular_economy_action_plan.pdf
- European Commission. (2020). Brief on food waste in the European Union 12 Key messages. https://www.eu-fusions.org/
- European Commission. (2021). REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on the making available on the Union market as well as export from the Union of certain commodities and products associated with deforestation and forest degradation and repealing Regulation (EU) No 995/2010.
- European Commission EUROSTAT. (n.d.). Sewage sludge production and disposal. Retrieved from https://ec.europa.eu/eurostat/web/products-datasets/product?code=env_ww_spd
- European Environment Agency (EEA). (2018). The circular economy and the bioeconomy - Partners in sustainability. EEA Report 8/2018.
- European Environmental Agency (EEA). (2020a). Bio-waste in Europe — turning challenges into opportunities.
- European Environment Agency. (2020b). The European environment : state and outlook 2020 : knowledge for transition to a sustainable Europe.
- European Environmental Agency (EEA). (2020c). Marginal Land. Retrieved September 7, 2020, from https://www.eea.europa.eu/help/glossary/gemet-environmental-thesaurus/marginal-land
- European Environmental Agency (EEA). (2012). Soil organic carbon. Retrieved from https://www.eea.europa.eu/data-and-maps/indicators/soil-organic-carbon-1/assessment
- European Union. (2018). Greenhouse gas emission statistics - emission inventories. Eurostat, 63(3), 175–180. Retrieved from https://ec.europa.eu/eurostat/statisticsexplained/%0Ahttps://ec.europa.eu/eurostat/statistics-explained/index.php/Greenhouse_gas_emission_statistics_-_emission_inventories%0Ahttp://ec.europa.eu/eurostat/statisticsexplained/
- FAO. (2017). Crop technologies. Good Agricultural Practices for greenhouse vegetable production in the South East European countries. Retrieved from http://www.fao.org/3/a-i6787e.pdf
- FAO. (2017). GLEAM_Data_public_release.
- FAO. (2019). Global Livestock Environmental Assessment Model (GLEAM). Retrieved September 2, 2020, from http://www.fao.org/gleam/results/en/
- FAO. (2020). New Food Balances. Retrieved from http://www.fao.org/faostat/en/#data/FBS
- FAOSTAT. (n.d.). FAOSTAT Livestock Manure. Retrieved from http://www.fao.org/faostat/en/#data/EMN/visualize
- FAOSTAT. (2019). Emission intensities. Retrieved September 3, 2020, from http://www.fao.org/faostat/en/#data/EI
- FAOSTAT. (n.d.). FAOSTAT Crops and livestock products. Retrieved from http://www.fao.org/faostat/en/#data/TP
- Federation of American Societies for Experimental Biology. (2016, March 30). Quantifying the environmental benefits of skipping the meat. Science Daily. Retrieved from https://www.sciencedaily.com/releases/2016/04/160404170427.htm

- Feliciano, D., Ledo, A., Hillier, J., & Nayak, D. R. (2018). Which agroforestry options give the greatest soil and above ground carbon benefits in different world regions? Agriculture, Ecosystems and Environment, 254(July 2017), 117–129. https://doi.org/10.1016/j.agee.2017.11.032
- Fowles, T. M., & Nansen, C. (2019). Insect-based bioconversion: Value from food waste. In Food Waste Management: Solving the Wicked Problem (pp. 321–346). Springer International Publishing. https://doi.org/10.1007/978-3-030-20561-4_12
- Garnett, T., Godde, C., Muller, A., Röös, E., Smith, P., De Boer, I., … Godfray, C. (2017). Grazed and confused? Ruminating on Cattle, Grazing Systems, Methane, Nitrous Oxide, the Soil Carbon Sequestration Question-and what it All Means for Greenhouse Gas Emissions. Food Climate Research Network, 1–127. Retrieved from https://www.fcrn.org.uk/sites/default/files/project-files/fcrn_gnc_report.pdf
- Gerber, P. J., Steinfeld, H., Henderson, B., Mottet, A., Opio, C., Dijkman, J., … Tempio, G. (2013). Tackling climate change through livestock – A global assessment of emissions and mitigation opportunities. Rome, Italy. Retrieved from http://www.fao.org/3/i3437e/i3437e.pdf
- Gerber, P., Steinfield, H., Henderson, B., Mottet, A., Opio, C., Dijkman, J., … Tempio, G. (2013). Tackling climate change through livestock- a global assessment of emissions and mitigation opportunities. Rome, Italy. Retrieved from http://www.fao.org/3/a-i3437e.pdf
- Gerwin, W., Repmann, F., Galatsidas, S., Vlachaki, D., Gounaris, N., Baumgarten, W., … Freese, D. (2018). Assessment and quantification of marginal lands for biomass production in Europe using soil-quality indicators. Soil, 4(4), 267–290. https://doi.org/10.5194/soil-4-267-2018
- Gilbert, N. (2012). One-third of our greenhouse gas emissions come from agriculture. Retrieved from https://www.nature.com/news/one-third-of-our-greenhouse-gas-emissions-come-from-agriculture-1.11708
- Grant, C. A., & Hicks, A. L. (2018). Comparative life cycle assessment of milk and plant-based alternatives. Environmental Engineering Science, 35(11), 1235–1247. https://doi.org/10.1089/ees.2018.0233
- Gromko, D. (2015). Combining cattle and forestry: five benefits of silvopastoralism. Retrieved from https://blogs.iadb.org/bidinvest/en/benefits-of-silvopastoralism/
- Haake, D. (2019). Which milk has the smallest impact on the planet? Retrieved September 14, 2020, from https://blog.datawrapper.de/cow-milk-and-vegan-milk-alternatives/
- Hamerschlag, K., & Venkat, K. (2011). LIFECYCLE ASSESSMENTS: METHODOLOGY & RESULTS Meat Eaters Guide: Methodology Table of Contents. Meat Eateers Guide, 63.
- Hawken, P. (2017). Silvopasture. Retrieved September 15, 2020, from https://drawdown.org/solutions/silvopasture
- Heller, M. C., & Keoleian, G. A. (2018). Beyond Meat's Beyond Burger Life Cycle Assessment: A detailed comparison between a plant-based and an animal-based protein source. Center for Sustainable Systems University of Michigan, 1–42. Retrieved from http://css.umich.edu/publication/beyond-meats-beyond-burger-life-cycle-assessment-detailed-comparison-between-plant-based
- Hendriks, C., Noothout, P., Zakkour, P., & Cook, G. (2013). Implications of the Reuse of Captured CO_2 for European Climate Action Policies Final report. Retrieved from www.ecofys.com
- HortiDaily. (2018). Sustainable vertical farming found to reduce CO_2 outputs by 70% over other agricultural methods. Retrieved from https://www.hortidaily.com/article/9045632/sustainable-vertical-farming-found-to-reduce-co2-outputs-by-70-over-other-agricultural-methods/
- International Union for Conservation of Nature (IUCN). (2015). The IUCN Red List of Threatened Species. Retrieved October 20, 2015, from http://www.iucnredlist.org/
- IPCC, 2018: Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [V. Masson-Delmotte, P. Zhai, H. O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, T. Waterfield (eds.)]. In Press.
- Kay, S., Rega, C., Moreno, G., den Herder, M., Palma, J. H. N., Borek, R., … Herzog, F. (2019). Agroforestry creates carbon sinks whilst enhancing the environment in agricultural landscapes in Europe. Land Use Policy, 83(July 2018), 581–593. https://doi.org/10.1016/j.landusepol.2019.02.025
- Kleter, G., McFarland, S., Bach, A., Bernabucci, U., Bikker, P., Busani, L., … Einspanier, R. (2018). Surveying selected European feed and livestock production chains for features enabling the case-specific post-market monitoring of livestock for intake and potential health impacts of animal feeds derived from genetically modified crops. Food and Chemical Toxicology, 117, 66–78. https://doi.org/10.1016/j.fct.2017.10.004

- Lal, R., Smith, P., Jungkunst, H. F., Mitsch, W. J., Lehmann, J., Ramachandran Nair, P. K., … Ravindranath, N. H. (2018). The carbon sequestration potential of terrestrial ecosystems. Journal of Soil and Water Conservation, 73(6), 145A-152A. https://doi.org/10.2489/jswc.73.6.145A
- Lawson, S. (2015). Stolen Goods: The EU's complicity in illegal tropical deforestation. Retrieved from www.fern.org
- le Den, X., Porteron, S., Collin, C., Sorensen, L. H. H., Herbst, A., Rehfeldt, M., Pfaff, M., Hirschnitz-Garbers, M., & Velten, E. (2020). Quantification methodology for, and analysis of, the decarbonisation benefits of sectoral circular economy actions. https://www.ecologic.eu/
- Louwagie, G., Gay, S. H., & Burrell, A. (2009). Final report on the project 'sustainable agriculture and soil conservation (SoCo)', European Commission Joint Research Centre: Brussels.
- Lugato, E., Bampa, F., Panagos, P., Montanarella, L., & Jones, A. (2014). Potential carbon sequestration of European arable soils estimated by modelling a comprehensive set of management practices. Global Change Biology, 20(11), 3557–3567. https://doi.org/10.1111/gcb.12551
- Lugato, E., Panagos, P., Bampa, F., Jones, A., & Montanarella, L. (2014). A new baseline of organic carbon stock in European agricultural soils using a modelling approach. Global Change Biology, 20(1), 313–326. https://doi.org/10.1111/gcb.12292
- Lum, K. K., Kim, J., & Lei, X. G. (2013, December 21). Dual potential of microalgae as a sustainable biofuel feedstock and animal feed. Journal of Animal Science and Biotechnology. https://doi.org/10.1186/2049-1891-4-53
- Luske, B. (2010). Reduced GHG emissions due to compost production and compost use in Egypt: Comparing two scenarios. Soil & More International, 30.
- Luyckx, K., Bowman, M., Woroneicka, K., Taillard, D., & Broeze, J. (2019). D6.7 Technical Guidelines Animal Feed: The safety, environmental and economic aspects of feeding surplus food to omnivorous livestock., (641933).
- Manfredi, S., Cristobal, J., Matos, C. T. de, Giavini, M., Vasta, A., Sala, S., … Tuomisto, H. (2015). Improving Sustainability and Circularity of European Food Waste Management with a Life Cycle Approach. https://doi.org/10.2788/182997
- Marchi, B., Zanoni, S., & Pasetti, M. (2018). Industrial Symbiosis for Greener Horticulture Practices: The CO_2 Enrichment from Energy Intensive Industrial Processes. In Procedia CIRP (Vol. 69, pp. 562–567). Elsevier B.V. https://doi.org/10.1016/j.procir.2017.11.117
- Martindale, W., & Schiebel, W. (2017). The impact of food preservation on food waste. British Food Journal, 119(12), 2510–2518. https://doi.org/10.1108/BFJ-02-2017-0114
- Mata, T. M., Cameira, M., Marques, F., Santos, E., Badenes, S., Costa, L., … Martins, A. A. (2018). Carbon footprint of microalgae production in photobioreactor. Energy Procedia, 153, 432–437. https://doi.org/10.1016/j.egypro.2018.10.039
- McAdam, J., Short, I., & Hoppé, G. (2006). Opportunities for silvopastoral systems in Ireland. Environmental Science, 276–281.
- Mills, J., Ingram, J., Dibari, C., Merante, P., Karaczun, Z., Molnar, A., … Ghaley, B. B. (2019). Barriers to and opportunities for the uptake of soil carbon management practices in European sustainable agricultural production. Agroecology and Sustainable Food Systems, 44(9), 1185–1211. https://doi.org/10.1080/21683565.2019.1680476
- Miranda, A., & Klug, I. (2018). Strengthening sector policies for better food security and nutrition results Public food procurement. Retrieved from http://www.wipo.int/amc/en/mediation/rules
- Mogensen, L., Heusal, H., Sinkko, T., Poutanen, K., Sözer, N., Hermansen, J. E., & Knudsen, M. T. (2020). Potential to reduce GHG emissions and land use by substituting animal-based proteins by food containing oat protein concentrate. Journal of Cleaner Production, 274.
- Mohammad Ibrahim Khalil, Rosa Francaviglia, Beverley Henry, Katja Klumpp, Peter Koncz, Mireia Llorente, Beata Emoke Madari, M. M.-R. and R. N. (2019). Strategic Management of Grazing Grassland Systems to Maintain and Increase Organic Carbon in Soils. https://doi.org/10.1016/j.colsurfa.2011.12.014
- Montanarella, L., & Panagos, P. (2021). The relevance of sustainable soil management within the European Green Deal. Land Use Policy, 100, 104950. https://doi.org/https://doi.org/10.1016/j.landusepol.2020.104950
- Nathan, A. J., & Scobell, A. (2012). How China sees America. https://doi.org/10.1017/CBO9781107415324.004
- Nicholls, E., Ely, A., Birkin, L., Basu, P., & Goulson, D. (2020). The contribution of small-scale food production in urban areas to the sustainable development goals: a review and case study. Sustainability Science. https://doi.org/10.1007/s11625-020-00792-z
- Notarnicola, B., Tassielli, G., Renzulli, P. A., Castellani, V., & Sala, S. (2017). Environmental impacts of food consumption in Europe. Journal of Cleaner Production, 140, 753–765. https://doi.org/10.1016/j.jclepro.2016.06.080

- Oonincx, D. G. A. B., van Itterbeeck, J., Heetkamp, M. J. W., van den Brand, H., van Loon, J. J. A., & van Huis, A. (2010). An exploration on greenhouse gas and ammonia production by insect species suitable for animal or human consumption. PLoS ONE, 5(12). https://doi.org/10.1371/journal.pone.0014445
- Orefice, J., Carroll, J., Conroy, D., & Ketner, L. (2017). Silvopasture practices and perspectives in the Northeastern United States. Agroforestry Systems, 91(1), 149–160. https://doi.org/10.1007/s10457-016-9916-0
- Ourom, J. (2014). Carbon Emissions in the Food and Beverage Sector. Retrieved from www.climatesmartbusiness.com
- Patricio, J., Angelis-Dimakis, A., Castillo-Castillo, A., Kalmykova, Y., & Rosado, L. (2017). Method to identify opportunities for CCU at regional level - Matching sources and receivers. Journal of CO_2 Utilization, 22(November), 330–345. https://doi.org/10.1016/j.jcou.2017.10.009
- Pelletier, N., Pirog, R., & Rasmussen, R. (2010). Comparative life cycle environmental impacts of three beef production strategies in the Upper Midwestern United States. Agricultural Systems, 103, 380–389.
- Piwowar, A., & Harasym, J. (2020). The importance and prospects of the use of algae in agribusiness. Sustainability (Switzerland), 12(14), 1–13. https://doi.org/10.3390/su12145669
- Pol-van Dasselaar, A. (2018). EIP-AGRI Focus Group Grazing for Carbon, (September), 1–32.
- Pomar, C., Canada, A., Remus, A., & Canada, A. (2019). Poultry and pig nutrition. Poultry and Pig Nutrition, (July). https://doi.org/10.3920/978-90-8686-884-1
- Poore, J., & Nemecek, T. (2018). Reducing food's environmental impact through producers and consumers. Science, 360(6392).
- Porter, S. D., Reay, D. S., Bomberg, E., & Higgins, P. (2018). Avoidable food losses and associated production-phase greenhouse gas emissions arising from application of cosmetic standards to fresh fruit and vegetables in Europe and the UK. Journal of Cleaner Production, 201, 869–878. https://doi.org/10.1016/j.jclepro.2018.08.079
- Ragonnaud, G. (2013). the Eu Seed and Plant Reproductive Material Market in Perspective: a Focus on Companies and Market Shares. Journal of Chemical Information and Modeling, 53(9), 1689–1699. https://doi.org/10.1017/CBO9781107415324.004
- Reckmann, K., Traulsen, I., & Krieter, J. (2013). Life Cycle Assessment of pork production: A data inventory for the case of Germany. Livestock Science, 157(2–3), 586–596.
- Report, F., Commission, E., & Environment, D. (2011). Manure Processing, (Ii), 1–8.
- Ritchie, M. E. (2020). Carbon Dynamics Mechanisms.
- Rob Sudmeyer, & Department of Primary Industries and Regional Development. (2018). Carbon farming: reducing methane emissions from cattle using feed additives. Retrieved from https://agric.wa.gov.au/n/1241
- Rose, C., Parker, A., Jefferson, B., & Cartmell, E. (2015). The characterization of feces and urine: A review of the literature to inform advanced treatment technology. Critical Reviews in Environmental Science and Technology, 45(17), 1827–1879. https://doi.org/10.1080/10643389.2014.1000761
- Sala, S. (2019). Consumer and Consumption Footprint: assessing the environmental impacts of consumption in the EU. Publications Office of the European Union.
- Sandström, V., Valin, H., Krisztin, T., Havlík, P., Herrero, M., & Kastner, T. (2018). The role of trade in the greenhouse gas footprints of EU diets. Global Food Security, 19(August), 48–55. https://doi.org/10.1016/j.gfs.2018.08.007
- Sassi, J., & Commission, A. E. (2019). Livre Turquoise - Algues, filières du futur, (August 2011).
- Sathasivam, R., Radhakrishnan, R., Hashem, A., & Abd_Allah, E. F. (2019, May 1). Microalgae metabolites: A rich source for food and medicine. Saudi Journal of Biological Sciences. Elsevier B.V. https://doi.org/10.1016/j.sjbs.2017.11.003
- Scarborough, P., Appleby, P. N., Mizdrak, A., Briggs, A. D. M., Travis, R. C., Bradbury, K. E., & Key, T. J. (2014). Dietary greenhouse gas emissions of meat-eaters, fish-eaters, vegetarians and vegans in the UK. Climatic Change, 125(2), 179–192. https://doi.org/10.1007/s10584-014-1169-1
- Scarlat, N., Fahl, F., Dallemand, J. F., Monforti, F., & Motola, V. (2018). A spatial analysis of biogas potential from manure in Europe. Renewable and Sustainable Energy Reviews, 94(September 2017), 915–930. https://doi.org/10.1016/j.rser.2018.06.035
- Schade, S., & Meier, T. (2020). Distinct microalgae species for food—part 1: a methodological (top-down) approach for the life cycle assessment of microalgae cultivation in tubular photobioreactors. Journal of Applied Phycology. https://doi.org/10.1007/s10811-020-02177-2
- Scherhaufer, S., Moates, G., Hartikainen, H., Waldron, K., & Obersteiner, G. (2018). Environmental impacts of food waste in Europe. Waste Management, 77, 98–113. https://doi.org/10.1016/j.wasman.2018.04.038

- Schils, R., Kuikman, P., Liski, J., Van Oijen, M., Smith, P., Webb, J., … Hiederer, R. (2008). Review of existing information on the interrelations between soil and climate change. (ClimSoil). Final report. https://doi.org/10.2779/12723
- Schoenaker, N., & Delahaye, R. (2017). Environmental Input-Output Analyses for the Netherlands, (05121), 1–30.
- Schröder, P., Beckers, B., Daniels, S., Gnädinger, F., Maestri, E., Marmiroli, N., … Sæbø, A. (2018). Intensify production, transform biomass to energy and novel goods and protect soils in Europe—A vision how to mobilize marginal lands. Science of the Total Environment, 616–617, 1101–1123. https://doi.org/10.1016/j.scitotenv.2017.10.209
- Schulze, E. D., Luyssaert, S., Ciais, P., Freibauer, A., Janssens, I. A., Soussana, J. F., … Gash, J. H. (2009). Importance of methane and nitrous oxide for Europe's terrestrial greenhouse-gas balance. Nature Geoscience, 2(12), 842–850. https://doi.org/10.1038/ngeo686
- Searchinger, T., Waite, R., Hanson, C., Ranganathan, J., Dumas, P., & Matthews, E. (2019). Creating a Sustainable Food Future a CREATING A SUSTAINABLE FOOD FUTURE WORLD RE SOURCE S REP OR T. Retrieved from www.SustainableFoodFuture.org.
- Sjøgren, K. (2017). How much more environmentally friendly is it to eat insects? Retrieved from https://sciencenordic.com/agriculture--fisheries-climate-climate-solutions/how-much-more-environmentally-friendly-is-it-to-eat-insects/1445691
- Smetana, S., Palanisamy, M., Mathys, A., & Heinz, V. (2016). Sustainability of insect use for feed and food: Life Cycle Assessment perspective. Journal of Cleaner Production, 137. https://doi.org/10.1016/j.jclepro.2016.07.148
- Soto, I., Barnes, A., Balafoutis, A., Beck, B., Sánchez, B., Vangeyte, J., … Gómez-Barbero, M. (2019). The contribution of precision agriculture technologies to farm productivity and the mitigation of greenhouse gas emissions in the EU. https://doi.org/10.2760/016263
- Stadler, K., Wood, R., Bulavskaya, T., Södersten, C. J., Simas, M., Schmidt, S., … Acosta-Fernández, J. (2018). SUPPORTING INFORMATION FOR: EXIOBASE 3 SI_energy Supporting Information for energy accounts 1 Method 1.1 Basic concepts 1.1.1 From energy balances to energy accounts, 1–28. Retrieved from www.wileyonlinelibrary.com/journal/jie
- Steen-Olsen, K., Weinzettel, J., Cranston, G., Ercin, A. E., & Hertwich, E. G. (2012). Carbon, land, and water footprint accounts for the European Union: consumption, production, and displacements through international trade. Environmental science & technology, 46(20), 10883-10891.
- Steinegger, T. (2019). Investigating the Environmental Footprint of Swedish Household Consumption Linking Swedish Expenditure Surveys with Environmentally Extended Multiregional.
- Stenmarck, Å., Jensen, C., Quested, T., Moates, G., Cseh, B., Juul, S., … Östergren, K. (2016). FUSIONS - Estimates of European food waste levels. Fusions. Retrieved from https://www.eu-fusions.org/phocadownload/Publications/Estimates of European food waste levels.pdf%5Cnhttps://phys.org/news/2016-12-quarter-million-tonnes-food-logistics.html#nRlv
- Strapasson, A., Woods, J., Meessen, J., Mwabonje, O., Baudry, G., & Mbuk, K. (2020). EU land use futures: modelling food, bioenergy and carbon dynamics. Energy Strategy Reviews, 31. https://doi.org/10.1016/j.esr.2020.100545
- Swain, M., Blomqvist, L., McNamara, J., & Ripple, W. J. (2018). Reducing the environmental impact of global diets. Science of the Total Environment, 610–611, 1207–1209. https://doi.org/10.1016/j.scitotenv.2017.08.125
- Toensmeier, E. (2016). The carbon farming solution: a global toolkit of perennial crops and regenerative agriculture practices for climate change mitigation and food security.
- Tukker, A., Bulavskaya, T., Giljum, S., de Koning, A., Lutter, S., Simas, M., … Wood, R. (2014). The global resource footprint of nations. Carbon, water, land and materials embodied in trade and final consumption calculated with EXIOBASE (Vol. 2). Retrieved from http://www.researchgate.net/profile/Stefan_Giljum/publication/264080789_The_Global_Resource_Footprint_of_Nations._Carbon_water_land_and_materials_embodied_in_trade_and_final_consumption/links/02e7e53cd0969e6723000000.pdf
- Tuomisto, H., Angileri, V., Camillis, C., Loudjani, P., Nisini, L., Pelletier, N., & Haastrup, P. (2013). Final Technical Report: Certification of Low Carbon Farming Practices. https://doi.org/10.2788/46851
- Uggetti, E., García, J., Álvarez, J. A., & García-Galán, M. J. (2018). Start-up of a microalgae-based treatment system within the biorefinery concept: From wastewater to bioproducts. Water Science and Technology, 78(1), 114–124. https://doi.org/10.2166/wst.2018.195
- van den Pol-van Dasselaar, A., Hennessy, D., & Isselstein, J. (2020). Grazing of dairy cows in Europe-an in-depth analysis based on the perception of grassland experts. Sustainability (Switzerland), 12(3). https://doi.org/10.3390/su12031098

- Van Niekerk, D., Markley, B., Li, Y., Rodriguez-Santiago, V., Thompson, D., Mohan, A. R., … Song, C. (2006). Utilization of carbon dioxide from coalfired power plant for the production of value-added products. 23rd Annual International Pittsburgh Coal Conference, PCC - Coal-Energy, Environment and Sustainable Development, (Egee 580).
- Vanham, D., Bouraoui, F., Leip, A., Grizzetti, B., & Bidoglio, G. (2015). Lost water and nitrogen resources due to EU consumer food waste. Environmental Research Letters, 10(8). https://doi.org/10.1088/1748-9326/10/8/084008
- Voisin, A. S., Guéguen, J., Huyghe, C., Jeuffroy, M. H., Magrini, M. B., Meynard, J. M., … Pelzer, E. (2014). Legumes for feed, food, biomaterials and bioenergy in Europe: A review. Agronomy for Sustainable Development, 34(2), 361–380. https://doi.org/10.1007/s13593-013-0189-y
- Walsh, B. J., Rydzak, F., Palazzo, A., Kraxner, F., Herrero, M., Schenk, P. M., … Obersteiner, M. (2015). New feed sources key to ambitious climate targets. Carbon Balance and Management, 10(1). https://doi.org/10.1186/s13021-015-0040-7
- Walsh, M. J., Gerber Van Doren, L., Sills, D. L., Archibald, I., Beal, C. M., Lei, X. G., … Greene, C. H. (2016). Algal food and fuel coproduction can mitigate greenhouse gas emissions while improving land and water-use efficiency. Environmental Research Letters, 11(11). https://doi.org/10.1088/1748-9326/11/11/114006
- Waste360. (n.d.). Steel Cans Recycling. Retrieved from https://www.waste360.com/Landfill_Management/steel_cans_recycling
- Waste360. (n.d.). Glass Container Facts. Retrieved from https://www.waste360.com/Recycling_And_Processing/glass-container-facts-200903
- Weiss, F., & Leip, A. (2012). Greenhouse gas emissions from the EU livestock sector: A life cycle assessment carried out with the CAPRI model. Agriculture, Ecosystems & Environment, 149, 124–134.
- Westhoek, H., Lesschen, J. P., Rood, T., Wagner, S., De Marco, A., Murphy-Bokern, D., … Oenema, O. (2014). Food choices, health and environment: Effects of cutting Europe's meat and dairy intake. Global Environmental Change, 26(1), 196–205. https://doi.org/10.1016/j.gloenvcha.2014.02.004
- White, R. R. (2016). Increasing energy and protein use efficiency improves opportunities to decrease land use, water use, and greenhouse gas emissions from dairy production. Agricultural Systems, 146, 20–29. https://doi.org/10.1016/j.agsy.2016.03.013
- Willem, D., Page, S., Cantore, N., King, M., Boysen, O., & Keijzer, N. (2014). the EU's CAP and development, (79).
- Williams, H., Wikström, F., Otterbring, T., Löfgren, M., & Gustafsson, A. (2012). Reasons for household food waste with special attention to packaging. Journal of Cleaner Production, 24, 141–148. https://doi.org/10.1016/j.jclepro.2011.11.044
- Zomer, R. J., Bossio, D. A., Sommer, R., & Verchot, L. v. (2017). Global Sequestration Potential of Increased Organic Carbon in Cropland Soils. Scientific Reports, 7(1). https://doi.org/10.1038/s41598-017-15794-8
- Zulian, G., Maes, J., & Paracchini, M. (2013). Linking Land Cover Data and Crop Yields for Mapping and Assessment of Pollination Services in Europe. Land, 2(3), 472–492. https://doi.org/10.3390/land2030472

APPENDICES

APPENDIX I: FULL LIST OF CE ACTIONS

Basic information table for long-list of actions

CE ACTION	DESCRIPTION	ASSUMPTIONS	QUANTIFIABILITY	APPLICABILITY
Agroforestry	Agroforestry is a collective name for land-use systems where trees, shrubs, palms, bamboos, etc. are grown on the same land as agricultural crops and/or animals.	European Agroforestry Federation (2020) estimations that Excluding protected areas (NATURA 2000, Ramsar) and areas with existing agroforestry, an area of 119,890 million ha (arable 95.89 Mha, permanent grassland 24.00 Mha) is the possible target area for new and regenerated agroforestry by 2030. Kay et al. (2019) estimates that between 17 and 448 tonnes of CO_2e can be stored per km2 per year.	High. A lot of research has been done on this already, though estimated ranges are pretty wide	Medium. It would be impossible to apply this universally and there are a lot of barriers to applying widely across the EU.
Algae-based feed	Algae-based feed has been explored as a less land-intensive source of high-quality animal feed. Additionally, waste CO_2 or other waste carbon can also be utilized directly in algae production systems, which makes it possible to use as a form of sequestration.	This article highlights an enormous potential for minimizing GHG emissions, both through LUC prevention as well as direct sequestration. In the research, they are taking the assumption that up to 25% of energy-production emissions can be sequestered in algae production. However, further research indicates high uncertainties, often increased emissions compared to a baseline, and an indication that massive scale up will be needed to achieve economies of scale which can also prevent impacts	Low. Quite some relevant studies have been done, but many are quite experimental pilot projects. Results are contradictory.	Low. Quite some relevant studies have been done, but many are quite experimental pilot projects. Results are contradictory. Medium. Would need to be applied in regions with access to high purity CO_2 sources.
Algae-based food	Algae can also be grown as a direct alternative food source for human consumption. A potential benefit in addition to saving land and sequestering carbon is that algae can be used to produce renewable fuel and food as coproducts.	In this article, it is assumed in one scenario to replace around 15% of food/feed consumption, which is quite an extreme example. In the end, the impact potential is clearly very high however, and it is just the many aspects of feasibility that keeps the potential low.	Low. Quite some relevant studies have been done, but many are quite experimental pilot projects. Results are contradictory.	Low. Would need to be applied in regions with access to high purity CO_2 sources. Additionally, there are major socio-cultural barriers to adopting algae-based food
Alternative pesticides	Some companies produce lower-impact pesticides from natural organic sources that are supposed to result in a lower production impact as well as less impact on the environment.	Pesticides only account for a very small fraction of emissions and are mostly interesting for their biodiversity implications. They would also have an impact indirectly (e.g. effects on pollinators, soil quality, etc, could also have an impact on emissions), but these systemic effects would be difficult to quantify).	Medium. There is LCA data on some pesticides, but likely very little on novel "low-impact" types.	High. If the alternative options are proven to work well and at a comparable price, then there would be no reason to avoid adoption.

CE ACTION	DESCRIPTION	ASSUMPTIONS	QUANTIFIABILITY	APPLICABILITY
Animal byproduct composting	One treatment option for animal byproducts (for example from meat or dairy processing) is composting and use of the compost in gardening or agriculture	"Composting is only acknowledged as an emission reduction project if the "baseline scenario" in a specific country causes significant greenhouse gas emissions (UNFCCC/CCNUCC, 2008)." This essentially only applies to landfill, so the emissions reduction potential of Europe would be relatively low. Additionally, the volume/mass of animal byproducts in the total organic waste stream is very small compared to, say, food waste in general.	High. Impacts are fairly well studied for different types of organic wastes and their treatment options	High. Compost use is ubiquitous and this action is not difficult to apply in any context
Aquaponics	Aquaponics is the co production of fish and crops in a closed greenhouse system. Nutrients from fish in the water are used to fertilize the plants, while the plants clean the water, reducing filtration demands	While there are some GHG emissions savings from using a landless system and from minimizing fertilizer demands, these systems typically have a higher impact due to both the embodied impacts of the equipment and the energy required for operating this equipment (e.g. heating, cooling, light, pump operation).	Medium. Well studied, but every system is different.	Medium-high. This could be applied most places, but it does require a fairly high capital input.
Biogas for heating greenhouses	The conventional best practice in greenhouses is to use natural gas for heating, power, and CO_2 inputs. However, if the gas inputs were from organic sources (e.g. manure, food waste) in the form of biogas, this could prevent some additional emissions.	In Europe, there was around 400k hectares of greenhouse horticulture in 2017 (concentrated mostly in a few countries). In 2012, the total GHG emissions of around 200,000 hectares of EU greenhouses was around 9.2 Mt, which only comes out to around 2% of the total impact. In certain countries, like the NL, it is an important decarbonization strategy, but this isn't the case EU wide. Of course, if greenhouses were expanded as well (e.g. as a potential sink for carbon, in vertical systems to minimize land intensity), then this could become more significant in the future.	High. Plenty of studies available on biogas and greenhouse systems, especially in the NL	Low. Most regions do not have considerable emissions associated with greenhouses (though for some countries it can be quite significant)

CE ACTION	DESCRIPTION	ASSUMPTIONS	QUANTIFIABILITY	APPLICABILITY
Biogas production from manure	Biogas can be made through digestion of organic material, such as manure or food waste	The "realistic biogas potential from manure in the EU" was estimated at 16 billion m3, compared to the EU's 470 billion m3 of natural gas consumption. Additionally, natural gas has a higher energy value than biogas (meaning you can't substitute these 1-1). 1 m3 natural gas has an emission of around 1.9 kg CO_2eq, with biogas saving around 80% of this carbon footprint. This comes out to roughly 24 Mt CO_2eq	High.	Low to medium. Only relevant in systems where manure can be easily collected
Cellulosic waste packaging	Organic wastes such as crop residues or food processing wastes can also be used to produce packaging (either bioplastics or other materials like pressed bagasse).	Packaging only accounts for a small share of agrifood-related emissions. Even if bioplastics or other alternative packaging materials were able to significantly reduce the impacts compared to the current system, this would still be only a small share. The size of that impact in a complete adoption scenario is dependent on the impact accounting approach. If the process of converting cellulosic waste into packaging is nearly negligible, and the impact accounting approach assigns no impact to that waste material, then it could save nearly the full amount of packaging impact if universally adopted.	Medium-high. Many LCAs available for various materials.	High. Many of these materials can act as drop-in solutions
Coffee grounds based substrate	Coffee grounds can be used to grow products like mushrooms, instead of soil	Very minimal - it is a convenient substrate, but not particularly low impact compared to alternatives	High	Low - only relevant for mushrooms
Compostable packaging	Compostable packaging is mainly pursued as an alternative in order to prevent the impacts of plastics that end up in the environment.	Less than 1% of EU agrifood related emissions are due to packaging end-of-life treatment (e.g. recycling, incineration). Even of this amount, likely a large share is due to logistics, instead of the processing. If anything, separate collection of compostable packaging might increase emissions.	Medium-high. Data available from various studies	High. Could act as a drop-in solution
Conservation tillage	Increases soil's capacity to hold carbon by preventing erosion	"There's limited scientific understanding of what keeps soil carbon sequestered, and, as a result, uncertainty about whether regenerative practices actually sequester additional carbon. For example, there is an active scientific debate about whether no-till, the primary practice relied upon by proponents of regenerative agriculture to generate climate benefits, actually increases soil carbon when properly measured."	Hard to quantify, seen more as a way of reducing soil erosion.	Conservation tillage can be universally applied, though there is some concern that it can result in additional need for pesticides in different contexts (e.g. fungicides in wetter climates)
Crop genetic optimization	Crop varieties with higher yields or lower input demands can decrease the overall GHG footprint	We're near the ceiling with non-GMO optimization that can occur in the short-medium term. GMOs that can increase yields are possible, but they could come at the expense of long-term soil heath, or other tradeoffs	Low.	Low

CE ACTION	DESCRIPTION	ASSUMPTIONS	QUANTIFIABILITY	APPLICABILITY
Crop rotation	Crop rotation can result in higher yields, less fertilizer or pesticide consumption, and less NOx emissions	"Comparing the corn phase of a corn-soybean rotation to continuous corn showed an average yield benefit of more than 20 percent and a cumulative reduction in nitrous oxide emissions of approximately 35 percent." If these types of benefits are applied to all crop production, there would be an enormous decrease of CO_2e emissions. However, these types of rotations are well known and widely applied, so we would need to also take into account where this provides an additional benefit over the current system.	Low.	High
Edible packaging	Much like natural fruit and vegetable peels protect produce quality, edible packaging has been suggested as an approach to prevent packaging waste. Instead, products would be packaged in packaging that can be eaten at the end of life.	Presumably this could prevent all downstream packaging emissions, though upstream production emissions would likely be the same or even higher for edible packaging. The potential applications of edible packaging in the short to medium term are low, so this should be considered a niche action at best.	Low. Only experimental, design prototype style products with no LCAs	Low. Food safety regulations and technical requirements limit the potential applications
Equipment sharing	Some farm equipment is infrequently used and could potentially be shared among farmers to prevent unnecessary consumption	Only accounts for a very tiny share of the impacts and really is infeasible to apply on a meaningful scale (too much effort, very little use case since equipment is generally needed around the same time, etc)	Low.	Low
Farming automation	Farming automation entails using machinery instead of human labor for a large share of the farming work	Negligible or even negative.	Medium	High
Fertilizers from faeces	Instead of mining and industrial production of fertilizers using the energy-intensive Haber-Bosch process, high-quality fertilizers can be produced from manure	Fertilizers are only accounting for around 1% of the total emissions	High	High

CE ACTION	DESCRIPTION	ASSUMPTIONS	QUANTIFIABILITY	APPLICABILITY
Fertilizers from food waste	Instead of mining and industrial production of fertilizers using the energy-intensive Haber-Bosch process, high-quality fertilizers can be produced from food waste	Fertilizers are only accounting for around 1% of the total emissions	High	High
Fertilizers from processed manure	Instead of mining and industrial production of fertilizers using the energy-intensive Haber-Bosch process, high-quality fertilizers can be produced from manure	Fertilizers are only accounting for around 1% of the total emissions	High	High
Fertilizers from urine	Instead of mining phosphorus, it can be recovered in high volumes from urine	Fertilizers are only accounting for around 1% of the total emissions	High	High
First gen bioplastics	First generation bioplastics are plastics made from primary crops, such as sugarcane, corn, or other crops grown for this purpose. In addition to many environmental tradeoffs in production, bioplastics also can have a questionable impact downstream. While some bioplastics are compostable, most are only compostable under industrial composting conditions that the majority never reaches, while bioplastics also commonly contaminate general plastics recycling.	Packaging only accounts for a small share of agrifood-related emissions. Even if bioplastics or other alternative packaging materials were able to halve the impacts compared to the current system, this would still be only a small share. For bioplastics in general, the benefits are questionable. While most LCA studies find carbon savings, this is largely due to exclusion of the LUC impacts associated with additional demands for primary crops. For first generation bioplastics, we should consider the carbon savings as negligible.	Medium-high. There are many studies, though the accounting approaches are hotly debated.	High. Bioplastics are typically slightly more expensive, but can serve as drop-in solutions for fossil-fuel based plastics in many cases.

CE ACTION	DESCRIPTION	ASSUMPTIONS	QUANTIFIABILITY	APPLICABILITY
Food loss prevention: on farm	On farm wastage occurs when farmers dispose of food that does not meet buyers' stringent aesthetic requirements or over produce as an insurance against a poor harvest that might lead to under-supplying strict supply contracts, (Stuart, 2009)	Around 22.5% of food waste is occuring at the farm level. As production-based emissions in the EU related to food waste treatment come out to around 4.7%, only around 2.4% of emissions could be prevented directly through mitigation. However, there are also impact savings that come from minimizing the food that needs to be produced to meet demand. While there is not a 1-1 ratio of food waste prevention and a decrease in overall consumption, we assume the majority of food waste prevented translates to less production - up to 30% which is the share of all food that is wasted. However, most food waste on the farm level is from crop production, which only accounts for around 12-14% of the total emissions. If loss at the farm level is prevented entirely, this could add up to nearly 1% of the total emissions.	High. Many studies available on food losses and plenty of data available on embodied impacts of food production and food waste treatment	There isn't likely to be major differences in applicability across regions
Food manufacturing efficiency	Some of the largest consumption-based emissions in Exiobase come from food processing. If we look at the sources of emissions in the food processing sector, it seems they largely come from refrigerants and from energy use in manufacturing. In particular, refrigerants have a high impact, though the type with the highest impact is being phased out from 2020 onwards.	This would need to be explored much further, but we are assuming here that a 10% reduction could be achieved in emissions intensity globally. For consumption-based emissions, this could mean a 4% reduction.	Medium-low. Could be pieced together, but data is very limited.	High. Since there are relatively few processors with influence in this part of the value chain, it would be easier to apply universally.

CE ACTION	DESCRIPTION	ASSUMPTIONS	QUANTIFIABILITY	APPLICABILITY
Food preservation	Food preservation (e.g. canning, drying, etc) can extend the lifespan of products considerably, reducing food waste. Additionally, consumers want the same foods year round, whether or not they are in season and food preservation can also maintain nutrient content of products.	There are several factors at play and no good reports that accounts for all of these issues: - Food preservation costs more energy in processing - It may also mean more packaging - However, it can greatly extend the lifespan of foods and minimize waste. For example, at-home reported food waste in Austrian households was six times higher for fresh foods than for preserved foods. - Food processing may mean a higher nutrient delivery than fresh foods which lose nutritional quality over time - Many fresh foods (e.g. produce, fish) may require refrigeration during storage and transport, while dried or canned goods do not - Food preservation can either add or remove mass or volume (e.g. canning means adding water, drying results in removing it), which can affect the impacts of transportation - Some preserved foods (e.g. dried beans) might take more energy to prepare at home, while others (e.g. canned beans) would take less energy than fresh All taken together, it seems that the opportunity for positive impacts are greater than the potential negative ones. And between the potential for minimizing consumer food waste by up to ~80% and replacing long periods of refrigeration with a single time of processing energy, it seems like the impacts would be very positive. In this situation, as a rough assessment, we will only consider an extreme food preservation scenario where all foods are preserved, minimizing at-home food waste by 80%	Low. Lots of complexities to be considered	Medium. Could be broadly applied, but consumer preferences would likely limit potential application

CE ACTION	DESCRIPTION	ASSUMPTIONS	QUANTIFIABILITY	APPLICABILITY
Food waste management (composting, biodigestion)	Composting food waste can result in much lower impacts than landfilling, as well as providing benefits by returning nutrients to the soil	Overall production-based emissions associated with food waste landfill is around 6-7%, so if this can be minimized through composting, then it is a fair amount of savings. "When organic waste is land filled, a fermentation or rotting process will start due to a lack of oxygen. During fermentation microbes will emit methane, a greenhouse gas which is ca 25 times stronger than carbon dioxide. The new composting scenario, "avoids" the emission of methane for a substantial part, but on the other hand causes more emissions due to the transport of biomass and fuel use on the composting facility. The emissions of N2O due to microbial activities may also be higher during composting than during fermentation." We assume here for this scenario that all food waste could be collected and composted, and that this system can halve the emissions associated with food waste landfill.	High, but we would need to look more comprehensively at food waste collection and treatment.	Could be easily universally applied, though there would be feasibility issues associated with collection
Food waste prevention: food processing	Manufacturing processes also require standardised sizes and weights, leading to trimmings which are often cheaper to dispose of than re-use processing ~19% of food loss in EU with a large range of uncertainty http://www.eu-fusions.org/phocadownload/Publications/Estimates%20of%20European%20food%20waste%20levels.pdf by-products destined for animal feed and bio-based products are not included in this figure	Around 10.6% of food waste occurs at the food processing level. However, it should also be noted that preventing this waste doesn't actually lead to preventing production in the same way - the majority of food waste from processing ends up as feed or is used in another extractive industry. Only a small share of impact could be prevented through waste prevention at this level for this reason (though any unutilized waste should obviously be diverted).	Low. Not much data available on the details of processing food waste	High. The same types of actions that can be taken in one region would likely be applicable in another.
Food waste prevention: household	Food waste results in more food being produced than is needed and additional impacts during waste treatment. Minimizing food waste can have a considerable impact. The majority of food waste occurs at home.	Almost 50% of all food waste occurs in the home, which is around 15% of all production. This contributes to around half of the emissions associated with food waste treatment (around 5% of overall sector production-related emissions). If food waste at home was halved, we are in the range of 5-10% of overall emissions.	High. Embodied impacts of food and the impacts of waste treatment are well known	High, but some barriers due to cultural practices

CE ACTION	DESCRIPTION	ASSUMPTIONS	QUANTIFIABILITY	APPLICABILITY
Food waste prevention: restaurants/ catering	70% of EU food waste arises in the household, food service and retail sectors, with production and processing sectors contributing the remaining 30% http://www.eu-fusions.org/phocadownload/Publications/Estimates%20of%20European%20food%20waste%20levels.pdf	Around 9.8% of food waste occurs at the level of food services (around 3% of overall production). If this could be prevented entirely, it could offset up to around 3% of overall agrifood sector impacts.	Medium. There are some studies on food waste in the food service industry, but this is quite different from there being data available.	High, but some barriers due to cultural practices
Food waste prevention: retail	A reliance on overly cautious "sell by" dates also leads to large wastage by retailers (Gustavsson et al., 2011; Stuart, 2009). 70% of EU food waste arises in the household, food service and retail sectors, with production and processing sectors contributing the remaining 30% http://www.eu-fusions.org/phocadownload/Publications/Estimates%20of%20European%20food%20waste%20levels.pdf	Despite the huge focus on food waste at the retail level, only around 6.8% is wasted at this part of the value chain. If all of this waste could be prevented however, it would make a small, but significant impact in terms of preventing excess food demand and resulting in additional, unnecessary production (e.g. up to around 2%).	Low. Probably quite difficult both to get information about how much food is wasted at the retail level, as well as get insight into what type of food products are wasted.	Actions that can work in retail would likely be possible to apply universally to retail in Europe.
Green and gray water utilization	Instead of using "blue" fresh water, agriculture can make use of rain water or greywater for irrigation	Since water consumption is not contributing significantly to the overall carbon impact, the savings would be small	Medium	High
Green waste composting	Green waste can be composted or even turned into higher-quality fertilizers, but the impact savings potential is small	Fertilizers are only accounting for around 1% of the total emissions	High	High
Hydroponics	Hydroponics is a closed-system form of horticulture where plants are grown on a non-soil substrate	The potential for land savings is there, but these systems generally require a lot of energy to operate. Even if that energy is renewable, on the short to medium term that will mean that less renewable energy is available to meet other demands. The carbon impact of this is therefore marginal.	Medium. Some data available, but not comprehensive	High

CE ACTION	DESCRIPTION	ASSUMPTIONS	QUANTIFIABILITY	APPLICABILITY
Improved food labeling	Food labeling is known to be confusing to consumers, resulting in food being thrown away while it is still edible, nutritious, and safe. Additionally, it is not only consumers that react to these labels - wholesalers and retailers also throw away food based on labels, even before "best by" dates have past, to minimize complaints from consumers.	Assumptions here depend on understanding how much food is thrown away due to labelling vs other reasons and it is difficult to find any data on this. Since the total potential for impact savings from retail, food service, and home food waste prevention is so high, I would think this is very significant. Also, my own experiences in food rescue work indicate it is extremely important in value chain waste (e.g. distributors will throw away entire shipments of food if they are within a week or two of their "best by" dates, since by the time they make it to shelves it will be cutting it close).	Low. No good studies found quantifying this.	Very high, as long as labeling requirements are universally applied
Increased dairy alternatives	Dairy alternatives are alternatives to products made from milk (e.g. milk itself, cheese, yogurt) from grains, legumes, seeds, or nuts	In this scenario, we assume that dairy can be replaced entirely with alternative products. Only the savings from eliminating dairy are considered. There would obviously be some impact from producing the alternatives, though these would be marginal compared to the savings and still likely put this action in the same rank.	Medium-high. Impacts of dairy production are well covered. The alternatives are varied with big difference between them	This alternative can be applied universally, though obviously there are stronger cultural, economic, and political barriers in different regions.
Industrial CCU in greenhouses	Fairly pure or purified CO_2 from energy or manufacturing can be used in greenhouse horticulture to increase the production efficiencies of the crops. This offers an opportunity for sequestration directly in the food system.	This article highlights an enormous potential for minimizing GHG emissions, both through LUC prevention as well as direct sequestration. In the research, they are taking the assumption that up to 25% of energy-production emissions can be sequestered in algae production. However, further research indicates high uncertainties, often increased emissions compared to a baseline, and an indication that massive scale up will be needed to achieve economies of scale which can also prevent impacts.	Low. Quite some relevant studies have been done, but many are quite experimental pilot projects. Results are contradictory	Medium. Would need to be applied in regions with access to high purity CO_2 sources
Insect-based feed	Insects like crickets and larvae can efficiently convert food waste into protein with a far lower impact than meat production	Insects can be used as feed for poultry and pigs, but not for cattle. 7-8% of the total emissions of agrifood are due to the production of poultry and pigs. If we assume that half of this is due to the feed and that insect-based feed could halve impacts compared to other alternatives, then this comes out to a small, but not negligible savings of around 1.5-2% of overall agrifood impacts.	Medium-high. There is some data available on insect production, but it is still piecemeal as it isn't very widely applied yet	The main challenges to applicability are due to sources of safe, high-quality food waste with no contaminants to use in the insect production.

CE ACTION	DESCRIPTION	ASSUMPTIONS	QUANTIFIABILITY	APPLICABILITY
Insect-based protein	Insects like crickets and larvae can efficiently convert food waste into protein with a far lower impact than meat production	The emissions savings are anywhere from 50-90% compared to poultry or beef. We assume for this max benefit scenario that all meat can be replaced with insect protein at a 70% average reduction.	Medium-high. There is some data available on insect production, but it is still piecemeal as it isn't very widely applied yet	Medium. The feasibility of widespread adoption is low, but it could technically be applied anywhere that food waste is available. The protein isn't as easy to replace meat with however.
Integrated pest management strategies	Integrated pest management entails minimizing pesticide use (but not eliminating it) through a holistic approach to pest management	Pesticides are only a small share of the GHG emissions. We assume that yield is not significantly affected by this	Medium, through pesticides LCAs for specific products	High. Can be applied fairly universally, though feasibility would be lower in regions with higher labor costs.
Lab-grown protein/precision fermentation	Lab-grown meat has been in the news for the last decade, but going beyond only meat, precision fermentation in general is claiming to be a replacement for arable farming as well as livestock production. The claims are that this would be far more resource efficient, except when it comes to energy	There is no way to quantify the impacts of precision fermentation at the moment, or lab-grown meat, since this is just now being piloted. We can assume however, that this has the potential to eliminate meat consumption, but at a much higher energy cost than simply growing plant-based protein through arable farming. Since renewable energy is a limited resource, even if this were done with renewables, that would come at the cost of renewables being used somewhere else. So for now, it is safer to assume that this action has a much lower carbon savings potential compared to "more conventional" meat replacement.	Very low. Experimental technologies, so little basis for comparison	High - presumably the meat alternatives at least could be made indistinguishable from meat.
Livestock CCU	Some experiments have been done to capture methane from livestock either through very ridiculous bags attached to cattle, or in intensive systems through collection in the buildings used to house livestock	Enteric fermentation from cattle is the main source of emissions (accounting for around 14% of all emissions globally). Emissions from cattle (dairy and ruminant meat) account for more than 40% of EU agrifood emissions. We assume that at least 30% of this is due to enteric fermentation alone. If it were to be captured, then the carbon savings are potentially very large, though feasibility is a huge issue.	Medium. Some data available, but mostly very experimental	Low. Can only really be applied to livestock who are kept indoors in intensive systems
Livestock genetic optimization	The genetic makeup of cattle determines how efficiently they can process feed and also how much methane they produce in digestion. Selecting species with a lower impact or selective breeding to produce livestock with less impact is a hot topic currently.	No actual data available, so assumed very low	Low. No studies found quantifying this, though many pointing to this as a point of research	Low. Different regions have their own varieties of cattle suited to the climate, etc

CE ACTION	DESCRIPTION	ASSUMPTIONS	QUANTIFIABILITY	APPLICABILITY
Local food	The local food movement is about minimizing "food miles" or the transportation distances that food needs to travel before it reaches the consumer.	Local food can reduce transportation impacts (which do account for up to 5-6% of the total agrifood impacts), but often a small difference in production efficiencies can make up for a longer travel distance.	High	High
Low-impact diets	In order of impact: Plant-based, reduce animal protein by half, 70% less beef, mediterranean	Plant-based (56% GHGe reduction) reduce animal protein by half (43% GHGe reduction), 70% less beef (35% GHGe reduction), mediterranean (11% GHGe reduction)	HIgh	High
Low-impact freight	As the freight sector decarbonizes, this can also cut down emissions from the food system	Transportation accounts for around 5-6% of the total food impacts, so a more efficient freight system can also reduce impacts allocated to the agrifood value chain. Shipping is already far more efficient per tonne-km than other modes of transportation (50% emissions reduction compared to rail, 80% compared to truck, 2% compared to air). Even though it is more efficient, it still accounts for a large share of impacts - and switching to cleaner fuels like LNG or even just diesel, already makes a huge difference. On land, truck routes and vehicles are as energy efficient as possible to minimize costs. The next step for reducing impacts will be to switch to cleaner fuels or electric. Even air is working on cleaner fuels (e.g. biofuel), but they have much further to go before a feasible option can be adopted. The best way to go is to minimize the amount of air freight used for food products. All in all, if we assume big changes in the freight system can halve the impact of freight over the coming decades, then it could reduce overall impacts by 2.5-3%	High, but also very scenario-dependent	High
Low-impact irrigation	Low-impact irrigation could include techniques to minimize water consumption in agriculture	Since water consumption is not contributing significantly to the overall carbon impact, the savings would be small	Medium	High
Manual weeding	Manual weeding is labor intensive but can provide an alternative to pesticide use	Very low potential. Pesticides are only a small share of the carbon impact and weeds are only one type of pest.	High.	Low. Labor costs are too high, especially for the benefit

CE ACTION	DESCRIPTION	ASSUMPTIONS	QUANTIFIABILITY	APPLICABILITY
Manure composting	Instead of mining and industrial production of fertilizers using the energy-intensive Haber-Bosch process, manure can be composted and used to provide nutrients for production	Fertilizers are only accounting for around 1% of the total emissions	High	High
Manure-based substrate	Manure can be used directly as a substrate for growing crops in	Very minimal - it is a convenient substrate, but not particularly low impact compared to alternatives	High	High
Meat replacement	Increasingly there are meat replacement products on the market made from plant-based ingredients that taste like and have similar nutrient profiles to meat. It seems that the main barriers to eliminating meat consumption are slowly being addressed.	In this scenario, we are assuming that meat is replaced entirely. However, it would probably not be entirely eliminated (some livestock can be raised on waste or marginal land that is otherwise of little value). Additionally, even if meat were entirely eliminated, there would be some additional impacts coming from producing additional plant-based products.	Medium-high. Impacts of meat production are well covered. The alternatives are varied with big differences between them, which would need to be explored further.	This alternative can be applied universally, though obviously there are stronger cultural, economic, and political barriers in different regions.
Methane capture from waste treatment	A large share of emissions arise from landfilling food waste that ends up in municipal waste streams. If methane emissions from landfills were captured, it could prevent loss of these emissions and be used as an energy source.	Nearly 9% of agrifood related emissions are due to food waste landfill. The assumption here is that the methane emissions from landfilling account for the entire share, while some is likely due to logistics, etc.	High	High
More efficient cold chain	Refrigerants along the entire agrifood value chain prevent food loss, but it comes at the cost of emissions from refrigeration	Almost 3% of the agrifood sector's emissions are due to refrigeration. If the efficiency of this were to be doubled, then we could achieve around a 1.5% emissions reduction.	Medium.	High
Optimizing stocking intensity and rotational grazing patterns	It is claimed that careful grazing of cattle on degraded marginal land can be done in a way that is climate neutral.	Hotly debated, but some research indicates that careful grazing pattern management (which is a labor intensive process) can make meat cattle production carbon neutral. If this claim were true, that means that climate-neutral cattle could be produced (insofar as degraded marginal lands were available to accommodate them). If we assume ALL cattle is produced in conventional intensive systems in Europe and that all could be shifted to an alternative, low-impact grazing system feasibly, this could account for close to 22% of EU emissions. Even if we assume that half of this or less is possible, then it would still put the action in the top impact tier.	Medium. Some studies out there, but I think a lot of piecemeal calculations would have to made to assess this properly.	Medium to low - would need to be further explored. It would only save emissions where you could transition a high-impact production system to marginal land

CE ACTION	DESCRIPTION	ASSUMPTIONS	QUANTIFIABILITY	APPLICABILITY
Organic production	Organic production includes crops and livestocks produced without fertilizers or pesticides that are deemed unnatural and sometimes with more eco-friendly production practices as well.	While it is not necessarily the case that there will be a yield gap, this is the current reality, which means that more land is necessary to produce the same amount of product. This makes up for most, if not all, carbon savings due to other differences with non-organic agriculture.	Medium.	High
Organics recycling into non-agrifood products	Different organic waste streams can be used to make non-food products (e.g. textiles, building materials, etc)	The size of the impact depends on the material that is replaced and what is produced. There are hundreds of niche products (fruit leather, coffee scrubs, etc) made from organic waste streams. However, the potential of each of these is limited both by the availability of specific waste streams, as well as by the market for these products. We should assume therefore that the potential impact savings is small.	Very low. Too many options and impact profiles, most of them very niche with poor data	Low
Packaging downcycling	Plastics in particular are often difficult to recycle back into similar products. Instead, plastics are often downcycled into low-quality composite materials that are used in things like park benches	The carbon savings of this action are minimal	Low. Many different options available	High
Packaging prevention	Packaging can be prevented/minimized by larger pack sizes, lightweighting, etc	Overall, agrifood related packaging accounts for around 2.5% of production-based emissions and 1.7% of consumption-based emissions. We assume that packaging could be halved with no negative tradeoffs (e.g. food waste) for this extreme scenario.	Medium.	High
Packaging recycling	Much packaging used in agrifood products is not captured for recycling in current systems	Packaging only accounts for around 2.5% of production-based impacts or 1.7% of consumption-based impacts in the agrifood system. A 100% recycling scenario might save a high amount of this impact (e.g. 50%) but this would still be a fairly low total impact even in an extreme case.	High	High
Plant-based diets	Eating plant based: high impact individual carbon mitigation step. Lessens land use change by eliminating feed crops.	Reduction of 0.9 tonnes of CO_2e per yr, Animal products (meat, eggs, and dairy) account for around 41% of production-based emissions of the agrifood system in the EU, and 22% of the consumption-based emissions.	HIgh	High

CE ACTION	DESCRIPTION	ASSUMPTIONS	QUANTIFIABILITY	APPLICABILITY
Polyculture	Polyculture is the simultaneous production of two or more species of crops or livestock together in a symbiotic way which brings benefits in terms of yield, but requires a different system for harvest, for example. This is in opposition to monoculture, where a production system is optimized for producing large amounts of a single species.	It seems like yield boosts are in the range of 10-20%, so for this rough assessment we can assume that crop production impacts are decreased by around 15%. This doesn't however take into account any additional energy use, etc that might be required for harvesting, for example.	Low - will depend a lot on which species are combined and there will only be case study data available, rather than much empirical data	High
Precision agriculture	Precision agriculture uses sensing technologies (e.g. satellite, UAV, etc) to determine where and when to add fertilizers or pesticides, reducing the overall demand to what is truly required	Pesticides and fertilizers account for only a small share of the total impact (e.g. around 1% or less), so even major savings here would be marginal in the big picture	Medium-low. Some studies available, but difficult to apply on a grander scale	Feasibility is low due to costs, but could be applied anywhere
Precision feeding of livestock	Tailored feed mixes can reduce the amount of emissions from cattle through enteric fermentation	Precision feeding can reduce enteric fermentation methane by up to 15-20%	Medium, quite a number of studies	High
Recyclable packaging	Much of the packaging that is used in food packaging is not well recyclable (e.g. laminates, flexibles), so shifting to more recyclable packaging could give a boost to the recycling industry	Packaging only accounts for around 2.5% of production-based impacts or 1.7% of consumption-based impacts in the agrifood system. A 100% recycling scenario might save a high amount of this impact (e.g. 50%) but this would still be a fairly low total impact even in an extreme case.	High	High
Reduced cold chain	Refrigerants along the entire agrifood value chain prevent food loss, but it comes at the cost of emissions from refrigeration	Almost 3% of the agrifood sector's emissions are due to refrigeration. If the demand for cooling along the supply chain were halved (for example by other forms of food preservation), then this impact could be halved. We assume that there would not be increased packaging or other negative tradeoffs as a simplification.	Low. We would need to make a lot of assumptions about what happens in the system with less refrigeration (e.g. is food dried, or canned instead?)	High

CE ACTION	DESCRIPTION	ASSUMPTIONS	QUANTIFIABILITY	APPLICABILITY
Reduced dairy consumption	Dairy is considered by most to be an important part of our diet and eliminating it entirely may not be feasible. However, as we recognize the impact that dairy has, a reasonable action would be to reduce consumption of dairy to some degree.	We look at the scenario where dairy production/consumption is eliminated as a maximum impact potential scenario. This is however an oversimplification - dairy production likely should not be eliminated entirely because cattle can convert inedible plant protein into edible protein for people. Additionally, even if this consumption were entirely eliminated, there would be some additional crop production to make up for nutrients lost.	HIgh	High
Reduced ruminant meat consumption	Ruminant animals like cattle and sheep produce a lot of methane gas due to their digestion process, so even where they can be fed on only marginal lands, they still produce a high amount of greenhouse gas emissions. Reducing consumption of ruminant animals in particular can have a large carbon impact reduction potential	We look at the scenario where ruminant meat production/consumption is eliminated as a maximum impact potential scenario. This is however an oversimplification - ruminant meat consumption should not be eliminated entirely because they can convert inedible plant protein into edible protein for people. Additionally, even if this consumption were entirely eliminated, there would be some additional crop production, or production of other livestock potentially to make up for the difference.	HIgh	High
Renewable greenhouse heating	Greenhouse heating can be produced from renewable sources (e.g. geothermal, solar PV, biogas, etc) instead of natural gas	As mentioned under "Biogas for heating greenhouses", only a small share of EU agrifood emissions (around 2%) result from greenhouses. So even if the heating/lighting systems are carbon-neutral, this could only reduce emissions by up to 2% (though this could become more significant in the future if greenhouse agriculture continues expanding.	High.	Medium-high. As mentioned, CO_2 sources for greenhouses are also generally from burning the natural gas for heating and electricity. So an alternative CO_2 source would be necessary
Reusable packaging	Reusable packaging, like Loop's products, are being promoted as an alternative to single-use packaging, but there are still a lot of logistical challenges to work out and it is unclear if the benefits are truly there	Packaging only accounts for around 2.5% of production-based impacts or 1.7% of consumption-based impacts in the agrifood system. If all packaging could be reused, reducing overall material production and waste processing load by 75%, then the impacts would still be fairly small.	Low. Very little information available still.	Low - difficult to implement

CE ACTION	DESCRIPTION	ASSUMPTIONS	QUANTIFIABILITY	APPLICABILITY
Seasonal diets	Seasonal diets have been proposed as a way to minimize impacts because produce that is not in season must be imported from far away and/or stored for long periods of time, which can result in high impacts	On its own it will not necessarily even reduce food miles in a meaningful way, so the impact should be considered negligible	Low	High
Silvopastoralism	Silvopastoralism is the use of shrubs and other types of vegetation in pastures as a feed source for livestock grazing. It can provide a higher amount of feed of a higher quality on the same amount of land, as well as storing more carbon in the vegetation and soil than conventional pasture systems. The varied vegetation also provides extra benefits for biodiversity.	A project in Colombia showed that 8 tonnes more CO_2 was stored per hectare. If we assume only half this amount could be achieved in Europe (4 tonnes extra per hectare), this already exceeds total EU agrifood emissions if it could be applied universally to all EU pastures (173 mln ha)	Medium. Quantifying the benefits would be challenging and based on case studies rather than empirical data.	Medium. In the NL at least, there is a lot of resistance to anything but open pasture. There might be a strong cultural resistance to change.
Sustainable procurement	Some organizations are commiting to sustainable procurement - making procurement decisions based on specific impact outcomes (e.g. halving the CO_2 footprint of the food that is purchased).	We assume that all procurement decisions, for example in the public sector, are done using a commitment of reducing emissions by 50%. Could not quickly find a good indication of percentage procurement, but overall public procurement is around 12% of GDP, so we will assume it also accounts for 12% of food procurement.	Medium. Easy to quantify implications of procurement decisions per unit of product, but difficult to say how large a share this is of the total food consumption.	Very high. Can be applied anywhere.
Urban agriculture	Urban agriculture is food production in urban areas, whether that is in community plots in neighborgoods, rooftop greenhouses, or balcony gardens	This action will depend largely on the way it is implemented (e.g. energy intensive greenhouses, or urban fruit trees). The main emissions savings come from minimizing transportation and land use change, which could be considerable. Some cities have managed to produce fairly high shares of their total food consumption. In Shanghai for example, the majority of vegetables and eggs are produced within the city. In cities, it might be possible to take advantage of waste heat, waste sources, etc, in efficient ways.	Low - depends a lot on the way it is done	Medium

Scoring table for long-list of actions

LEGEND

- Water use
- Other emissions
- Biodiversity
- Land use
- Nutrient cycles
- Social
- Economic
- Practical
- Political
- Technical
- Average
- Impact
- Feasibility
- Total
- Positive
- Negative
- Score modifier
- Modified effectiveness score
- Modified total score

	IMPACT						
CE ACTION	GREENHOUSE GAS EMISSIONS		TRADEOFFS AND COBENEFITS				
	Max impact on CO_2e	CO_2e rank	Water use	Other emissions	Biodiversity	Land use	
Agroforestry	235 million t CO_2eq	5					
Algae-based feed	Uncertain - assumed low until proven otherwise	1					
Algae-based food	Very high by scenarios assessed - in the hundreds of millions	5					
Alternative pesticides	Low	1					
Animal byproduct composting	Low	1					
Aquaponics	Low	1					
Biogas for heating greenhouses	The total impacts of greenhouses in Europe are less than 2% of the total. Even it were feasible to halve these impacts, it would still be in the range of a 2.	2					
Biogas production from manure	~24 Mt CO_2eq max --> ~4.8% of EU agrifood emissions	4					
Cellulosic waste packaging	The total impacts of packaging in the agrifood system are around 2.5% of the total. If this were halved or more, this would put us in the range of a rank of 3	3					
Coffee grounds based substrate	Negligible	1					
Compostable packaging	Negligible to negative	1					
Conservation tillage	Negligible to negative	1					
Crop genetic optimization	Minimal	1					
Crop rotation	Overall, somewhere in the range of 1-3%, assuming no crop rotation is currently applied	3					

	FEASIBILITY						SCORE							
	FEASIBILITY SCORES						OVERALL SCORE (UNWEIGHTED)			TRADEOFF AND COBENEFIT MODIFICATIONS				
	3	3	2	3	5	3.2	5	3.2	4.1	0	0	0	5	4.1
	5	2	2	3	2	2.8	1	2.8	1.9	3	0	1.5	2.5	2.65
	2	2	1	3	3	2.2	5	2.2	3.6	3	0	1.5	6.5	4.35
	5	3	3	5	5	4.2	1	4.2	2.6	1	0	0.5	1.5	2.85
	5	5	4	5	5	4.8	1	4.8	2.9	1	0	0.5	1.5	3.15
	4	2	2	3	3	2.8	1	2.8	1.9	4	0	2	3	2.9
	5	3	3	4	4	3.8	2	3.8	2.9	0	0	0	2	2.9
	3	2	4	3	4	3.2	4	3.2	3.6	0	1	-0.5	3.5	3.35
	5	3	4	4	4	4	3	4	3.5	0	0	0	3	3.5
	5	4	2	5	5	4.2	1	4.2	2.6	1	0	0.5	1.5	2.85
	5	3	5	4	4	4.2	1	4.2	2.6	0	3	-1.5	-0.5	1.85
	5	4	3	4	4	4	1	4	2.5	1	1	0	1	2.5
	2	4	3	3	3	3	1	3	2	2	1	0.5	1.5	2.25
	5	4	3	5	4	4.2	3	4.2	3.6	0	0	0	3	3.6

	IMPACT					
CE ACTION	GREENHOUSE GAS EMISSIONS		TRADEOFFS AND COBENEFITS			
	Max impact on CO_2e	CO_2e rank				
Edible packaging	Negligible	1				
Equipment sharing	Negligible	1				
Farming automation	Negligible	1				
Fertilizers from faeces	Marginal	1				
Fertilizers from food waste	Marginal	1				
Fertilizers from processed manure	Marginal	1				
Fertilizers from urine	Marginal	1				
First gen bioplastics	Negligible	1				
Food loss prevention: on farm	Medium. Up to around 3.4% in a scenario with total elimination of food losses at the farm level.	3				
Food manufacturing efficiency	4%	3				
Food preservation	15% of food is wasted at home. If this were reduced by 80%, this would come out to 12% of the total food footprint saved.	5				
Food waste management (composting, biodigestion)	Medium - around 3-3.5%	3				
Food waste prevention: food processing	low	1				
Food waste prevention: household	High	5				
Food waste prevention: restaurants/catering	Low	2				
Food waste prevention: retail	Medium. If all waste were prevented, ~2% total emissions reduction possible	3				
Green and gray water utilization	Small	1				
Green waste composting	Marginal	1				
Hydroponics	Negligible	1				
Improved food labeling	Medium-high. Could be anywhere from 2-4 reasonably.	3				
Increased dairy alternatives	~17% production-based emissions or ~13% consumption-based emissions	5				

	FEASIBILITY						SCORE							
	FEASIBILITY SCORES						OVERALL SCORE (UNWEIGHTED)			TRADEOFF AND COBENEFIT MODIFICATIONS				
	2	2	1	2	2	1.8	1	1.8	1.4	0	2	-1	0	0.9
	2	4	2	5	5	3.6	1	3.6	2.3	1	0	0.5	1.5	2.55
	2	4	3	3	3	3	1	3	2	0	0	0	1	2
	1	3	2	1	2	1.8	1	1.8	1.4	1	0	0.5	1.5	1.65
	4	3	2	4	3	3.2	1	3.2	2.1	1	0	0.5	1.5	2.35
	4	3	3	4	3	3.4	1	3.4	2.2	1	0	0.5	1.5	2.45
	2	3	1	1	2	1.8	1	1.8	1.4	1	0	0.5	1.5	1.65
	5	3	4	4	4	4	1	4	2.5	0	5	-2.5	-1.5	1.25
	4	4	3	3	3	3.4	3	3.4	3.2	5	0	2.5	5.5	4.45
	5	4	4	5	2	4	3	4	3.5	2	0	1	4	4
	2	4	4	4	3	3.4	5	3.4	4.2	0	0	0	5	4.2
	2	4	1	5	4	3.2	3	3.2	3.1	1	0	0.5	3.5	3.35
	4	3	4	3	2	3.2	1	3.2	2.1	5	0	2.5	3.5	3.35
	2	4	2	5	4	3.4	5	3.4	4.2	5	0	2.5	7.5	5.45
	4	5	4	3	3	3.8	2	3.8	2.9	5	0	2.5	4.5	4.15
	5	4	3	5	4	4.2	3	4.2	3.6	5	0	2.5	5.5	4.85
	3	3	3	2	2	2.6	1	2.6	1.8	1	0	0.5	1.5	2.05
	4	4	2	5	4	3.8	1	3.8	2.4	0	0	0	1	2.4
	4	2	2	4	2	2.8	1	2.8	1.9	4	0	2	3	2.9
	4	3	2	3	4	3.2	3	3.2	3.1	5	0	2.5	5.5	4.35
	3	4	4	3	5	3.8	5	3.8	4.4	5	0	2.5	7.5	5.65

	IMPACT					
CE ACTION	GREENHOUSE GAS EMISSIONS		TRADEOFFS AND COBENEFITS			
	Max impact on CO_2e	CO_2e rank				
Industrial CCU in greenhouses	Uncertain - assumed low until proven otherwise	1				
Insect-based feed	1.5-2%	3				
Insect-based protein	Up to 14% of production-based impacts or 6% of all consumption-based impacts, which puts this either in the range of a 4 or a 5	4				
Integrated pest management strategies	Low	1				
Lab-grown protein/precision fermentation	Much lower than the potential of replacing meat with plant-based proteins grown in arable systems	3				
Livestock CCU	Assuming all emissions from enteric fermentation could be captured, up to around 30% of the agrifood emissions	5				
Livestock genetic optimization	Assume low	1				
Local food	Negligible	1				
Low-impact diets	~50% reduction in GHG emissions	5				
Low-impact freight	2.5-3%	3				
Low-impact irrigation	Small	1				
Manual weeding	Negligible	1				
Manure composting	Marginal	1				
Manure-based substrate	Marginal	1				
Meat replacement	~24% of production-based emissions or ~9% of consumption-based emissions for all meat production (even with additional impacts from the production of plant-based alternatives puts this action in the max rank).	5				
Methane capture from waste treatment	High, up to 9% if universally applied	4				
More efficient cold chain	3	1				
Optimizing stocking intensity and rotational grazing patterns	High	5				
Organic production	Negligible to negative	1				
Organics recycling into non-agrifood products	Low	1				

	FEASIBILITY						SCORE							
	FEASIBILITY SCORES						OVERALL SCORE (UNWEIGHTED)			TRADEOFF AND COBENEFIT MODIFICATIONS				
	5	2	2	4	2	3	1	3	2	0	0	0	1	2
	3	3	3	2	2	2.6	3	2.6	2.8	5	0	2.5	5.5	4.05
	1	3	3	2	2	2.2	4	2.2	3.1	5	0	2.5	6.5	4.35
	5	4	3	5	3	4	1	4	2.5	2	0	1	2	3
	3	1	3	3	1	2.2	3	2.2	2.6	5	0	2.5	5.5	3.85
	2	2	1	4	1	2	5	2	3.5	0	0	0	5	3.5
	4	4	2	5	3	3.6	1	3.6	2.3	1	0	0.5	1.5	2.55
	4	2	4	4	5	3.8	1	3.8	2.4	1	0	0.5	1.5	2.65
	2	4	4	2	4	3.2	5	3.2	4.1	0	1	-0.5	4.5	3.85
	5	2	3	5	3	3.6	3	3.6	3.3	0	1	-0.5	2.5	3.05
	5	4	3	5	4	4.2	1	4.2	2.6	0	0	0	1	2.6
	5	2	2	5	5	3.8	1	3.8	2.4	2	0	1	2	2.9
	4	4	3	5	5	4.2	1	4.2	2.6	1	0	0.5	1.5	2.85
	4	4	3	5	5	4.2	1	4.2	2.6	1	0	0.5	1.5	2.85
	3	2	3	3	2	2.6	5	2.6	3.8	5	0	2.5	7.5	5.05
	5	3	3	5	4	4	4	4	4	0	0	0	4	4
	5	3	3	5	4	4	1	4	2.5	1	0	0.5	1.5	2.75
	5	2	2	5	4	3.6	5	3.6	4.3	2	0	1	6	4.8
	5	3	2	5	4	3.8	1	3.8	2.4	2	1	0.5	1.5	2.65
	4	3	2	4	3	3.2	1	3.2	2.1	3	0	1.5	2.5	2.85

CE ACTION	IMPACT					
	GREENHOUSE GAS EMISSIONS		TRADEOFFS AND COBENEFITS			
	Max impact on CO_2e	CO_2e rank				
Packaging downcycling	Marginal	1				
Packaging prevention	0.85-1.25%	2				
Packaging recycling	0.85-1.25%	2				
Plant-based diets	~70% reduction in GHG emissions	5				
Polyculture	Somewhere in the range of 1.5-2%	3				
Precision agriculture	Marginal	1				
Precision feeding of livestock	Up to 6%	4				
Recyclable packaging	0.85-1.25%	2				
Reduced cold chain	Up to a maximum of 3%, if eliminated entirely with not tradeoffs	3				
Reduced dairy consumption	~17% production-based emissions or ~13% consumption-based emissions	5				
Reduced ruminant meat consumption	~22% production-based emissions or ~4% consumption-based emissions just for cattle production alone	5				
Renewable greenhouse heating	Up to 2% maximum	3				
Reusable packaging	1.3-1.9%	3				
Seasonal diets	Negligible on its own	1				
Silvopastoralism	Very high if universally applied	5				
Sustainable procurement	Around 6% of total EU emissions in max scenario	4				
Urban agriculture	Medium, but would need to be explored further	3				
Vertical farming	Around 2-2.5% reduction potential	3				
Waste heat for heating greenhouses	Up to 2% maximum	3				
Waste ingredients / byproduct utilization	Low	1				
Waste-based feed	Low	1				

	FEASIBILITY						SCORE							
	FEASIBILITY SCORES						OVERALL SCORE (UNWEIGHTED)			TRADEOFF AND COBENEFIT MODIFICATIONS				
	4	4	4	4	4	4	1	4	2.5	0	0	0	1	2.5
	2	3	2	3	3	2.6	2	2.6	2.3	0	0	0	2	2.3
	3	3	2	5	3	3.2	2	3.2	2.6	0	0	0	2	2.6
	1	3	3	2	5	2.8	5	2.8	3.9	3	1	1	6	4.4
	5	4	3	5	4	4.2	3	4.2	3.6	3	0	1.5	4.5	4.35
	5	2	2	5	3	3.4	1	3.4	2.2	3	0	1.5	2.5	2.95
	5	4	3	5	3	4	4	4	4	5	0	2.5	6.5	5.25
	3	3	2	3	4	3	2	3	2.5	0	0	0	2	2.5
	3	3	2	4	3	3	3	3	3	1	0	0.5	3.5	3.25
	4	3	3	3	5	3.6	5	3.6	4.3	5	0	2.5	7.5	5.55
	3	3	3	3	5	3.4	5	3.4	4.2	5	0	2.5	7.5	5.45
	5	3	2	5	4	3.8	3	3.8	3.4	0	0	0	3	3.4
	3	3	2	4	3	3	3	3	3	0	1	-0.5	2.5	2.75
	3	5	3	5	5	4.2	1	4.2	2.6	0	0	0	1	2.6
	5	4	3	3	4	3.8	5	3.8	4.4	3	0	1.5	6.5	5.15
	5	4	3	5	4	4.2	4	4.2	4.1	5	0	2.5	6.5	5.35
	5	3	3	4	4	3.8	3	3.8	3.4	0	0	0	3	3.4
	5	2	3	4	2	3.2	3	3.2	3.1	1	0	0.5	3.5	3.35
	5	4	2	4	3	3.6	3	3.6	3.3	0	0	0	3	3.3
	4	4	3	4	2	3.4	1	3.4	2.2	5	0	2.5	3.5	3.45
	5	5	3	4	5	4.4	1	4.4	2.7	5	0	2.5	3.5	3.95

APPENDIX II: ASSUMPTIONS & REFERENCES FOR SHORTLISTED ACTIONS

ASSUMPTIONS FOR CIRCULAR ACTIONS				
Circular Economy Action	**Baseline Assumptions**	**Individual Assumptions**	**Combined Storyline Assumptions**	**Sources**
Dairy alternatives	Production-based impacts of dairy (Exiobase data used in baseline study)	All dairy replaced with alternatives. LCA impacts for almond milk are used for the high value and low value for rice milk. LCA values for dairy alternatives from Poore & Nemecek, 2018.	Dairy is replaced with alternatives insofar as the marginal land (as silvopasture) cannot support the existing milk production. Since this is combined with silvopastoralism, we also take into account a reduction of carrying capacity on this land (70%), based on McAdam et al (2006). This comes out to around 14% of the current production. The amount of marginal land available is 11.35 Mha (Strapasson et al, 2020).	*Exiobase (2016)* *Poore & Nemecek, (2018)* *Haake (2019)* *McAdam et al (2006)* *Strapasson et al. (2020)*
Meat replacement	Production-based impacts of livestock farming for meat production (Exiobase data used in baseline study)	All meat is replaced with alternatives. Low value is when all meat is replaced with lupine protein; High value is when all meat is replaced with beyond meat alternatives. LCA values for meat alternatives from Broekema et al. (2017) and for Beyond meat from Braun (2019).	Meat is replaced with plant-based materials insofar as the marginal land and feed from food waste cannot support the existing meat production. LCA values for meat alternatives from Broekema et al. (2017) and for Beyond meat from Braun (2019). Since this is combined with silvopastoralism, we also take into account a reduction of carrying capacity on this land (70%), based on McAdam et al (2006). This comes out to around 14% of the current production.	*Exiobase (2016)* *Heller & Keoleian (2018)* *Braun (2019)* *McAdam et al (2006)* *Broekema et al. (2017)*
Precision feeding of livestock	EU-27 enteric fermentation emissions from livestock	All ruminant livestock fed precise diets in order to prevent enteric fermentation. White (2016) was used to determine the greenhouse gas emissions savings.	Excluded, as it is assumed that no feeding on primary feed crops occurs in this scenario.	*White (2016)*
Agroforestry	Production-based emissions for all crop production in EU-27	European Agroforestry Federation, 2020: Excluding protected areas (NATURA 2000, Ramsar) and areas with existing agroforestry, EURAF estimates that an area of 119,890 million ha (arable 95.89 Mha, permanent grassland 24.00 Mha) is the possible target area for new and regenerated agroforestry by 2030. For this individual action, only the amount of arable land (95.89 Mha) was used in order to avoid double counting due to the permanent grassland that is being considered for the silvopastoralism action. The potential additional carbon sequestration per hectare of land was taken from Kay et al (2018). The median value of a range of cases was used for this factor, which comes out to 2.32 T C/ha/year.	Arable land area on which it is technically possible to successfully introduce agroforestry in Europe according to Aertsens et al. 2013 (90 Mha, compared to 96 Mha estimated by EURAF). The potential additional carbon sequestration per hectare of land was taken from Kay et al (2018). The median value of a range of cases was used for this factor, which comes out to 2.32 T C/ha/year.	*Kay et al (2018)* *Aertsens et al (2013)* *European Agroforestry Federation (2020)*

ASSUMPTIONS FOR CIRCULAR ACTIONS

Circular Economy Action	Baseline Assumptions	Individual Assumptions	Combined Storyline Assumptions	Sources
Silvopastoralism	EU-27 Pastureland emissions	All pastures are replaced with more diverse silvopastoral systems. The total land area of pastures used is 67Mha (Strapasson et al., 2020). The potential additional carbon sequestration per hectare of land was taken from Kay et al (2018). The median value of a range of cases was used for this factor, which comes out to 1.5 T C/ha/year.	All marginal land is replaced with silvopastoral systems. The amount of marginal land available is 11.35 Mha (Strapasson et al, 2020).	*Hawken (2017)* *Feliciano et al (2018)* *Aertsens et al (2013)* *McAdam et al (2006)* *Strapasson et al. (2020)*
Optimising livestock grazing patterns	EU-27 Pastureland emissions	All grazing on total EU-27 pasture land is replaced with high intensity, rotational grazing patterns. The total land area of pastures used is 67Mha (Strapasson et al., 2020). Garnett et al., (2017) used for the potential sequestration factor.	All grazing on marginal land is replaced with high intensity, rotational grazing patterns. The amount of marginal land available is 11.35 Mha (Strapasson et al, 2020). Garnett et al., (2017) used for the potential sequestration factor.	*Garnett et al (2017)* *Strapasson et al. (2020)*
Industrial CCU in greenhouses	EU-27 emissions from greenhouses	It is assumed that all greenhouses use industrial CO_2. In Ros et al (2014) they studied the potential reduction of CCU in greenhouse natural gas and determined the amount of CO_2 that could be saved on 1900 acres of greenhouses in Rotterdam, we used this number to determine the potential savings throughout the footprint of EU greenhouses. The total hectares of agriculture under glass comes from Eurostat, 2016. There were a couple of other sources used to confirm the feasibility and rates of CCU (Marchi et al 2018) and an Ecofys report (Hendriks et al 2013). In Bibbiani et al (2016) a study was completed to determine how much CO_2 from industry could be used in greenhouses in Greece, Italy, Netherlands, and Spain. These numbers were scaled and used to determine how much CO_2 is captured by the total footprint of EU27 greenhouses.	It is assumed that all greenhouses use industrial CO_2. In Ros et al (2014) they studied the potential reduction of CCU in greenhouse natural gas and determined the amount of CO_2 that could be saved on 1900 acres of greenhouses in Rotterdam, we used this number to determine the potential savings throughout the footprint of EU greenhouses. The total hectares of agriculture under glass comes from Eurostat, 2016. There were a couple of other sources used to confirm the feasibility and rates of CCU (Marchi et al 2018) and an Ecofys report (Hendriks et al 2013). In Bibbiani et al (2016) a study was completed to determine how much CO_2 from industry could be used in greenhouses in Greece, Italy, Netherlands, and Spain. These numbers were scaled and used to determine how much CO_2 is captured by the total footprint of EU27 greenhouses.	*Bibbiani et al (2016)* *Marchi et al (2018)* *Ros et al (2014)* *Hendriks et al (2013)*

ASSUMPTIONS FOR CIRCULAR ACTIONS

Circular Economy Action	Baseline Assumptions	Individual Assumptions	Combined Storyline Assumptions	Sources
Food waste prevention: restaurants/ catering	MFA value of food waste produced at restaurants/ catering, which is multiplied by the impact of that food waste from the Exiobase data	All food waste from restaurants/ catering (1,076 kT, derived from Caldeira et al. (2019)) is prevented. The impact of this food waste per unit is determined based on Exiobase data on food waste, divided by the total amount of food waste. A share of the food waste is unavoidable, but no information was found on the breakdown of avoidable and unavoidable food waste per step in the value chain. However, the total size of the impact would be roughly the same, as the impacts of the food waste would also be proportionately scaled (split across a smaller amount of avoidable food waste) to match. A share of the food waste is unavoidable, but no information was found on the breakdown of avoidable and unavoidable food waste per step in the value chain. However, the total size of the impact would be roughly the same, as the impacts of the food waste would also be proportionately scaled (split across a smaller amount of avoidable food waste) to match.		*Exiobase (2016) Caldeira et al. (2019)*
Food loss prevention: on farm	MFA value of the food waste produced at farm level, which is multiplied by the impact of that food waste from the Exiobase data	Food waste from farms is 27,564 kt, derived from Caldeira et al. (2019). The impact of this food waste per unit is determined based on Exiobase data on food waste, divided by the total amount of food waste.		*Exiobase (2016) Caldeira et al. (2019)*
Food waste prevention: home	MFA value of the food waste produced at household level, which is multiplied by the impact of that food waste from the Exiobase data	All food waste from households prevented (derived from MFA, (28,817 kT, derived from Caldeira et al. (2019)). The impact of this food waste per unit is determined based on Exiobase data on food waste, divided by the total amount of food waste. A share of the food waste is unavoidable, but no information was found on the breakdown of avoidable and unavoidable food waste per step in the value chain. However, the total size of the impact would be roughly the same, as the impacts of the food waste would also be proportionately scaled (split across a smaller amount of avoidable food waste) to match.		*Exiobase (2016) Caldeira et al. (2019)*

ASSUMPTIONS FOR CIRCULAR ACTIONS

Circular Economy Action	Baseline Assumptions	Individual Assumptions	Combined Storyline Assumptions	Sources
Food waste prevention: manufacturing	MFA value of the food waste produced at manufacturing level, which is multiplied by the impact of that food waste from the Exiobase data	All food waste from manufacturing is prevented (derived from MFA. 35,993 kt, derived from Caldeira et al. (2019)). The impact of this food waste per unit is determined based on Exiobase data on food waste, divided by the total amount of food waste. A share of the food waste is unavoidable, but no information was found on the breakdown of avoidable and unavoidable food waste per step in the value chain. However, the total size of the impact would be roughly the same, as the impacts of the food waste would also be proportionately scaled (split across a smaller amount of avoidable food waste) to match.		*Exiobase (2016)* *Caldeira et al. (2019)*
Food waste prevention: retail	MFA value of the food waste produced at retail level, which is multiplied by the impact of that food waste from the Exiobase data	All food waste from retail is prevented (derived from MFA, 3,879, derived from Caldeira et al. (2019)). The impact of this food waste per unit is determined based on Exiobase data on food waste, divided by the total amount of food waste. A share of the food waste is unavoidable, but no information was found on the breakdown of avoidable and unavoidable food waste per step in the value chain. However, the total size of the impact would be roughly the same, as the impacts of the food waste would also be proportionately scaled (split across a smaller amount of avoidable food waste) to match.		*Exiobase (2016)* *Caldeira et al. (2019)*
Food waste as feed	Soy and oil feed production in EU-27	15,9% of processed food waste from manufacturing, retail & food service replaces pig feed, based on the share that is feasible to use as feed (Luyckx et al 2019). CO_2 eq per unit of feed replaced comes from Cederberg et al. (2009) & Boer et al. (2014).	15,9% of processed food waste from manufacturing, retail & food service replaces pig feed, based on the share that is feasible to use as feed (Luyckx et al 2019). CO_2 eq per unit of feed replaced comes from Cederberg et al. (2009) & Boer et al. (2014).	*Luyckx et al (2019)* *Cederberg & Berglund (2009)* *De Boer et al (2014)*
Insect-based feed	Feed is produced from food waste based on the MFA values for food waste.	Insect-based feed reared on food waste (from crop production, animal husbandry, manufacturing, point-of-sale, food service) replaces as much feed for pigs and poultry as possible. The feed conversion rate comes from Fowles and Nansen (2019). CO_2e emissions factors come from Oonincx et al (2010).	Insect-based feed reared on food waste (from crop production, animal husbandry, manufacturing, point-of-sale, food service) replaces as much feed for pigs and poultry as possible, once the amount of food waste that can be directly fed to pigs is subtracted. The feed conversion rate comes from Fowles and Nansen (2019). CO_2e emissions factors come from Oonincx et al (2010).	*Fowles & Nansen (2019)* *Oonincx et al (2010*

ASSUMPTIONS FOR CIRCULAR ACTIONS

Circular Economy Action	Baseline Assumptions	Individual Assumptions	Combined Storyline Assumptions	Sources
Improved food labelling		All food wasted due to labelling is prevented (3,444 kt, based on European Commission, 2018). The impact saved per unit of food waste is derived from the up and downstream impacts of food production and food waste from the MFA and MRIO assessment.	All food wasted due to labelling is prevented (3,444 kt, based on European Commission, 2018). The impact saved per unit of food waste is derived from the up and downstream impacts of food production and food waste from the MFA and MRIO assessment.	*European Commission (2018)*
Preventing food waste through preservation	MFA value related to food waste generated at retail, household, and restaurant level, which is multiplied by the impact of that food waste from the Exiobase data	Different waste reduction percentages have been attributed to each food category (fruit/vegetables, meat, dairy, bakery), both at retail and household level. We calculate the share of this waste prevented with “best practice” packaging case studies (Denkstatt GmbH, 2017). The emissions due to additional packaging have been calculated and subtracted from the CO_2eq saved (Denkstatt GmbH, 2017). Overall, 22,865 kt of food waste is prevented with this action.	Different waste reduction percentages have been attributed to each food category (fruit/vegetables, meat, dairy, bakery), both at retail and household level. We calculate the share of this waste prevented with “best practice” packaging case studies (Denkstatt GmbH, 2017). The emissions due to additional packaging have been calculated and subtracted from the CO_2eq saved (Denkstatt GmbH, 2017). Overall, 22,865 kt of food waste is prevented with this action.	*Denkstatt GmbH (2017) Williams et al (2012)*
Preventing food loss for aesthetic reasons	MFA value related to food waste produced at farm level, which is multiplied by the impact of that food waste from the Exiobase data	All food lost due to aesthetics is prevented (7,097 kt, Beretta et al., 2013).	All food lost due to aesthetics is prevented (7,097 kt, Beretta et al., 2013).	*Beretta et al (2013*

APPENDIX III: GLOSSARY

- **AFOLU:** Common abbreviation for Agriculture, Forestry and Other Land Use
- **CE** (see: Circular economy)
- **Circular economy:** The Ellen MacArthur Foundation defines the circular economy as "an economy that is restorative or regenerative by design and aims to keep products, components, and materials at their highest utility and value at all times, distinguishing between technical and biological cycles."
- **Consumption-based impact:** Consumption-based impacts occur due to consumption of materials, products, and services by a person, company, or region, and are attributed to the consumer regardless of where those materials, products, and services are produced.
- **CRF:** Common Reporting Format. The standardised sectoral classification used in the UNFCCC framework.
- **Embedded impacts:** Embedded impacts are the impacts that happen "upstream" in the production of raw materials or products before they are consumed (also frequently called "embodied impacts".
- **Environmentally-Extended Multi-Regional Input-Output Tables (EE-MRIO/MRIO):** an analysis method that uses trade data to evaluate the direct and indirect environmental impacts of economic sectors and products traded among countries. Often referred to as IO or MRIO.
- **ETS/Non-ETS: European Emissions Trading System** - the European market for carbon trading, which includes a framework for which greenhouse gases and sectors are eligible for participation.
- **EU27:** All 27 member countries of the European Union as of 2020
- **Production-based impact:** Production-based impacts are impacts that happen within a region due to the production of materials, products, or services, and are attributed to the producer of the impact regardless of where they are ultimately consumed.
- **Industrial Symbiosis:** a principle in which the waste or by-products of an industry can be used as raw materials in another industrial process
- **LULUCF:** Land use, land-use change, and forestry. This category of emissions is sometimes excluded from policy frameworks on greenhouse gas emissions or handled in a different way than other sectoral emissions.
- **Material Flow Analysis (MFA):** an analysis method that assesses the resource flows in a well-defined system by quantifying its stocks and flows in a certain space and time.
- **MFA** (see: Material Flow Analysis)
- **Planned obsolescence:** products that are designed to stop being useful or functional after a certain period of time
- **Regenerative agriculture:** a set of diverse farming and grazing practices that promote carbon sequestration in soils and above ground while improving soil health, biodiversity and water quality
- **UNFCCC:** United Nations Framework Convention on Climate Change - an international treaty for preventing "dangerous human interference with the climate system. Part of this framework includes categories for different sectoral emissions, which are used in this report to provide further policy context.

COLOFON

AUTHORS:

Erin Kennedy
Andrew McCue
Margaux Sleckman
Natalie Pelekh
Brian Shaw

RESEARCH AND ANALYSIS TEAM:

Heidi Lampen
Margaux Sleckman
Dora Xu
Louisa Durkin
Natalie Pelekh
Giulia Sardano
Kerri Robinson
Vittorio Coletti

OTHER CONTRIBUTORS AND QUALITY CONTROL:

Xavier Le Den (project manager)
Martin Hirschnitz-Garbers
Eike Velten
Martin O'Connor
Peter Iversen

GRAPHIC DESIGN:

Svetlana Lezina
Cassie Bjorck
Sunniva Unneland
Marta Sierra Garcia

EEA REVIEW TEAM AND MANAGEMENT:

Suzanne Dael
Ybele Hoogeveen
Mieke De Schoenmakere
Almut Reichel

SPECIAL THANKS TO:

Jacomijn Pluimers
Dr Saskia Visser
Serenella Sala
Hedwig Boerrigter
Peder Jensen
Henk Westhoek
Caroline Ward
Maria Jose Baptista
Jean-Paul Cadoret
Justin Lukoff
Freek van Rijn
Rita Araujo Ph.D.
Montse Jorba Rafart
Sonja Kay
Arnold van Huis

METABOLIC

+31 (0) 203690977
info@metabolic.nl
www.metabolic.nl

Klimopweg 150
1032HX Amsterdam
The Netherlands