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"Carbon Farming as a technique to improve environmental performances in the Agri-food Sector: Corn cultivation in Italy"

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SOMMARIO

Gli effetti del cambiamento climatico in atto sono riconosciuti a livello globale, insieme al contributo delle emissioni di gas serra derivanti dalle attività antropiche. Tra le attività che apportano un contributo significativo all'aumento delle emissioni climalteranti, vi è il settore agroalimentare, che, come tutti i processi industriali, è caratterizzato lungo il suo ciclo di vita da impatti ambientali significativi. L'individuazione di strumenti per minimizzare tali impatti attraverso tecniche ambientali più efficienti è pertanto fondamentale e deve essere accompagnata da una valutazione del potenziale di sequestro del carbonio delle colture in modo da effettuare un bilancio del carbonio che tenga conto sia delle emissioni che degli assorbimenti. Il "Carbon Farming" rappresenta una modalità di gestione delle pratiche agricole volto ad incrementare il contributo del settore agricolo alla mitigazione dei cambiamenti climatici. Tali pratiche interessano la gestione sia del terreno che degli animali, - che rappresentano serbatoi di carbonio nel suolo, nei materiali e nella vegetazione – e prevedono una contabilizzazione dei flussi di anidride carbonica (CO_2), metano (CH_4) e protossido di azoto (N_2O), il calcolo della riduzione delle emissioni, il sequestro di carbonio e il suo stoccaggio permanente nel suolo e nella biomassa, oltre che le emissioni evitate. Il potenziale di mitigazione dei cambiamenti climatici di tali pratiche agricole è rilevante, ma dipende dal tipo di azienda e dalle diverse aree geografiche. Negli ultimi anni l'agricoltura è stata quindi oggetto di crescente interesse sia perché rappresenta un settore di fondamentale importanza per contribuire al raggiungimento degli obiettivi climatici dell'UE, ma anche perché essa stessa deve adattarsi agli impatti dei cambiamenti climatici. Lo scopo della tesi è quello di valutare diverse tecniche di carbon farming, il cui impatto ambientale è quantificato con metodologia Life Cycle Assessment. Verranno inoltre sviluppate alcune metodologie per tenere conto del potenziale di sequestro del carbonio, che saranno impiegate per calcolare l'effettiva "carbon footprint netta". La coltura scelta è il mais dolce. La scelta si basa sul fatto che questa coltura è una delle più coltivate a livello globale e, anche se ci sono piante più efficienti in termini di sequestro del carbonio, il suo potenziale complessivo è significativo. Dati relativi alla fase di coltivazione e alla preparazione dei prodotti finiti sono stati raccolti direttamente da Conserve Italia soc. coop. agr., una delle più grandi aziende europee del settore agroalimentare. I risultati ottenuti mostrano come alcune tecniche di carbon farming siano promettenti, mentre altre causano maggiori emissioni di Gas serra (GHG) lungo il ciclo di vita, rispetto allo scenario Business-As-Usual. Il carbon farming presenta quindi un alto

potenziale, ma il suo contributo alla mitigazione delle emissioni di GHG necessita ancora di ulteriori approfondimenti e regolamentazioni.

ABSTRACT

Climate is changing and the effects are recognized globally, it is a consequence of growing human activities and among those, the agri-food sector is for sure relevant. The agri-food sector, like all industrial processes, presents along its life cycle and production chain considerable environmental impacts. Identification of tools to minimize such environmental costs through more efficient environmental techniques is, therefore, crucial as well as accounting for carbon sequestration potential of crops. Carbon farming is usually referred to as a way to manage farm practices aiming to deliver climate mitigation in agriculture. This involves the management of both land and livestock, all pools of carbon in soils, materials, and vegetation, plus fluxes of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). It includes emissions reductions, carbon sequestration, and its permanent storage in soils and biomass and avoided emissions. Different farming systems can be profitable to provide climate mitigation, although the level of mitigation potential is different depending on farm types and different geographies. Carbon farming has been subject to growing interest in recent years because agriculture is a sector of fundamental importance also to contributes to meeting EU climate goals and because agriculture itself needs to adapt to climate impacts.

The purpose of the thesis is to evaluate different carbon farming techniques, which environmental impact are quantified through Life Cycle Assessment methodologies. Also, different methodologies to account for carbon sequestration potential will be developed and used to effectively calculate the “net Carbon footprint”. The selected crop is sweetcorn. The choice relies on the fact that this crop is one of the most cultivated globally and, even though there are more efficient plants in terms of carbon sequestration, its overall potential is significant. Data about the cultivation phase and the preparation of finished products for the market were directly collected from Conserve Italia soc. coop. agr., one of the biggest European companies in the agri-food sector. Results show that some carbon farming techniques are promising, whilst others cause higher greenhouse gas emissions (GHG) along the crops lifecycle compared to the Business-As-Usual scenario. So, carbon farming has a high potential, but its contribution to GHG mitigation should be still investigated and regulated.

Summary

1. INTRODUCTION

1.1. Climate change

One of the crucial challenges that humanity must face nowadays is Climate Change. Climate is the average weather at a given point and time of the year over a long time, more specifically in the scientific field, the reference period is about 30 years. Climate is the result of a balance between the rate at which energy arrives and leaves the Earth. Weather is expected to change a lot from day to day, but the climate instead is expected to remain relatively constant during long observations. If the climate does not remain regular the talk is about the concept of climate change. A significant change can be evaluated on the underlying level of climate variability.

It is fundamental to understand the difference between climate change and climate variability. Change and variability are two different concepts because the former is irreversible. Climate change usually refers to a change in the state of the climate that can be identified by changes in some physical properties in their mean values or a variability persisting for a relevant period, typically decades or longer. Climate change can be caused by natural internal processes or external forcings such as modulations of the solar cycles, volcanic eruptions, and persistent anthropogenic changes in the composition of the atmosphere or land use.

The Framework Convention on Climate Change (UNFCCC), in Article 1, defines climate change as a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods. The UNFCCC thus makes a distinction between climate change attributable to human activities altering the atmospheric composition and climate variability attributable to natural causes. Climate refers to time and space patterns of precipitation, temperature, and wind. Climate change occurs when the patterns change in time and space, some examples can be related to warmer winter months (change in time) or to monsoon rains that occur further south (change in space). Climate changes naturally on a range of timescales, from decadal, centennial, millennial, and long ages. It is evident how climate changes naturally on a range of spatial scales, from local and regional to global scales. It is fundamental to be interested in and aware of climate change because it determines the type and location of human-managed ecosystems, such as agricultural farmlands. Climate affects the weathering of rocks, the kind of soil that forms, and the rate of soil formation. It helps to determine the quantity and quality of water available for human purposes, and also determines the severity of droughts, storms, and floods. Climate also largely determines the nature and locations of biomes that are the major terrestrial ecosystems, defined based on their plant communities.

The amount of CO_2 in the atmosphere is significantly rising as a result of emissions from the burning of fossil fuels, industrial operations, and changes in land use. As a result, there is an increase in extreme weather events, biodiversity loss, acidification of the oceans, and global climate change. In turn, the effects of climate change on lands, forests, oceans, and the cryosphere alter short-term carbon cycles between vegetation and the atmosphere, and sea levels are increasing. This is made worse in some areas by the irresponsible use of natural resources. These feedback loops all pose a direct threat to the health of ecosystems and human societies while also accelerating the climate and biodiversity crises. [1]

1.1.1. Greenhouse effect

Climate change is defined as the shift in climate patterns mainly caused by greenhouse gas emissions. Greenhouse gas emissions cause heat to be trapped by the earth's atmosphere, and this has been the main driving force behind global warming. The main sources of such emissions are natural systems and human activities. Natural systems include forest fires, earthquakes, oceans, permafrost, wetlands, mud volcanoes, and volcanoes, while human activities are predominantly related to energy production, industrial activities, and those related to forestry, land use, and land-use change.

The earth's natural system can be considered self-balancing and anthropogenic emissions add extra pressure to the earth's system. In the atmospheric sciences, the greenhouse effect is a particular phenomenon of temperature regulation of a planet (or satellite) with an atmosphere, which consists of the accumulation within the same atmosphere of a part of the thermal energy coming from the star around which the celestial body orbits, due to the presence of certain gases in the atmosphere, called "greenhouse gases". These gases allow the input of solar radiation from the star (the Sun) while obstructing the exit of infrared radiation re-emitted from the surface of the celestial body. This leads on one hand to an increase in the temperature of the celestial body involved in the phenomenon and on the other hand to less intense thermal excursions than would occur in the absence of the greenhouse effect, as the absorbed heat is released more slowly outwards. The term "greenhouse effect" derives from the incorrect analogy with what happens in greenhouses for cultivation: in this case the increase in temperature is due to the absence of convection and not to the entrapment of the radiant energy. The greenhouse effect, understood as a natural phenomenon, is essential for the presence and development of life on Earth. On the contrary, the increase in the greenhouse effect causes variation in the normal thermal balance of the planet and can lead over the years to a significant change from the climatic and environmental points of view.

The interference of greenhouse gases with the dissipation of infrared terrestrial radiation involves the accumulation of thermal energy in the atmosphere and the increase in surface temperature until a point of thermal-radiative equilibrium between incoming solar radiation and outgoing infrared radiation. The greenhouse effect is the ability of the atmosphere to retain heat: it is not a unique phenomenon, but it brings together all those phenomena (local or global, short or long-lasting) that change the atmospheric content of water vapour, CO_2, and methane. A more humid atmosphere, with a higher water vapour content, retains more heat than a less humid atmosphere; an atmosphere containing more CO_2 or methane retains more heat than an atmosphere with less content of these gases.

The Earth's surface is heated using the energy from the Sun in 2 ways:

• 1/3 due to the direct absorption of the energy from the Sun;

• 2/3 due to the contact with the atmosphere that, thanks to the greenhouse effect, remains warm by retaining the "solar" energy re-generated from the Earth's surface in the form of infrared radiation (the atmosphere is not heated directly by the sun's rays but by the earth's surface when it absorbs the sun's rays).

Analyzing the Sun-Earth energy balance, part of the energy from the Sun (25+25+5= 55%) is immediately absorbed and reflected by the clouds and aerosols present in the atmosphere, while the remaining part (45%) reaches the Earth's surface and is absorbed by the Earth (by the seas, rocks, soils, vegetation). The Earth resends the absorbed energy in the form of infrared radiation and part of it (29+12+4= 35%) escapes the atmosphere by being radiated into space, a part of it (about 65%) is imprisoned and retained by the atmosphere which for this reason warms (especially in the layers closest to the Earth's surface). An increase or decrease in the greenhouse effect is referred precisely to as the increase or decrease in the ability to retain heat from the atmosphere due to a change in the concentration of greenhouse gases: if the atmosphere can retain more heat there will be an increase in the internal temperature of the planet if the atmosphere can retain less heat there will be a decrease in temperature.

Not all gases in the atmosphere have a greenhouse capacity (a capacity to retain heat) and the discussion on the greater or lesser influence of the various greenhouse gases is still open, the most important (Green House Gases) GHGs are:

Water vapour: represents about 70% of the greenhouse effect. It can be found quickly and equally quickly can be discarded from the atmosphere. It is important for daily and seasonal cycles. In general, the increase in air humidity increases the greenhouse effect while the formation of clouds intervenes to decrease the greenhouse effect by counteracting direct insolation and causing humidity loss in the atmosphere through rains.

Carbon dioxide and Methane: together represent 25% of the greenhouse effect. These gases remain in the atmosphere much more than water vapour and are important for regulating seasonal and ten-year cycles. These gases can retain heat on Earth by reflecting certain wavelengths and as happens with water vapour, they are continuously exchanged between the atmosphere, land, and seas (through evaporation, rain, plant respiration, and volcanic eruptions) resulting in variations both daily and seasonal in the atmosphere content of both CO_2 and methane.

Other gases together represent the remaining 5% of the greenhouse effect. These include **nitrous oxide** (N_2O), **chlorofluorocarbons** (CFC), and **sulfur hexafluoride** (SF_6).

1.1.2. Greenhouse gases emissions

The greenhouse gases widely discussed in the literature and defined by the Kyoto protocol are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and fluorinated gases such as hydrofluorocarbons (HFCs), perfluorocarbons 4 (PFCs) and sulphur hexafluoride (SF_6). According to the emissions gap report prepared by the United Nations Environment Programme (UNEP) in 2019, total greenhouse gas emissions in 2018 amounted to 5,.3 $GtCO_2$-eq, of which 37,5 $GtCO_2$ are attributed to fossil CO_2 emissions from energy production and industrial activities. An increase of 2% in 2018 is noted, as compared to an annual increase of 1,5% over the past decade for both total global greenhouse gas and fossil CO_2 emissions. The rise of fossil CO_2 emissions in 2018 is mainly driven by higher energy demand. Furthermore, emissions related to land-use change amounted to 3,5 $GtCO_2$ in 2018 [2]. Together in 2018, fossil-based and land-use-related CO_2 emissions accounted for approximately 74% of the total global greenhouse gas emissions. Methane (CH_4) had an emission rate increase of 1,7% in 2018 as compared to an annual increase of 1,3% over the past decade. Nitrous oxide (N_2O) emissions, which are mainly influenced by agricultural and industrial activities, saw an increase of 0,8% in 2018 as compared to a 1% annual increase over the past decade. A significant increase was, however, noted in the fluorinated gases during 2018 at 6,1% as compared to a 4,6% annual increase over the past decade [2]. Total anthropogenic GHG emissions have continued to increase from 1970 to 2010 with larger absolute increases between 2000 and 2010 (Figure 1), despite a growing number of climate change mitigation policies. Anthropogenic GHG emissions in 2010 reached 49 ± 4,5 $GtCO_2$-eq/yr [3].

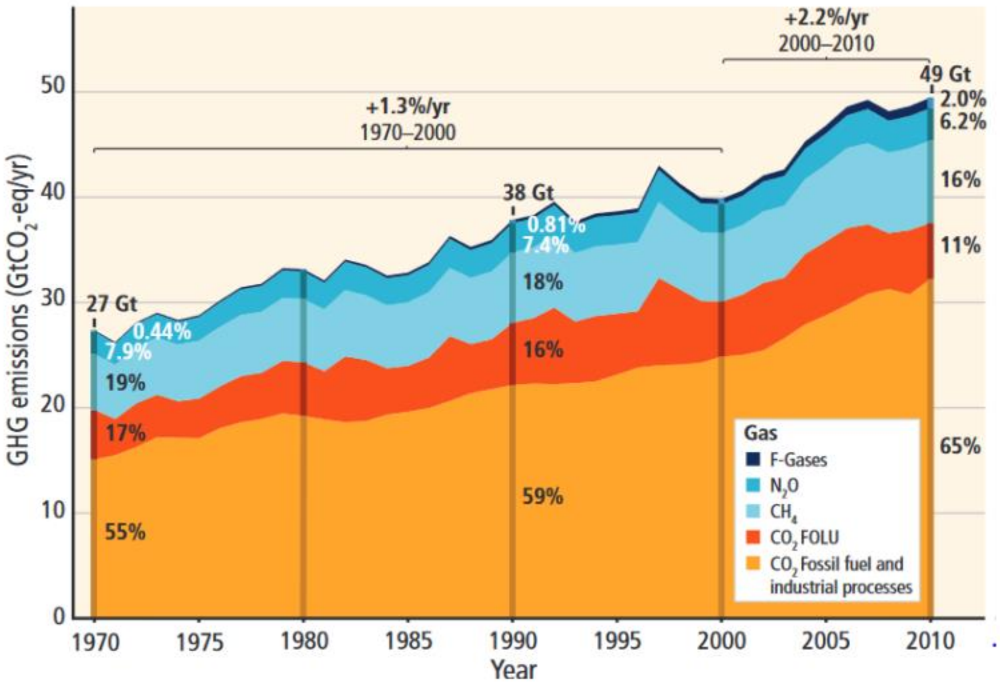


Figure 1: Total annual anthropogenic greenhouse gas (GHG) emissions (Gigatonne of CO_2-equivalent per year, Gt CO_2-eq/yr) for the period 1970 to 2010: CO_2 from fossil fuel combustion and industrial processes; CO_2 from forestry and other land use (FOLU); Methane (CH_4); Nitrous Oxide (N_2O); fluorinated gases covered under the Kyoto Protocol (f-gases). Source: IPCC [3].

To put these numbers into perspective, a recent Intergovernmental Panel on Climate Change (IPCC) report demonstrated that anthropogenic activities so far have caused an estimated 1.0 °C of global warming above the pre-industrial level, specifying a likely range between 0.8 and 1.2 °C. It is stated that global warming is likely to reach 1.5 °C between 2030 and 2052 if the current emission rates persist [4].

1.1.3. Policies addressing climate change

By 2050, carbon dioxide (CO_2) and other greenhouse gas emissions must have decreased by half in order to keep global warming below 2 °C, according to the Intergovernmental Panel on Climate Change (IPCC) (compared with 1990 levels). By 2050, developed nations will need to reduce emissions by 80% to 95% more; advanced developing nations with high emissions, such as China, India, and Brazil, will need to restrain their emission increase.

The Kyoto Protocol, adopted by the UNFCCC in 1997, is a first step towards attaining more significant global carbon reductions. It establishes binding carbon targets for ratified industrialized nations, such as the EU Member States, and caps the growth of emissions in the remaining nations during the first commitment period, which runs from 2008 to 2012. The collective emission reduction goal of the 15 pre-2004 EU Member States (the EU-15) is 8% below 1990 levels. Some EU Member States are allowed to increase their emissions through the internal "burden-sharing agreement," while others are required to decrease them. Most EU members who joined after May 1, 2004, have goals of between -6% and -8% from their base years (mostly 1990).

The emissions from the EU account for 10% of all emissions worldwide. Despite contributing significantly to global GHG emissions, the United States has not signed the treaty. There are no legally binding emission objectives under the agreement for China and a number of other nations with significant GHG emissions. Countries are anticipated to reach their goal mostly through internal policies and initiatives. By funding emission-reduction initiatives in developed or developing nations (Joint Implementation or the Clean Development Mechanism), they may be able to partially achieve their emission reduction goals. The CDM aims to aid in sustainable development by funding initiatives involving renewable energy. The UN Climate Conference in Mexico (December 2010) resulted in the adoption of the Cancun Agreements, which include a comprehensive financial, technological, and capacity-building support package to assist developing countries in adapting to climate change and pursuing sustainable paths to low-emission economies. A timeline for evaluating the goal of limiting the average global temperature rise to 2 °C is also included in the agreements. By 2020, wealthy countries will generate $100 billion USD in climate assistance for developing nations yearly, according to the agreements, which also establish a Green Climate Fund through which a large portion of the funds will be channelled. [5]

1.1.4. EU-Emission Trading System

The EU emissions trading system (EU ETS) is a cornerstone of the EU's policy to combat climate change and it is a key tool for reducing greenhouse gas emissions. It is the world's first major carbon market and remains the biggest one. The EU ETS operates in all EU countries, Iceland, Liechtenstein, and Norway. It limits emissions from more than 11,000 heavy energy-using installations (power stations and industrial plants) and airlines operating between these countries, covering around 40% of the EU's greenhouse gas emissions.

The ETS has proven to be an effective tool in driving emissions reductions cost-effectively. Emissions from installations covered by the ETS declined by about 35% between 2005 and 2019. The introduction of the Market Stability Reserve in 2019 has led to a higher and more robust carbon price, which helped to ensure a year-on-year total emissions reduction of 9% in

2019, with a reduction of 14,9% in electricity and heat production and a 1,9% reduction in the industry. Under the European Green Deal, the Commission presented in September 2020 an impact-assessed plan to increase the EU's greenhouse gas emission reduction target to at least 55% by 2030. All Parties to the Paris Agreement were invited to communicate, by 2020, their mid-century, long-term low greenhouse gas emission development strategies.

The European Parliament endorsed the net-zero greenhouse gas emissions objective in its resolution on climate change in March 2019 and its resolution on the European Green Deal in January 2020. The European Council endorsed in December 2019 the objective of making the EU climate-neutral by 2050, in line with the Paris Agreement. The EU submitted its long-term strategy to the United Nations Framework Convention on Climate Change (UNFCCC) in March 2020. To achieve a climate-neutral EU by 2050 and the intermediate target of at least 55% net reduction in greenhouse gas emissions by 2030, the Commission is proposing to revise and possibly expand the scope of the EU ETS. The Commission has published an inception impact assessment and launched an open public consultation on the revision of the system. Therefore, Member States were required to submit their first national long-term strategies to the Commission by 1 January 2020. The next strategies are due by 1st January 2029 and every 10 years thereafter. Member States should, where necessary, update their strategies every five years. The EU ETS works on the **'cap and trade' principle**. A cap is set on the total amount of certain greenhouse gases that can be emitted by installations covered by the system. The cap is reduced over time so that total emissions fall. Within the cap, companies receive or buy emission allowances, which they can trade with one another as needed. They can also buy limited amounts of international credits from emission-saving projects around the world. The limit on the total number of allowances available ensures that they have a value. Every year a company must surrender enough allowances to cover all its emissions, otherwise heavy fines are imposed. If a company reduces its emissions, it can keep the spare allowances to cover its future needs or else sell them to another company that is short of allowances. Trading brings flexibility that ensures emissions are cut where it costs the least to do so. A robust carbon price also promotes investment in clean, low-carbon technologies.

1.2. Relation between climate change and agriculture

The processes of climate change and agriculture are interconnected; their interdependence is particularly significant when the gap between the global population and food production widens [6]. Due to decreased water supply in areas that most need irrigation and increased water demand, climate change will have a severe negative impact on agriculture [7]. A crucial factor in agricultural production is the climate. The productivity of agriculture, farm incomes, and farm prices are all necessarily impacted by changes in the average levels of precipitation and temperature. On the other hand, numerous studies show that since existing agricultural practices are a large source of GHGs, they exacerbate climate change. By generating carbon dioxide, methane, and nitrous oxide, agriculture directly causes climate change. It also indirectly affects net carbon emissions due to its effects on soil, forests, and other land uses [8]. In order to produce the food and fibre required to sustain human life, agriculture is highly reliant on weather and the environment. It is easy to see why agriculture is considered to be an industry that is susceptible to climate variability and change. It involves natural processes that frequently call for specific ratios of temperature, nutrients, precipitation, and other factors. Agriculture is impacted by climate change in a variety of ways, such as through changes in average temperatures, rainfall, and climate extremes (such as floods, droughts, etc.), changes in pests and diseases, changes in the growing season, changes in the nutritional value of some foods, and changes in sea level [6]. Beyond the effects of mean climate change, an increase in the frequency of climate change extremes may reduce agricultural productivity. The direct damage caused to crops at particular developmental phases by more frequent extreme events, such as floods and droughts, may result in poorer long-term yields. Heavy rains have the potential to cause significant agricultural losses due to soil erosion. Animal mortality and drought have been positively correlated in several studies conducted in Africa [9]. In many places of the world, the effects of a warming planet are already apparent, and they are predicted to worsen over the next few decades. Increased atmospheric temperature will shorten the growth season practically everywhere else but lengthen it in the northern temperate zones [8]. Some summer crops might be grown in the winter in certain Mediterranean regions because the summers are so hot and dry. Due to hot, dry summers, yields in other regions, like south-eastern Europe and western France, are predicted to decline without the option of shifting crop production into the winter. In some circumstances, higher CO_2 levels or warmer weather may speed up crop development or improve yields. However, yields begin to drop at a specific ideal temperature that varies per crop, and crops produced in high CO_2 environments produce less protein, iron, and other nutrients [10]. As temperatures rise, photosynthetic efficiency reaches a maximum and subsequently declines, while the respiration rate rises until a plant reaches its death point. Plants are typically more susceptible to heat stress during specific earlier growth stages (sometimes over very short periods of time) than they are to seasonal average temperatures [7]. Depending on the crop, local mean temperature rises of up to 1-3°C are expected to cause a minor increase in crop productivity at mid to high latitudes, but beyond that, crop output is expected to decline in some areas. Crop productivity is predicted to decline at lower latitudes, particularly in tropical and seasonally dry regions, with even small local temperature rises (1-2°C), which would raise the risk of hunger. In many developing nations, notably in areas of Asia and sub-Saharan Africa, crop yields are predicted to decrease as a result of temperature, precipitation, and severe weather changes. For regions with marginal or previously damaged lands, lower levels of development, and little capacity for adaptation, the impact and consequences of climate change on agriculture are likely to be more severe (Figure 2) [6].

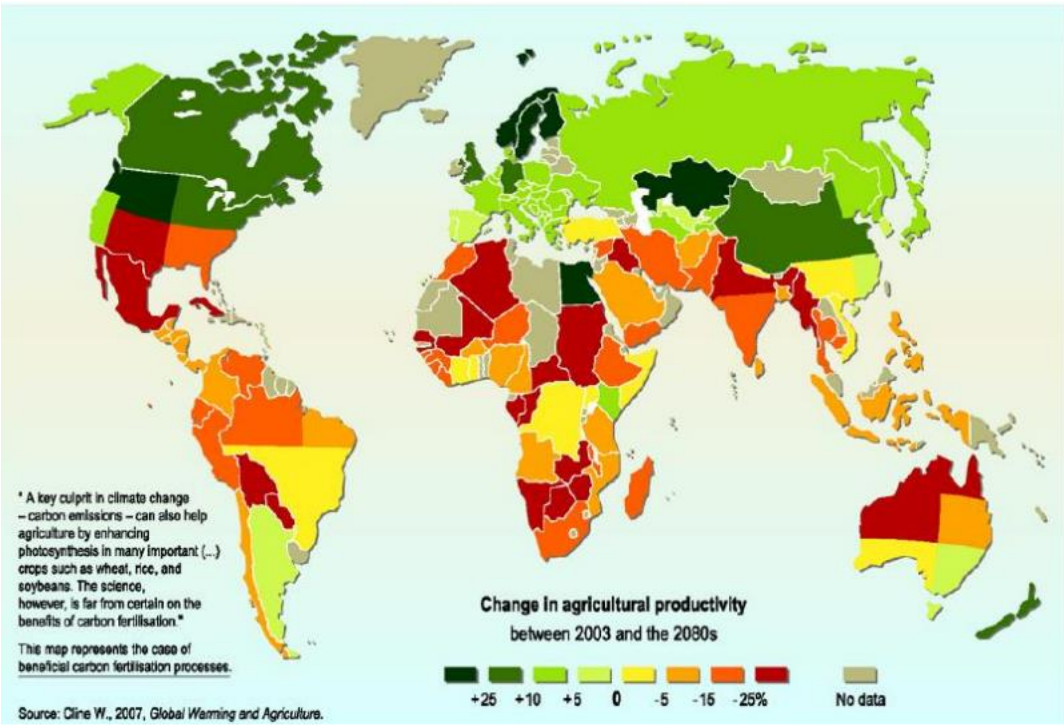


Figure 2: Projected impact of climate change on agricultural yield in different latitudes [11].

According to simulations for sub-Saharan Africa, all emission scenarios predict that nations like Sudan, Nigeria, Somalia, Ethiopia, Zimbabwe, and Chad could lose their ability to produce cereals by 2080 [11].

In addition, increased temperatures promote the growth of pests, weeds, and parasites; extreme weather can harm agriculture, crops, and cattle; and rising sea levels can erode and salinate fields [10]. Insect activity has accelerated this spring in Canada and the US due to recent warming patterns, and certain species, like the mountain pine beetle, have multiplied. With more frequent El Nino events, epidemics of the rift valley fever, which always coincide with El Nino events, may become more common. The health of the continent's people and animals is severely harmed by this [11]. Regarding the rise in sea level, it is expected that agriculture would incur higher expenditures as a result of saltwater intrusion into coastal surface water and groundwater. In order to avoid recharging aquifers with sea water, groundwater abstraction rates may need to be lowered as tidal penetration increases in depth [12].

As was already said, one of the economic sectors most responsible for climate change is agriculture. Emissions from agriculture are both direct and indirect. Fertilized agricultural soils and livestock manure are the primary sources of direct emissions. While indirect emissions are caused by fertilizer runoff and leaching, they are also caused by changes in land use, the use of fossil fuels for transportation, mechanization, and the manufacturing of agrochemicals and fertilizers [7]. Among other resources, the production of agricultural products typically entails the co-use of land, water, pesticides, fertilizers, livestock, and energy. Today, about 40% of the world's land is used for agriculture, a 466% increase in total cultivated land area during the 1700s to the 1980s [13] [14]. This remarkable scientific and technological outcome is largely attributable to the intensification of agricultural land management, which was accomplished by using a variety of high-yield crops, chemical fertilizers and pesticides, irrigation, mechanization, as well as genetic engineering-derived products [14]. Agriculture has an impact on soil resources, wooded lands, biodiversity, and water resources because it consumes 70% of the freshwater used globally and takes up approximately 40% of the planet's geographical area. Agriculture's usage of pesticides, fertilizers, and energy can have an adverse effect on the environment, such as pesticide poisoning of the water supply. In particular, a 6,87-fold increase in nitrogen fertilization, a 3,44-fold increase in phosphorus-based fertilization, a 1,68-fold increase in the amount of irrigated farmland, and a 1,1-fold increase in land under cultivation have all been linked to a 35-year increase in agricultural food production [15]. It has been dubbed the "Green Revolution" in developing nations and has allowed conventional agriculture to be intensified, or "industrial agriculture," since the 1960s. The share is highest in Ireland (31%), Lithuania (23%) and Latvia (22%) and lowest in Malta (2,5%), Luxembourg and the Czech Republic (about 6% each) [16]. N_2O and CH_4 are also produced in considerable quantities by agriculture. These non-carbon GHGs are more durable than CO_2 and have potent greenhouse effects. Methane is mostly produced by animals during digestion, as a result of enteric fermentation, when rice is grown, and when organic fertilizers are managed. The application of fertilizers with organic and mineral nitrogen and the use of energy both directly and indirectly produce nitrous oxide emissions. In terms of possible future scenarios, the IPCC projects that, in the absence of corrective actions, agricultural production of nitrous oxide and methane will rise by 35–60% and 60%, respectively, by 2030.

1.2.1. Common agricultural policy (CAP)

The common agricultural policy (CAP), which was established by the EU in 1962, is a cooperation between agriculture and society as well as between Europe and its farmers. It seeks to:

- Encourage farmers and raise agricultural output to provide a steady supply of reasonably priced food;
- Protect the ability of farmers in the EU to earn a living;
- Assist manage natural resources sustainably and combat climate change;
- Preserve rural regions and landscapes throughout the EU;
- Encourage employment in farming, agri-food industries, and related sectors to maintain the viability of the rural economy.

All EU nations share a common policy called the CAP. It is controlled and financed at the European level using funds from the EU budget.

The CAP has changed over time to take into account the changing needs and demands of citizens as well as shifting economic conditions in order to solidify the position of European agriculture for the future. The European Commission issued legislative recommendations for a revised CAP in June 2018. The ideas highlighted a simpler, more effective course of action that will take the European Green Deal's sustainable goals into account. The new CAP was formally accepted on December 2, 2021, following protracted talks between the European Parliament, the Council of the EU, and the European Commission. The revised CAP is scheduled to go into effect on January 1, 2023.

The environment and climate are directly addressed by three out of ten of the CAP's particular objectives, which encompass biodiversity, natural resource management, and climate change. The CAP's overall aims will include all three aspects of sustainability (environmental, economic and social).

When assessing Member States' draft CAP Strategic Plans against the CAP's specific objectives, the Commission will do so in the light of Green Deal targets for 2030 as set out in the Farm to Fork Strategy and the EU Biodiversity Strategy for 2030. To this end, it will use the recommendations that it issued to each Member State in December 2020.

1.2.2. Climate change mitigation policies in the agricultural sector

The EU's framework for energy and climate policy is essential since it establishes the overall climate ambition and imposes duties on specific economic sectors. The EU's climate mitigation goals have risen in ambition over the past ten years, from a 20% cut from 1990 levels by 2020 (EU 2020 climate and energy package) to a 55% cut by 2030 and economy-wide carbon neutrality by the middle of the century (European Climate Law under the European Green Deal). The relevant laws' purview has also changed concurrently, with implications for climate action in the agriculture and land use sectors.

1.2.3. Agriculture in the EU 2030 climate and energy policy framework

In order to achieve a reduction in emissions of at least 40% across the EU by 2030, the EU 2030 climate and energy policy framework was established in 2018. Agriculture produces and eliminates greenhouse gases, both CO_2 and non-CO_2 (GHGs). The framework's many pillars each address one of these emissions. The Effort Sharing Regulation covers non-CO_2 GHG emissions from agriculture as well as emissions from other industries not included in the EU Emission Trading System (EU ETS) (ESR). Although there is flexibility regarding the possible contribution of various ESR sectors, the ESR sets legally binding targets for Member States. According on the relative wealth of Member States, the 2030 targets range from 0% to 40% reduction compared to 2005, and they are intended to collectively achieve a 30% reduction in emissions in those sectors. The Land Use, Land Use Change, and Forestry (LULUCF) Regulation, on the other hand, covers agricultural CO_2 emissions (or removals) connected to changes in carbon stored in soils and biomass as a result of cropland and grassland management techniques. The Regulation establishes a "no-debit" norm that mandates Member States make sure that in the years 2021 to 2030, accounted emissions (debits) from all land-use categories within the LULUCF sector are fewer than accounted removals (credits). To assist Member States in adhering to the no-debit rule, the legislation includes a number of flexibility features. These include banking credits for future periods, credit transfers between various land use categories and Member States, as well as a compensation mechanism in the managed forest land category that is only available under specific circumstances. While the LULUCF sector does not count toward the 2030 emission reduction target, Member States are allowed to use the LULUCF sink to offset 280 Mt of emissions from their ESR sectors in 2021-2030. This flexibility has been criticized claiming that it disincentivizes the reduction of GHG emissions in the ESR sector.

From a carbon farming point of view, the following observations can be made about the current (2030) EU climate and energy policy framework:

- The ESR and LULUCF Regulation set targets and requirements for Member States and therefore they provide no direct incentives for individual farmers. As such, it does not alone provide sufficient incentives for the reduction of non-CO_2 GHGs from the agriculture sector. Across all effort-sharing sectors, agricultural emissions decreased the least in the period 2005-2018. Agriculture remains the sector where projections foresee only limited changes in emissions in the period up to 2030.
- Existing rules do not prevent the decrease of the EU's carbon sink. Between 2010 and 2019, the LULUCF sink in the EU decreased by 21% from -315 Mt CO_2-eq to -249 Mt CO_2-eq. While this is in part due to the age structure of forests, a Commission impact assessment from 2020 concluded that "left without a revised policy framework, the net removal of CO_2 from the atmosphere by the LULUCF sector in the EU will at best remain stable – or even decrease" [17].

1.2.4. The Fit for 55 package

The European Climate Law, which was adopted in June 2021, boosted the 2030 EU-wide emission reduction target to at least 55% relative to 1990 levels in order to put Europe on a responsible path toward becoming climate neutral by the middle of the century. The LULUCF sector's contribution to this goal is capped at 225 Mt CO_2-eq. In order to reach the higher ambition outlined in the European Climate Law, the European Commission proposed a set of adjustments (the Fit for 55 package) to the current 2030 framework for energy and climate policy in July 2021. The reform of the Effort Sharing and LULUCF Regulations is one of the main components of the Fit for 55 package. Among the most significant modifications are:

- The ambition level in the ESR sectors is proposed to increase from the current 30% to 40% by 2030 (compared to 2005 levels). Flexibilities remain, but with a number of changes that will likely restrict offsetting until 2030, although after this it is then expected to increase again.
- An overall target of 310 Mt CO_2-eq of removals is proposed in the land use and forestry sector for the period from 2026 to 2030, which will be divided between Member States as annual national targets based on the verified emissions and removals from years 2021, 2022 and 2023.

This idea was put up to persuade Member States to expand carbon sinks beyond 225 Mt CO_2-eq, the maximum amount that the LULUCF sector could contribute toward the 55% target. The 2030 net aim will then rise to 57% as a result. With the goal of making the agricultural, forestry, and land use (AFOLU) sector carbon neutral by 2035, an integrated policy framework for AFOLU is suggested starting in 2030. The shift to this integrated framework is anticipated to occur in stages, including:

- 2021-2025: No major changes in the LULUCF regulatory framework;
- 2026-2030: An overall EU removal target of 310Mt CO_2-eq will apply as described above;
- From 2031 onwards the LULUCF sector will include the non-CO_2 GHG emissions from agriculture with the objective of reaching a climate-neutral EU land sector by 2035 at the latest;
- From 2036 onwards the EU land sector will be expected to become net sink.

These removals from the land sector are anticipated to be used to offset any leftover emissions from other sectors that have used up all of their available emission-reduction options or that, for example, have reduced emissions by over 90%. Two other pertinent policy actions should be emphasized in addition to these modifications to the Effort Sharing and LULUCF Regulations: The Commission's Carbon Farming Initiative will support a new economic model that compensates land managers for employing climate-friendly management techniques in the EU farming industry. Although the initiative's precise scope is still unknown, the Commission appears to be concentrating on carbon sequestration and storage (as opposed to non-CO_2 emissions).

To promote reliability and transparency, a new legislative framework for carbon removal certification will spell out specific guidelines for monitoring, confirming, and accounting for carbon removals throughout the EU. The Commission's proposal is anticipated at the end of 2022. If adopted as planned, these modifications could have a number of effects on carbon farming. First and foremost, the introduction of an EU carbon farming strategy that is centered on sequestration and the anticipated target on removals would probably inspire Member States to take action to boost the absorption of CO_2 on agricultural and forest land.

The suggested objective of 310 Mt CO_2-eq, however, is still much below the potential found in current scientific research, which shows that by 2030, the EU LULUCF sector may reach annual reductions of up to 600 Mt CO_2-eq. Second, the EU's climate policy continues to offer only modest incentives for farmers to adopt carbon farming practices that reduce non-CO_2

emissions. Even though there is ample evidence that agricultural GHG emissions may be decreased profitably, this is the case. The planned inclusion of agriculture in the LULUCF sector could further stall efforts to reduce non-CO_2 emissions in the agricultural sector. Thirdly, the upcoming regulatory framework to track and confirm carbon removals in agriculture and forestry will determine the environmental integrity of the EU carbon farming effort.

To overcome these challenges and ensure that carbon farming makes a significant and lasting contribution to the EU's climate mitigation efforts, the following policy recommendations can be made:

- Avoiding and reducing GHG emissions should be the first and main priority of climate mitigation efforts in the land use sectors. This avoidance and reduction of emissions first principle should be reflected in the carbon farming initiative. This requires that non-CO_2 emissions are within the scope of the initiative.
- Setting a quantified GHG emission reduction target for agriculture could help reduce the risk that Member States rely extensively on removals to meet net targets. This is especially important in the context of a combined agriculture and LULUCF sector (AFOLU) foreseen after 2030.
- The development of a robust, transparent, and science-based certification system for carbon removals is essential to ensure the environmental integrity of the EU carbon farming initiative and the wider climate policy regime [17].

1.2.5. Sustainable Carbon Cycles

The European Union has enacted legislation establishing its goal of achieving economy-wide climate neutrality by 2050 in response to the urgency for climate action emphasized in the IPCC's subsequent assessments. According to the European Climate Law, the balance between GHG emissions and removals must be achieved inside the European Union by 2050, to achieve negative emissions after that. In order to endure the inevitable effects of climate change, the European Union has also established the objective that by 2050, it will be climate resilient.

To achieve such ambitious objectives, we must establish sustainable and climate-resilient carbon cycles through three key actions, as shown on figure 3.

First and foremost, our dependency on carbon must be substantially reduced. To do this, suggestions are to increase the efficiency of our businesses, buildings, and transportation systems; cut back on the consumption of raw materials; transition to a circular economy; and increase the use of renewable energy. The European Climate Law firmly establishes the target of achieving climate neutrality by 2050 and the EU's present use of fossil carbon energy must be cut by 95% in order to achieve this goal. Our current energy, environmental, and climate policies are built around this decarbonization approach in order to achieve the 2030 target of a 55% decrease in EU GHG emissions compared to 1990.

Second, in order to replace fossil carbon in the economic sectors that will inevitably continue to be carbon-dependent, we must recycle carbon from waste streams, from sustainable biomass sources, or straight from the atmosphere. This goal can be met through the circular economy and sustainable bioeconomy sectors, which should support technological advancements in carbon capture and utilization (CCU), as well as the creation of sustainable synthetic fuels and other non-fossil-based carbon products.

Third, in accordance with the precautionary and do no significant harm principles, it is necessary to scale up carbon removal strategies that capture CO_2 from the atmosphere and store it for a long time, either in ecosystems through nature protection and carbon farming strategies or in other storage forms through industrial strategies.

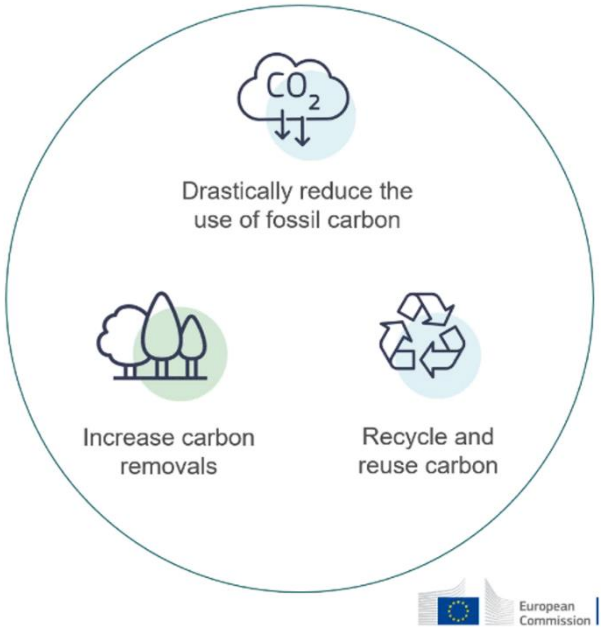


Figure 3: Key actions in the sustainable carbon cycles

To achieve climate neutrality, carbon removal techniques must be developed and widely applied. This will require major targeted funding over the coming ten years. Therefore, the long-term goal of the European Green Deal and accompanying measures is to gradually phase out the usage of fossil fuels. Thanks to cutting-edge technologies, the remaining carbon needed for the operation of our civilization won't be obtained by burning fossil fuels but rather by sustainably harvesting it from our ecosystems and our industries. However, present global climate action is insufficient to keep atmospheric CO_2 concentrations at levels that are consistent with the Paris Agreement's goal. Scientific advice indicates that in order to keep global warming to 1.5°C, this concentration will need to be actively reduced in the future. The restoration of the planet's climate balance, at least in part, by the end of this century is likely to require more than just all major economies achieving climate neutrality by the middle of the century. After climate neutrality is attained and negative emissions are required to stabilize global warming, carbon removals will need to play a larger role and become the main focus of activity. The implementation of existing solutions based on adaptable natural ecosystems and commercial carbon capture and storage (CCS) should be efficient, sustainable, and mindful of their unique qualities. To be recognized as a contribution to EU climate and environmental goals, carbon removal from ecosystems and industrial solutions must meet strict monitoring, reporting, and verification standards. Regardless of where they come from, all carbon removals must be fully transparently reported, taking into account factors like the amount of time the carbon will be stored, the risk that it will reverse, the measurement's uncertainty, and the possibility that the carbon will leak and cause GHG emissions elsewhere. The establishment of long-term carbon cycles in the economies and ecosystems of the EU calls for coordinated action right away. The purpose of this communication is to promote a new industrial value chain for the sustainable capture, recycling, transport, and storage of carbon, with a particular emphasis on the short-term actions to scale up carbon farming as a business model that incentivizes practices on natural ecosystems that increase carbon sequestration. All of these initiatives will help the Union's mitigation efforts by lowering GHG emissions or extracting carbon from the atmosphere, and they will prepare the way for a future policy of negative emissions with significant added advantages for the Union's goal of reversing pollution and biodiversity loss. Creating a regulatory framework for the unambiguous identification of activities that clearly and unequivocally remove carbon from the atmosphere and can lower atmospheric CO_2 concentration is a crucial first step in making this possible. To that end, the EU is developing a framework for the certification of carbon removals, based on strict accounting guidelines, for high-quality sustainable carbon removals from both natural ecosystems and industrial solutions [1].

1.3. Sustainable agriculture

At the EU level, in December 2021 the Commission adopted the Communication on Sustainable Carbon Cycles (COM (2021) 800 Sustainable Carbon Cycles), as announced in the Farm to Fork Strategy, the heart of the European Green Deal to make food systems fair, healthy and environmentally friendly. The Communication defines short- and medium-term actions to address the current challenges of so-called "carbon farming", namely the link between sustainable farming and carbon sequestration resulting in reduced emissions, to improve this green business model that rewards land managers for adopting practices that lead to carbon sequestration, along with strong benefits for biodiversity.

Following the Technical Guidance Manual "Establishing and implementing performance-based carbon sequestration mechanisms in agricultural soils in the EU" [18] published in April 2021, results-based carbon farming can significantly contribute to the EU's efforts to tackle climate change. For its implementation, the development of pilot initiatives at local or regional level is recommended to gather experiences to improve carbon farming.

This will improve the design aspects, in particular the certification of carbon removals, and expand farmers' knowledge and understanding of the potential benefits to them.

Numerous pioneering initiatives in Europe have developed or started to develop schemes addressing greenhouse gas emissions/removals in agriculture. In particular:

- Some projects are purely information/awareness schemes, where farmers are informed but are not required to implement practices (approaches to carbon tools such as Cap2ER or Cool Farm Tool when these are not related to managing payments or results).
- Under the Common Agricultural Policy (CAP), many measures, including the agri-climate-environmental measure, help farmers to change management by providing compensation for additional costs and loss of earnings due to management changes. Farmers are not paid for improvements to a specific performance indicator but are encouraged and/or rewarded for management-focused changes. In some of these schemes, however, attempts have been made to capture mitigation effects more qualitatively, without a clear methodology for monitoring, verification, and reporting.
- Some projects in the EU have also been developed for the voluntary carbon market, where farmers receive carbon credits equivalent to their mitigation impact according to an approved methodology, which can buy private actors and companies wishing to reduce their climate footprint (e.g., MoorFutures, UK Woodland Carbon Code; Carbon AGRI).
- Finally, there are also existing or ongoing initiatives developed by retailers or agribusiness within their supply chain management, according to which farmers in their supply chains are rewarded for changes that help improve climate outcomes (e.g.

SPAR/WWF Healthy Soils for Healthy Food Project). Also taking it a step further, initiatives are pushing the desired food products and ingredients for carbon farming through short supply chains to meet the demand for sustainable, often organic food (e.g. Copenhagen, Milan) for a healthier diet (LIFE Organiko5 project).

Recently, a growing number of private carbon sequestration initiatives in agricultural soils have emerged under which land managers sell carbon credits on voluntary carbon markets (Verified Carbon Standard - VCS, Gold Standard). However, these private initiatives apply very different parameters and standards without a high degree of transparency, environmental integrity, and standardization of methodologies. Voluntary markets have therefore proved to be a valuable tool for launching a carbon sequestration program in agricultural soils, but the effectiveness and long-term price stability require adequate support from public or private sources. In the case of mandatory markets, the demand for carbon credits is generated by policies that impose emission reduction targets with cap-and-trade mechanisms, such as the EU ETS.

Crop simulation models represent an effective tool to analyze the culture-soil-atmosphere system, and as such have found wide use to support the strategic management of crop systems at different scales (e.g., Jones et al., 2003; Soltani and Sinclair; 2012;). They allow evaluating quantitatively the dynamics related to the nutrient balance (N), water, and carbon in response to genetic factors (e.g., species/cultivated variety), environmental (e.g., soil and climate characteristics), and management (e.g., sowing time, fertilization strategy) that characterize the agro-ecosystem investigated. Such assessments can be made in a spatially distributed way by continuous time series, thus allowing a comprehensive analysis of the dynamics at the territorial level [68] [70] [71]. They have been shown to effectively support the analysis of carbon fixation dynamics at the agro-ecosystem level [68] [69] [72], thanks to the explicit simulation of photosynthetic processes (gross assimilation and respiration)sink-source dynamics related to the development of the crop and the allocation of photosynthesis to the different organs of the plant, the processes of senescence and its carbon balance effects of the plant-soil-atmosphere system (Soltani and Sinclair, 2012; Zhou et al., 2021). The assessment of uncertainty in the estimates provided by the simulation models can be assessed by analyzing the correspondence between simulated values and observations for different variables, both related to crop growth and soil dynamics. However, the comparison with data obtained through direct measurements in the field allows the validation of the models, providing more accurate and specific data for the territory in question.

As for carbon absorption measurements, the eddy-covariance system is considered one of the most accurate methods of model validation and allows the overall analysis of carbon dynamics specific to the analyzed ecosystem (Zhou et al., 2021). The assimilation and emission of CO_2 is the balance between photosynthesis and respiration of an agricultural ecosystem (soil and plants) and is an important indicator of the sustainability of the ecosystem itself. Each agricultural system acts differently in terms of exchange of CO_2 equivalent, based on a specific balance between the physiological activities of the crop (photosynthesis, respiration, and soil contribution) and direct and indirect emissions due to the use of inputs in the management of the company (Rossi et al., 2021). While the fixation of stored CO_2 in the biomass of a crop can be easily estimated, carbon exchanges between the crown and atmosphere and carbon in the soil are more difficult to measure, especially on a large scale. The eddy-covariance system is a method of direct estimation in the field that allows estimating the "net ecosystem exchange" (NEE), that is the net exchange of Carbon (C) between the atmosphere and the ecosystem. NEE is a fundamental indicator of the ability of an ecosystem to absorb C. The system allows to deduce the gross primary production (GPP), which is the total amount of CO_2 absorbed by the ecosystem, and the respiration of the ecosystem (ER), that is the CO_2 released by all the metabolic activities of the ecosystem (Di Virgilio et al., 2019); in this way, it is possible to evaluate the ability to store carbon of the ecosystem (t CO_2 ha^{-1} $year^{-1}$) specific for the territory under consideration.

Concerning nitrous oxide (N_2O), the main greenhouse gas emitted in the field as a result of fertilization practices, the use of dynamic incubation chambers positioned on the soil of cultivation allows the direct measurement of emissions, which may also contribute to the validation of simulation models (Cowan et al., 2014). The contribution of the actual emissions of N_2O measured in the field can then be translated into carbon equivalent (CO_2 eq.) and accounted for in the calculation of the net carbon contribution (LCA) specific ecosystem studied and therefore more than ever representative of the regional territory.

1.4. Carbon Sequestration

By extracting excess carbon dioxide from the atmosphere and storing it in soil organic matter and the above-ground biomass of long-lived plants and trees, agriculture can reduce its impact on global warming. This organic component of the carbon cycle offers us a potent weapon for reducing climate change. It can be helpful to analyze it to better comprehend this phenomenon's potential and constraints.

Photosynthesis is the first step in the sequestration of carbon in agriculture. Carbohydrates are produced by plants from carbon dioxide in the atmosphere, water, and sunlight. Only carbon, hydrogen, and oxygen make up the molecules that make up carbohydrates. These consist of cellulose, starches, and sugars. The fundamental sugar molecule in plants is glucose, which has a short chain. A class of compounds known as polysaccharides is composed of extended sugar chains. 75 percent of all organic stuff on the planet, both alive and dead, is made up of polysaccharides; they are all by-products of photosynthesis. Polysaccharides include starch, fibre, and cellulose, which accounts for 40% of all organic matter. As a by-product of photosynthesis, many plants also create hydrocarbons, which are molecules made exclusively of hydrogen and carbon.

On average, 50% of the weight of dehydrated plant material is carbon. The carbon-rich aboveground biomass of the plant eventually decomposes and falls to the ground as leaf litter or other residues. As part of the global carbon cycle, about two thirds of this material is released as carbon dioxide into the atmosphere. The final third turns into long-lasting soil organic matter, which we shall talk about next. In the meantime, 25 to 40 percent of the weight of the aboveground biomass is made up of roots. Even on healthy plants, some root hairs perish each year. Some of the carbon in these roots is also converted into long-lasting soil carbon.

The carbon produced by photosynthesis can also enter the soil more quickly. More than 200 different chemicals, many of which are carbon-rich, are released by plant roots. By feeding soil organisms, which aid in the cycling of nutrients, the control of pests and diseases, and other advantages, these exudates nourish the plants in turn.

Within an hour, the roots absorb between 10 and 40% of all the carbon produced during photosynthesis.

In the soil, photosynthesized carbon is largely deposited. Then, a combination of physical, chemical, and biological processes, including glues from roots, fungi, and bacteria, bind soil carbon into clumpy aggregates. A stable, long-lasting form of carbon is produced when inorganic soil particles are combined with chemical bonds, making it ideal for long-term sequestration. These aggregates resemble humus in most respects. Carbon in the soil can be found up to a metre beneath the surface as well. About half of the total soil organic carbon is often found in these deeper soils, which also secure it for extended periods of time. A rough approximation of the total organic matter can be obtained by multiplying the soil organic carbon, which contains around 58 percent carbon, by 1.7 gives a hint on how 3.67 tonnes of atmospheric carbon dioxide are required to produce one tonne of soil organic carbon, which is half the weight of the organic matter. Typically, 1 percent of organic matter in the soil weights 36.5 tonnes, which equals 21.2 tonnes of carbon. Accordingly, every 1% increase in soil organic matter corresponds to approximately 21 tonnes of carbon stored per hectare [19]. Though it varies by habitat and agricultural techniques, aboveground biomass generally stores around one-third of the carbon in agroforestry systems. The earth stores the residual carbon. Living roots, which make up between 25 and 40 percent of the entire weight of aboveground biomass, include some soil carbon.

1.5. Carbon Farming

Carbon farming is usually referred to as a way to manage farm practices aiming to deliver climate mitigation in agriculture. This involves the management of both land and livestock, all pools of carbon in soils, materials, and vegetation, plus fluxes of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). It includes emissions reductions, carbon sequestration, and its permanent storage in soils and biomass and avoided emissions. Different farming systems can be profitable to provide climate mitigation, although the level of mitigation potential is different depending on farm types and different geographies. Carbon farming has been subject to growing interest in recent years because agriculture is a sector of fundamental importance also contributes to meeting EU climate goals and because agriculture itself needs to adapt to climate impacts. Carbon farming is made up of a variety of agronomic practices that range from land use changes to more technological solutions. Some practices such as cover crops, improved rotations, peatland restoration, or expanding agroforestry systems rely on and work with natural processes in agro-ecosystems.

On one hand, these solutions may bring a decrease in agricultural output because of the reduced intensity of production per hectare or land retirement. On the other hand, they can bring several co-benefits for the environment and the sustainability of agriculture.

Furthermore, with these solutions, it is possible to increase resilience against climate impacts, while contributing to greater stability of yields and benefit the farm business through more efficient use of crop nutrients and livestock feeding regimes, and diversification of crops, some benefits of carbon farming are shown in figure 4.

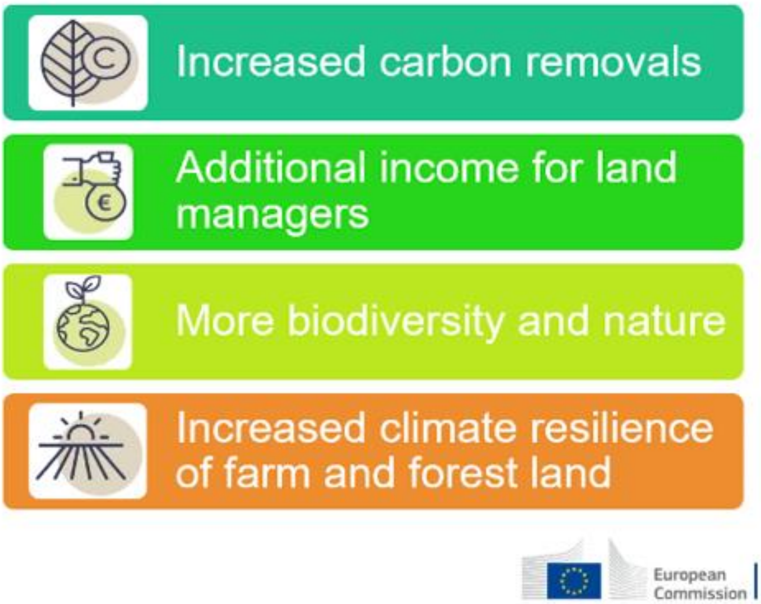


Figure 4: Some benefits of carbon farming

The activity related to Carbon Farming starts with an analysis of the local context, of the selected crops, which for evident reasons are area-dependent, and with the already available data. A baseline is also necessary to assess the feasibility of a Carbon Farming project and to define it there are existing standards and systems, at the international and European levels, to be analyzed along with inventories about emissions/removal of Green House Gases (GHG). Analyses on how Carbon Sequestration in agricultural soils can be coordinated with the ambitious policies of the European Union and national goals in terms of net absorption avoiding double counting issues. Selection of the actions that can bring to a more efficient Carbon Sequestration in agricultural soils and the assessment of the relative impact on the reduction of emissions, on absorption, and the environment, more specifically on biodiversity. Monitoring is key inside the whole process, this is done through indicators such as the production in the specific location, the identification of at least two different techniques for each crop studied, and two alternative managing options for the selected crops.

In order to combat climate change, carbon farming refers to the management of carbon pools, flows, and GHG fluxes at the farm level. This includes managing all carbon pools in soils, materials, and vegetation as well as the fluxes of carbon dioxide (CO_2), methane (CH_4), and nitric oxide (N_2O), which the Intergovernmental Panel on Climate Change (IPCC) has identified as some of the relevant fluxes of GHGs in the agricultural sector and is therefore regarded as a component of carbon farming. After the Kyoto Protocol (KP) entered into force in 2004, the land management concepts of carbon farming and carbon forestry initially attracted attention on a global scale.

Many nations and organisations, like New Zealand and the Verified Carbon Scheme (VCS), began experimenting with and researching market-based programmes that offered land managers incentives for managing terrestrial carbon at the farm or parcel level. Since the Paris Agreement and the acknowledgement of nature-based solutions as a crucial component of reaching climate neutrality by 2050 at the latest, the corporate sector's interest has risen. Despite this, no national or international compliance programme has awarded credits for the mitigating results of actions taken in the Land Use, Land Use Change, and Forestry (LULUCF) sector.

The 2019 European Green Deal altered the situation in the EU. To promote the essential transformational shift approaching 2050, the land-based industry requires more and better incentives for controlling carbon, according to the Farm to Fork Strategy, the Circular Economy Package, and the Fit for 55% Package. Along with a strong and transparent governance system that establishes uniform and clear norms for monitoring, reporting, and verification (MRV), improving land managers' awareness and usage of carbon farming will be a crucial enabling factor. For publication in 2023, the EC will create a legislative framework to track and confirm the legitimacy of carbon reductions in agriculture (and forestry) [20].

1.5.1. Carbon Farming Practices

The possibility of removing carbon from the atmosphere, reducing emissions, and protecting existing carbon stores varies with bioclimatic conditions and is also highly influenced by site characteristics including topography, soil type, and historical and present land use practises [1]. The long-term storage of carbon in agricultural soils is the goal of carbon sequestration (CS) farming practises. These methods have a strong connection to sustainable soil management strategies. The health and fertility of the soil are greatly enhanced by higher soil carbon content, which also improves soil structure, biodiversity, water retention, and nutrient availability. CS approaches include things like:

- **The use of cover crops:** cover crops are crops planted after the harvest of the main crop, to prevent the land to be fallow. They fix additional carbon from the atmosphere by photosynthesis and offer additional biomass to the soil. They protect soils against erosion, can break infections with soil borne diseases, increase infiltration of water, fix nutrients and might increase agrobiodiversity and the overall resilience of agricultural systems.

- **Enriched crop rotation:** When growing a wider diversity of crops and perennial forage crops, a more diverse agroecosystem is created. With increased diversity of soil life, roots and improved soil structure as a consequence. Such soils have a greater ability to store carbon. Introducing fewer intensive crops, such as cereals and grass and clover species, in the crop rotation, increases the carbon content in the soil through the extensive rooting system.
- **Agroforestry:** Agroforestry is the practice of introducing trees in agricultural systems. This can be in grasslands, but also on arable fields. Trees fix CO_2 from the atmosphere in stems, leaves and their extensive rooting system. Especially roots will increase the soil carbon content also in deeper soil layers.
- **Reduction of soil tillage:** Tillage is normally used to loosen and aerate the soil and to remove initial weeds. However, tillage often has a negative impact on soil life, soil structure and erosion. Additionally, it increases C mineralization leading to CO_2 emissions from the soil. Reducing of soil disturbance therefore is a useful tool to protect soil organic matter. Due to the accumulation of carbon in the upper topsoil layer with shallow cultivation in reduced or no-tillage systems the additional net CS effect is doubtful.
- **Fertilisers rich in organic carbon:** Fertilisers such as compost and solid and green manure with wide C/N ratios will have a slow carbon turnover compared to other materials. They should be part of the farming system. As all organic fertilisers today are traditionally used in agriculture their transfer from one place to another prohibits their use and CS at the place of export. Organic fertilisers therefore should be additionally produced on farms to really improve CS.
- **Permanent grassland:** Below grassland, organic matter is building up. When grassland is renovated (and therefore ploughed), the soil get in contact with more air and the organic matter mineralizes. Also, enrichment of swards with legumes and controlled grazing might increase CS there.

1.5.2. Carbon farming business model

Carbon farming can be considered as a green business model which rewards landowners for implementing better land management techniques that increase carbon sequestration in living biomass, dead organic matter, and soils by improving carbon capture and/or lowering carbon emissions, in accordance with ecological principles that are good for biodiversity and the natural capital as a whole. Public or private sources of funding may be used to provide financial incentives to land managers who increase atmospheric carbon storage through their management methods or who actually sequester more carbon.

Private carbon farming programmes have grown in popularity recently, where the landowners sell carbon credits on voluntary carbon markets. Carbon farming has enormous potential, and the time is opportune to increase the supply of high-quality goods at the EU level. To maximise this potential, obstacles that would prohibit a large-scale launch must be removed, and sufficient compensation for the carbon credits produced must be guaranteed.

On the supply side, land managers should be able to sell carbon farming credits alongside their standard goods like food and biomass as an additional "product." On the demand side, enterprises operating in the bioeconomy, including food processing businesses, who wish to lower the carbon footprint in their own value chains, might be the buyers of these credits. This is especially important since food with a low carbon footprint can have a recognised additional value that can give land managers using carbon farming techniques a competitive advantage. Companies and people who want to contribute financially to further climate action on the land and to offset their own unavoidable emissions may also be potential buyers of carbon farming credits.

Land managers would have a new source of income from carbon farming, and they would frequently also profit from the advantages of more resilient and productive soil in general. Additionally, carbon farming techniques frequently boost ecosystem services, promote biodiversity, and aid in making land management more climate-change adaptable.

However, it is essential to make sure that credits produced by carbon farming do not conflict with other mitigation strategies and are linked to a long-term value in terms of GHG emission reduction. This needs to be made very clear: in order for the EU to achieve climate neutrality, efforts must be directed at lowering GHG emissions. In circumstances where further GHG emission reduction is no longer feasible at tolerable socioeconomic costs, carbon farming credits can supplement existing efforts and assist address the issue while still allowing for further climate action through carbon sequestration. For their value chains, a number of food and biomass industries have established climate neutrality goals. This is where carbon farming transforms into a very helpful instrument to support the EU's goals of achieving climate neutrality and preventing the loss of biodiversity [1].

1.6. Carbon Credits

A carbon credit (also referred to as a carbon offset) represents either greenhouse gases (GHG) removed from the atmosphere or greenhouse gas emissions reduced. Credits are produced using rigorous, accurate, and full accounting procedures. Without the incentive offered by the carbon market, the credit does not result in GHG reductions.

Not all projects can generate carbon credits. It is therefore essential a preliminary verification of the project, which can allow the designer to understand if and how many carbon credits could be generated. Once it has been established that the project is eligible, moreover, to generate and sell carbon credits it is not enough to carry it out, but it is necessary to obtain the certification of the credits generated by an independent and recognized certifying body. The designer must therefore follow a predefined methodological process that requires different activities to be carried out during all phases of the project (before, during and after the implementation), aimed at certifying that the environmental impact of the same is real, additional, measurable and verifiable. Once the certification is obtained, the designer must undertake to maintain it over time through a series of monitoring activities to be carried out periodically to ensure the continuity of the impact generated.

1.6.1. Kyoto Flexible Mechanisms: CDM and JI

Countries that have pledged under the Kyoto Protocol to restrict or reduce their emissions of greenhouse gases must achieve their goals primarily through national initiatives. The Kyoto Protocol introduced three market-based mechanisms as an additional means of achieving these goals, resulting in the development of the “carbon market”, one of those is the ETS (emission trading System) which is a compliance carbon market, and the remaining two are the Clean Development Mechanism (CDM) and Joint Implementation (JI), that are voluntary carbon markets.

Two project-based flexibility mechanisms are the Clean Development Mechanism (CDM) and Joint Implementation (JI) of the Kyoto Protocol. These techniques are founded on the idea that cutting greenhouse gas emissions benefits the climate equally everywhere they are cut, no matter the region or geographical area. By implementing greenhouse gas reduction or removal projects in non-Annex I Parties, nations having emission reduction targets under the Kyoto Protocol (Annex I Parties) can produce Certified Emission Reductions (CERs). The JI allows Annex I Parties to carry out projects to produce Emission Reduction Units on the territory of other Annex I Parties (ERUs). CERs and ERUs can be utilized by Annex I Parties to reach their Kyoto targets, just like all other Kyoto units. They can also be traded on international carbon markets under the third flexibility mechanism: international emissions trading. The mechanism stimulates sustainable development and emission reductions, while giving industrialized countries some flexibility in how they meet their emission reduction or limitation targets.

1.6.2. Carbon Markets

Carbon markets exist under both mandatory (compliance) schemes and voluntary programs.

Compliance markets are created and regulated by mandatory national, regional, or international carbon reduction regimes. Compliance carbon markets are marketplaces through which a certain number of carbon credits are issued per company and per year. These are non-voluntary, and companies must fulfill them. In the case of cap-and-trade (or Emissions Trading Systems - ETS) programs, regulators set a limit on carbon emissions - the "cap", which slowly decreases over time. Then, participants - often including both emitters and financial intermediaries - are allowed to "trade" allowances to make a profit from unused ones or to meet regulatory requirements. The most active compliance carbon offset program is the United Nations Clean Development Mechanism (CDM) that was born from the Kyoto Protocol. But other well-known ones are the cap-and-trade systems from California, Canada, the UK, China, New Zealand, Japan, and South Korea, with many more countries and states considering implementation.

Voluntary markets function outside of compliance markets and enable companies and individuals to purchase carbon offsets on a voluntary basis with no intended use for compliance purposes. In order to be generated and sold, Carbon Credits must be certified by an independent third party. The most used certification bodies within the Voluntary Carbon Credit Market are the Gold Standard for the Global Goals (from the Gold Standard Foundation) and the Verified Carbon Standard or VCS (from Verra), but there are many more. In any case, all standards refer to the eligibility requirements for Carbon Credits defined by the Clean Development Mechanism (CDM) introduced by the Kyoto Protocol. According to these requirements, Carbon Credits must:

1. Be real: the emission reductions must have actually happened. There must be a reduction in the emissions underlying each carbon compensation that corresponds to the result of the implemented project.
2. Be additional: the income from the sale of carbon credits is a determining factor in the realization of the project. The survival of the project depends to some extent on the ability of the project developer to sell these carbon credits. In other words, this implies

that the project could not have emerged had it not been financially supported by a compensation scheme.

3. Be measurable and verifiable: emission reductions can be calculated with scientific rigour and monitored and verified. For this purpose, calculation and monitoring methodologies appropriate to the context and technology concerned shall be available.
4. Be permanent: emissions that have been reduced or avoided must last over time and must not be returned to the atmosphere by the project in question at a later date
5. Be unique: each carbon credit must correspond to a single t of CO_2-eq. This also means that procedures must be put in place to avoid double counting.

Today, almost all projects that sell Carbon Credits are certified through a recognized carbon certification standard, which issues Credits that meet these requirements. However, there are still many organizations that, due to the lack of knowledge of these dynamics or economic assessments, prefer not to buy certified Carbon Credits. Instead, they rely on realities that offer them the opportunity to communicate CO_2 Compensation, or even Carbon Neutrality, through tools that have nothing to do with Carbon Credits.

1.6.3. Carbon credits in agriculture

Carbon credits in agriculture require practice changes that limit farm emissions or store carbon in the fields or both. In the case of farming, carbon credits are created based on carbon dioxide drawn down into the soil and GHG emissions reduced above the soil beyond what was already happening on the field. Carbon credits measure and track the quantity of additional carbon sequestered in the soil and GHG emissions reduced. A carbon credit ought to be legitimate, additional, and long-lasting in addition to being independently validated and being only claimed. Net soil carbon pool changes permanently as a result of the project's adjustments to the carbon stock. Considering the practice of carbon farming, farms that effectively store carbon in their soil create verified credits, each of which is equal to one metric tonne of carbon. Organizations buy these credits to make up for emissions generated by their operations. It is important to note that companies must strive to reduce emissions as much as feasible and only buy credits for emissions that cannot be avoided.

As already mentioned, carbon credits generated from carbon farming are only sold on the voluntary market and are called Verified Emission Reductions (VER) and also referred to as Voluntary Carbon Credits. The Clean Development Mechanism (CDM) requires the application of a baseline and monitoring methodology in order to determine the amount of Certified Emission Reductions (CERs) generated by a mitigation CDM project activity in a host country. Methodologies are classified into five categories, carbon farming practices may fall into the category of "Methodologies for Afforestation and Reforestation CDM project activities". Nowadays these methodologies are used to account for CERs generation in the voluntary market.

The voluntary market has grown to be crucial for projects in forestry and agriculture. The private sector is the primary purchaser of voluntary carbon credits (VER). The most typical reasons for purchasing carbon credits are corporate social responsibility (CSR) and public relations [67]. Other factors include certification, reputation, and advantages for the environment and society. Some businesses allow customers to offset their carbon emissions. The private sector has some options for acquiring carbon credits: directly from initiatives, businesses, or carbon funds. In these markets, the backstory of the credits is quite important. Since AFOLU initiatives deal with people's livelihoods and the preservation of significant ecosystems, these benefits are typically highly valued.

Many commercial organisations looking to reduce their emissions outside of a regulated framework can buy offset credits in voluntary carbon credit markets in the absence of legally obligatory regulations. The markets for these carbon offsets are typically created by private organisations. Standards, practises, and measures therefore differ from one carbon programme to another, in contrast to compliance markets where rules are predetermined.

1.7. Life Cycle Approach

One of the major industrial sectors in the world, the food business consumes a lot of energy. Global warming is arguably the most significant issue that humanity is currently facing. It is caused by greenhouse gas emissions, which have noticeably increased as a result of enormous energy use. Energy is used in great quantities during food production, preservation, and distribution, which adds to overall CO_2 emissions. Additionally, customers in industrialised nations seek safe, high-quality food that has been produced with little harm to the environment. There is a growing understanding that future consumers who care about the environment will select foods based on ethical and ecological considerations. Therefore, it is crucial to assess the effects on the environment and resource usage in food production and distribution networks for sustainable consumption [21]. Products (goods and services) serve important purposes throughout their useful lives while simultaneously adding to resource depletion and other environmental concerns [22]. From raw materials to disposal, a life cycle approach reveals a product or technology's opportunities and risks. There is a continuum of life cycle methodologies available to accomplish this, ranging from qualitative (life cycle thinking) through thorough quantitative approaches (life cycle assessment studies). tools and techniques for the life cycle have been improved, are more widely used in both the public and commercial sectors, and they are already promoting and assisting the shift to a green economy. The life cycle thinking basket contains a variety of strategies, initiatives, and projects that are crucial to a green economy. These were created to support decision-making on product development, production, procurement, and disposal at all levels. They are applicable to all industries and provide the chance to look at a variety of key impact categories and indicators, evaluating the environmental and social impacts (for example, environmental LCA and social LCA, carbon footprint, water footprint, etc.) as well as the ultimate effects of these on all three key sustainability pillars (for example, life cycle sustainability assessment) [23]. In particular, Life Cycle Assessment (LCA), which is expanded upon in the following chapter, is a tool used to estimate the environmental costs associated with a process or product across its entire life cycle.

The scope of the present work is to assess the capacity of annual crops to mitigate climate through carbon farming practices. Using environmental methodologies to calculate its benefits and impacts. This is done through the description of three different methodologies to calculate carbon sequestration potential of the selected crop, corn, comparing the three and choosing one basing on some features, such as completeness and replicability. The impacts will be evaluated using LCA methodologies. The choice of annual crops is due to the fact that most of the crops used for human consumption derive from annual crops [19], and so the hectares covered by this typology of crops is relevant and thus their carbon sequestration potential is significative. Calculating carbon sequestration potential of an annual crop and then performing an LCA study on the same can allow also the calculation of eventual carbon credits generated.

2. METHODOLOGY

The scope of the present work is to assess environmental performances of agriculture, evaluated both in terms of emissions to the atmosphere and of the capacity to mitigate climate change through carbon sequestration, and to estimate the potential carbon credits that can be obtained through a better management of soil and more reliable cultivation techniques for what concerns environmental safeguard. This is done through the use of LCA, to assess environmental impacts of the considered crop, and carbon sequestration potential estimations that will be described.

At first LCA methodology will be presented, it allows for accounting the GWP (Global Warming Potential) and it is applied to the upstream phase (which includes cultivation, energy consumptions etc…) and to the core phase (including transportation, packaging etc…). Then three different methodologies to calculate carbon sequestration potential of the selected cultivation (corn) are introduced and compared. Among these, one methodology will be employed to actually get carbon sequestration values and that will be obtained by varying specific parameters related to the application of eventual carbon farming techniques. Finally, the obtained values of carbon sequestration potential are used to get a net carbon footprint and to estimate potential carbon credits earned through the use of more environmental performing techniques.

Data will be gathered from literature for what concerns carbon sequestration potential, using typical values for corn. Regarding LCA methodology, the necessary data are obtained directly form the company: Conserve Italia.

2.1. Phases of a Life Cycle Assessment

Life cycle assessment (LCA) is a tool to assess potential environmental effects of products, processes, or services over the course of their life cycle. The scope of an LCA analysis takes into account both upstream (such as raw materials) and the actual processing step. Downstream processes (such as product distribution, consumption or use phase, and waste disposal) as well as upstream processes (such as material production, agriculture, livestock, fisheries, aquaculture, and packaging production) include the transport activities required in all stages. Figure 5 depicts the life cycle's repetitive process, from raw material extraction through end of life.

Figure 5:Life Cycle Assessment stages.

The results of the life cycle impact assessment help identify the "hot spots" (i.e., the major life cycle impacts) by quantifying the various environmental consequences using a variety of characterization models, each with its own corresponding unit of measurement stages and actions connected to the most significant impacts). The earliest investigations into the life cycle characteristics of goods and materials come from the late 1960s and early 1970s, and they primarily examined concerns relating to waste disposal, raw material use, and energy efficiency [24]. For instance, the Coca-Cola Company's Midwest Research Institute (MRI) carried out a research in 1969 to compare the environmental discharges and resource use related to beverage containers [25]. The genesis of LCA as we know it today was initiated by a follow-up of this study undertaken by the same institute for the U.S. Environmental Protection Agency in 1974 [26] and a related study carried out in Switzerland [27]. The decades of LCA's conception were from 1970 to 1990, with wildly different methodologies, terminologies, and outcomes. International forums for scholarly discourse and exchange around LCA were clearly lacking. LCAs were carried done in the 1970s and 1980s utilising various techniques and lacking a unified theoretical foundation. The number of workshops, other forums, and guides developed during the 1990s reflects the significant increase in scientific and coordinating activities that occurred on a global scale [28].

The LCA framework, nomenclature, and technique were all defined in 1990 LCA seminars sponsored by the Society of Environmental Toxicology and Chemistry (SETAC) [29]. The International Organization for Standardization (ISO) has participated in LCA since 1994, together with SETAC. The official task of standardising methods and procedures was adopted by ISO, as opposed to SETAC working groups, which concentrated on developing and harmonising methodologies [28].

There are currently two international standards:

- ISO 14040 [30]: ‘Environmental management - Life cycle assessment - Principles and framework’;
- ISO 14044 [31]: ‘Environmental management - Life cycle assessment - Requirements and guidelines’.

While ISO 14044 outlines the requirements and recommendations for conducting an LCA assessment, ISO 14040 analyses the fundamentals and structure for an LCA [32].

The goal and scope definition of the LCA, the life cycle inventory analysis (LCI) phase, the life cycle impact assessment (LCIA) phase, the life cycle interpretation phase, the reporting and critical review of the LCA, the limitations of the LCA, the relationship between the LCA phases, and the conditions for use of value choices and optional elements are all included in ISO 14040's principles and framework for life cycle assessments (Figure 6). Only the first four of the aforementioned concepts really make up the work phases for an LCA research, and they are outlined in the paragraph that follows.

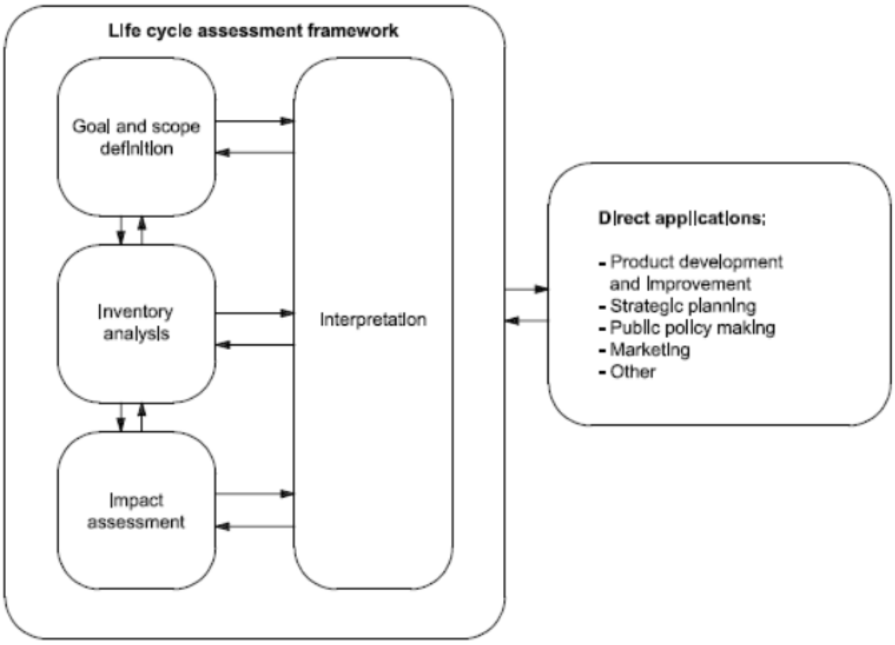


Figure 6: Phases of an LCA.

The "objective and scope definition" phase is aimed to clearly define the application's intention and may be refined during the research. On one hand, the study's objective should specify its intended use, the factors that motivated its inception, the audience that will be interested in its findings, and whether or not the findings are to be compared with other studies. On the other hand, the study's scope should outline the product system that was considered for the study, along with its functions, as well as the system's boundaries, the allocation methods that were used, the impact categories that were picked to be characteristic and representative of the study, the requirements for the quality of the data, and, generally, all the assumptions and decisions that were made for the realization of the study. The "functional unit" must be specified in the study's scope in order to serve as a point of comparison for other systems and LCA studies that use the same functional unit as well as a reference point for normalising input and output data. Data gathering and computation processes that enable quantifying the input and output flows of a product system are part of the "Life Cycle Inventory analysis (LCI)" phase. These entering and outgoing fluxes must take into account all of the energy, raw materials, and supplementary inputs. They may also take into account the system's resource usage and releases into the air, water, and soil. Additionally, information on product, co-product, and waste quantities must be gathered to enable normalisation with the functional unit. Since data can come from calculations as well as actual measurements, it is necessary to conduct a data validity check as part of the data collection process to confirm and show that the data quality requirements for the intended application have been met. Once the allocation technique has been described and explained, the input and output data can be assigned to the various products in accordance with clearly specified procedures. These data allow the study to draw certain interpretations about the objective and the area of application of the LCA study. The evaluation of the life cycle's influence is also supported by these statistics. The "Life Cycle Impact Assessment (LCIA)" phase includes gathering indicator results for the many impact categories, which collectively make up the LCIA profile for the product system and evaluating the environmental performance of the system under analysis. In order to determine which effect categories are the most representative, the impact category selection must be consistent with the purpose and scope specification. Each impact category has a minimum of one characterization model, which allows for the conversion of all data gathered during the LCI phase into clearly defined environmental impacts with their own units of measurement using a set of characterization or emission factors.

The most common impact categories refer to the following environmental impacts:

- the Acidification Potential (AP) – measured in moles of Hydrogen ions equivalents (mol H+ eq.) – consisting in a drop in pH of soils, lakes, forests, due to air 36 emissions of acidifying compounds, with harmful effects on living organisms, e.g. “acid rains”;

- the Ozone Depletion Potential (ODP) - the ratio of the total amount of ozone destroyed by that compound to the amount of the ozone destroyed by the same mass of CFC-11. The ODP of CFC-11 is defined to be 1.0.
- the Global Warming Potential (GWP) – measured in carbon dioxide equivalents (CO_2 eq.) – consisting in a change in the greenhouse effect, usually calculated for 100 years, due to emissions and absorptions attributable to humans, such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and other greenhouse gases;
- the Eutrophication Potential (EP) – measured in kilograms of phosphorous equivalents (kg P-eq) – consisting in a reduction in dissolved oxygen levels in water media with collapse of fish and other aquatic species due to excess addition of large quantities of mineral nutrients such as nitrogen and phosphorous and subsequent dramatic increase in flora that feed on these nutrients;
- the Photochemical Ozone Creation Potential (POCP) – generally measured in ethylene equivalents (C2H4 eq.) or in Non-methane volatile organic compound equivalents (NMVOC eq.) – consisting in the formation of ozone at ground level due to air emissions of unburnt hydrocarbons and nitrogen oxides in presence of solar radiation. This phenomenon is harmful for living organisms and often present in large urban centres. Other possible impact categories or indicators useful for the food sector may be:
- the Land Use – measured in square metres per year (m2 a) – consisting in an impact on biodiversity. Biodiversity depends on the type of use of soil and dimensions of area. In this impact category both regional and local impacts are taken into consideration and the damage related to land use results from both conversion and occupation of soil;
- the Abiotic Depletion Potential – measured in antimony equivalents (Sb eq.) for elements or in terms of energy (MJ, net calorific value) for fossil fuels – consisting in depletion of non-renewable resources, such as fossil fuels, metals and minerals;
- generic indicators on the water use and consumption being Water Scarcity Indicator (WSI) (e.g. Boulay 2017) or Water Footprint indicator in accordance to the ISO 14046 standard [33];
- indicators on the waste production;
- indicators on the use of resources.

The "Life cycle interpretation" phase, which follows the previous stages, consists of identifying the important concerns based on the findings of the LCI and LCIA phases, continuously evaluating the accuracy and consistency of the data gathered, and on the sensitivity of the final results in light of the data's probable uncertainties as well as the study's conclusions, restrictions, and recommendations [34].

2.1.1. Functional unit

A functional unit measures how well the product system's functional outputs perform. A functional unit's main goal is to act as a point of reference for the inputs and outputs. To ensure that LCA findings can be compared, this reference is required. When different systems are being evaluated, the comparability of LCA results is especially important to guarantee that these comparisons are performed on an equal footing [34].

2.1.2. System boundary

In relation to the functional unit, all processes connected to the product supply chain are included inside the system boundaries. As a default strategy, all attributional processes from Cradle to Grave are included. Foreground processes and background processes are two categories of system boundaries. Core operations that have direct access to information are considered to be in the foreground. Additionally, the life cycle of products can be divided into upstream processes (from cradle to gate), core processes (from gate to gate), and downstream processes (from gate-to-grave). It is necessary to incorporate all fundamental resource extraction flows.

For products of agriculture, the following attributional processes are usually part of the product system and classified as upstream processes:

- Production of seeds, cuttings or plants for the cultivation;
- Production of fertilizers used in the agriculture;
- Production of auxiliary products used such as detergents for cleaning, etc.
- Production of semi-products used in the core process, if applicable;
- Production of primary and secondary packaging;

The following attributional processes are part of the product system and classified as core processes:

- External transportation to the core processes;

- Agriculture including e.g. operations at the farm(s), emissions of nitrous gases. The cradle for the agriculture is soil preparation and cultivation;
- Maintenance (e.g. of the machines)
- Preparation of the final product;
- Waste treatment of waste generated during manufacturing
- Usually, the technical system do not include:
- Manufacturing of production equipment, buildings and other capital goods;
- Business travel of personnel;
- Travel to and from work by personnel;
- Research and development activities;

The following attributional processes can be part of the product system and classified as downstream processes:

- Transportation of the product to an average customer or consumer;
- Customer or consumer use of the product;
- End-of-life processes of any wasted part of the product (e.g. peel of oranges);
- End-of-life processes of packaging waste;

For live animals and animal products, the following additional attributional processes should be part of the product system and classified as upstream processes:

- Feed production, e.g. cultivation, harvest and refining;
- Animal breeding (including enteric fermentation) (e.g. mammals, poultry rearing, laying hen farming);
- Farm management;
- Slaughterhouse activities;
- Production of the product, e.g. milking of cows;
- Preparation of the final product (e.g. slaughter activities, meat processing, packaging of the final product);
- Manure management;
- Wastewater treatment generated during slaughterhouse process;

For fish and other fishing products, the system boundaries should include the following additional processes:

- Preparation before catching in ocean;

- Production of fish feed;
- The fishery, farming or catching in the ocean.
- This includes e.g. air and water emissions and emissions from energy wares used in the fishery;
- Fish processing near the coast;
- Maintenance of the ships; Boundaries to nature are defined as flows of material and energy resources from nature into the system.
- Emissions to air, water and soil cross the system boundary when they are emitted from or leaving the product system [34].

2.1.3. SimaPro software

For 25 years, SimaPro has been the top life cycle assessment software programme in the world. It is created by Prè Consultant [35], a Dutch company that has dedicated itself to developing a software suitable for analysing the contribution that elements, materials, and processes give environmental impact assessed in many respects. Prè Consultant has been interested in this type of study since the early 1990s. Currently, SimaPro is utilized in more than 80 nations throughout the world, particularly by major corporations, consulting firms, and academic institutions to undertake precise evaluations of the efficacy and effectiveness of various goods, processes, and services. SimaPro enables to [36]:

- Easily model and analyze complex life cycles in a systematic and transparent way;
- Measure the environmental impact of your products and services across all life cycle stages;
- Identify the hotspots in all aspects of your supply chain, from extraction of raw materials to manufacturing, distribution, use, and disposal.

SimaPro is utilized for a range of applications, including calculating the carbon footprint, water footprint, product design and eco-design (DfE), environmental product declarations (EPD), and key performance indicators. SimaPro is completely connected with multiple databases and impact assessments (KPIs). Here is a list of all the key characteristics [36]:

- Flexible and easy to use;

- Multi-user version – your entire team can work in a single database simultaneously, even when working from different locations around the world;
- Multiple impact assessment methods available;
- Large amount of data included;
- Highly transparent results – interactive results analysis can track any result back to its origins;
- Easily connected to other tools with COM interface;
- Intuitive user interface following ISO 14040;
- Monte Carlo analysis;
- Weak point analysis: use the process tree to identify any “hot spots”.

2.2. Methodologies to account for carbon sequestration

Several methodologies to account for carbon sequestration potential exist but none of those is approved as unique and commonly used. Now three different methodologies from literature will be resumed and compared.

Aquino et al. (2017) [37] have proposed a methodology to evaluate carbon sequestration potential of different cultivations. This methodology is based on the gathering of the following data: bulk density and soil organic carbon measured at 30, 60, and 90 days after sowing (DAS), respectively, while the shoot and root biomass are observed at the beginning at 30 DAS and every 15 days thereafter. If plants do not survive the waterlogged condition after 60 DAS, the shoot and root biomass during the rainy season can only tracked up to that point.

More in detail, it is important to know the features of shoot and root biomass of the crop under study**:** five plants from each treatment plot are chosen at random, and the roots of those plants need to be painstakingly extracted. Individual plant samples' roots and shoots are then divided and oven-dried at 70 °C for 72 hours, or until a constant dry weight was reached. Extremely wet samples need to be air dried first, then dried in the oven. The root and shoot samples are weighed individually once consistent dry weight is reached. The roots and shoots' % organic carbon content is measured in the dried tissues. In order to calculate the above- and below-ground carbon sequestration, the root and shoot biomass per hectare need estimated.

Carbon sequestration potential

By examining the carbon content of the shoot and root tissues individually, the potential for above- and below-ground carbon sequestration of maize is identified. From soil samples taken from each of the treatment plots, the amount of carbon sequestered by the soil can be calculated.

Plant carbon sequestration

For the examination of total carbon content, a 10-g composite sample of dried shoots and roots from each treatment combination must be brought laboratory.

The formula:

CS Plant = [(SDM)(SCC)] + [(RDM)(RCC)]

is used to determine the total amount of carbon sequestered.

Where:

- CS Plant: Plant Carbon Sequestration;
- SDM: Shoot Dry Matter (t/ha);
- SCC: Shoot Carbon Content (%);
- RDM: Root Dry Matter (t/ha);
- RCC: Root Carbon Content (%).

Soil organic carbon sequestration

Using an auger, soil samples between 0 and 25 cm deep need to be examined for the presence of organic carbon. By employing a core sampler to collect soil samples, bulk density has to be also calculated. Before drying the samples overnight at 105 C, the weight of the soil plus the core sampler is noted. After oven drying, the weight of the soil plus core sample is recorded to determine the bulk density. Using the following formula from Komatsuzaki and Syuaib (2010), the amount of soil organic carbon can be calculated:

SCS= BD*SOC*DP

Where:

- SCS: Soil Carbon Sequestration;
- BD: Bulk Density (g/cm3);
- SOC: Soil Organic Carbon content (%);
- DP: Soil depth (cm).

Popp et al. (2011) [38] have proposed a methodology to account for total carbon sequestration in soils of different cultivation based on the aboveground biomass and belowground biomass of the specific plants.

Kg of carbon (C) sequestered from aboveground biomass (AGB) per hectare for crop j in county i under tillage method t can be calculated using the following process:

$$\mathrm{AGB}_{ijt} = \left[Y_{ij} \lambda_j \left(1 - \alpha_j\right) \left(\frac{1}{H_j} - 1 \right) \beta_j \delta_t \eta_t \right]$$

where Y_{ij} are county-level grain or fibre yields for crop j reported conventionally in units per acre, j converts this yield to kilogrammes per hectare, j is the moisture content (wet basis) of the grain or fibre harvested so that yields can be converted to a dry-mass basis, H_j is the harvest index, j is the estimated fraction of C in the AGB, t is the estimated amount of AGB incorporated in the soil based on In this study, all aboveground waste was left on the field.

Kilograms of C sequestered from belowground biomass (BGB) per hectare for crop j in county i under tillage method are estimated by:

$$\mathrm{BGB}_{ijt} = \chi_j \eta_t \left[\frac{\phi_j Y_{ij} \lambda_j \left(1 - \alpha_j\right)}{H_j} \right]$$

where χ_j is the fraction of C in the belowground biomass and Φ_j is the shoot/root ratio. Both above- and belowground bio-mass C sequestration is multiplied by an estimated soil factor ξ_{is}, weighted by the area of land with each soil texture in each county, that adjusts soil C sequestration based on soil texture. Thus, total C sequestration S_{ijts} per hectare for crop j in county i under tillage method t and soil texture s can be estimated by:

$$S_{ijts} = \left(\mathrm{AGB}_{ijt} + \mathrm{BGB}_{ijt} \right) \xi_{is}$$

This analysis employs previously published statistics for the harvest index and root/shoot ratio for the corn crops, the carbon content of above- and below-ground biomass, parameters for belowground biomass sequestration by tillage method and soil-incorporated crop residues, information on soil factor modifications for clayey, loamy, and sandy soils as well as state-average minima and maximum for soil textures by county. The soil factors can be multiplied by the proportion of soils in each class for a specific county to get a quantity-weighted average soil factor for each county. This methodology in conditions comparable to conventional tillage ones gives a sequestration potential of 1247 $kgha^{-1}year^{-1}$ for corn as shown in figure 7.

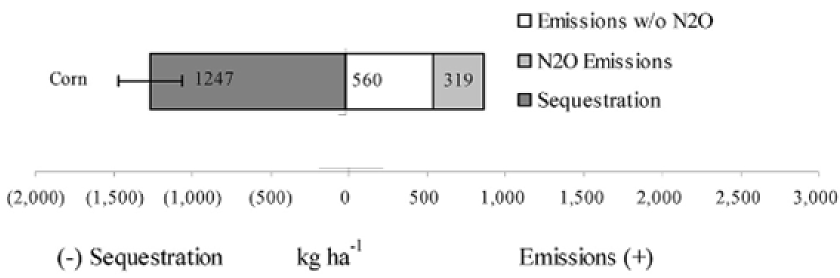


Figure 7: Carbon sequestration for a crop corn as calculated by Popp et al. (2011) [38]

Winans et al. (2015) [39] have introduced a methodology to account Carbon sequestration potential based on the Net Primary Productivity for different cultivations.

Calculations for C sequestration potential, and C in the production systems and soil

The C sequestration potential can be estimated with the NPP (Net Primary Productivity) approach described by Bolinder et al. (2007) [40].

They proposed a method for describing the accumulation and distribution of C in crop plants. The criteria for this method are:

1. It must contain every plant C portion. These fractions added together should provide an accurate estimate of NPP for agroecosystems and allow for comparisons with NPP of other ecosystems.
2. Its plant C fractions should be consistent with easily accessible data, especially with yield information that is generally available for the majority of agricultural crops.
3. It should make it possible to directly and simply estimate the annual carbon (C) inputs to the soil for use in simulations of the dynamics of soil C in response to crop type and management methods.

In order to satisfy these requirements, the carbon in crop plants was divided into four fractions, each of which was stated as a mass of carbon per unit of area per unit of time (g C m^2 yr^{-1}).

Briefly, the NPP approach quantifies C fixed annually in above- and below-ground biomass and determines the annual plant residue input to soil from litter, root turnover and exudates. The C sequestration potential is defined as the fraction of plant residue incorporated into the soil and then integrated into a stable SOC pool with a residence time 100 years (Fig. 6), considering isohumic coefficients (Bolinder et al. 2007; CRAAQ 2010). The NPP, which represents C gain in a system, is composed of the C associated with the different plant components, expressed as:

$$NPP = C_P + C_R + C_S + C_E$$

Each C component in the plant and pool taken into account by the method is also shown in figure 8.

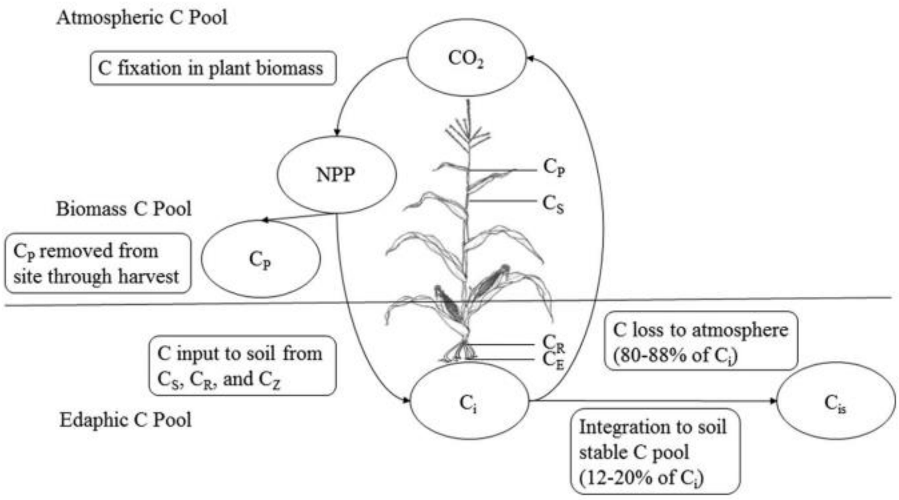


Figure 8: Carbon Pools and plant carbon fractions.[39]

CP is the plant Carbon in the agricultural product, the plant portion of primary economic value, and typically harvested and exported from the ecosystem. The ‘product’ can be either above-ground (e.g., grain, hay) or below-ground (e.g., tuber). For corn, the product is aboveground.

CS is the plant Carbon in straw, stover and other above-ground post-harvest residue. This fraction includes all above-ground plant materials excluding the ‘product’.

CR is the plant Carbon in root tissue, comprised of all below-ground, physically recoverable plant materials, excluding any ‘product’.

CE is the plant Carbon in extra-root material, including root exudates and other material derived from root-turnover, not easily recovered by physically collecting, sieving or removal. This fraction is roughly equivalent to that sometimes referred to as ‘rhizodeposition’. The amount of C in each of these four fractions (and thus also NPP) can be estimated from agricultural yields, using published or assumed values for harvest index (HI), S:R ratios, plant C in root exudates, and C concentrations in the plant parts.

The C uptake from the different plant components can be calculated as follows:

$$Y_P = \text{Yeld x } (1 - \text{Moisture}_{\text{Content}})$$

$$C_P = Y_P \text{ x } C_{\text{Content,AGB}}$$

$$C_R = Y_P \text{ x } \frac{\text{root}}{\text{shoot}} \text{ x } C_{\text{Content,BGB}}$$

$$C_S = Y_P \text{ x } \frac{1 - H_i}{H_i} \text{ x } C_{\text{Content,AGB}}$$

$$C_E = C_R \text{ x } Y_E$$

Here the harvest index represents the Dry Matter yield of harvested product relative to total Dry Matter yield of crop and YE represents the extra Carbon from roots exudates and root turnover relative to recoverable roots usually assumed to be 65%. The proportion of Carbon input to the soil from various plant fractions was calculated as:

$$C_i = [C_p \text{ x } S_P] + [C_S \text{ x } S_S] + [C_R \text{ x } S_R] + [C_E \text{ x } S_E]$$

where Ci represents the annual Carbon input to soil from plants and S is assumed to be the proportion of Carbon in the respective plant fraction that enters the soil, for example, where CP is Carbon in plant and SP is the fraction of the Carbon from plant that enters the soil, and the value of S ranges from 0 to 1, representing 0–100 % of a plant fraction incorporated into the soil at the end of a growing season (Bolinder et al. 2007). The amount of C added to soil in the simplest scenario, where only the "product" is gathered, is calculated as: NPP-CP. However, some fractions are frequently only partially recycled back into the soil. A new option is added, S, to account for this, which specifies the percentage of Carbon in a particular fraction that is returned to soil. Typically, SP = 0, SS = 1, SR = 1, and SE = 1 are set by default (where SP, SS, SR, and SE are the proportions of C in product, above-ground residue, roots, and extra-root C, respectively, that are returned to soil). When a fraction is reduced in size, SS is smaller than 1.

In the case of grain corn, C input to soil is defined as:

$$C_i = [C_P \times 0] + [C_S \times 1] + [C_R \times 1] + [C_E \times 1]$$

The crop C sequestration potential $\mathbf{C_{is}}$ is then the proportion of C input to soil potentially integrated into the stable soil C pool, assuming 12–20 % of C_i is integrated into the stable soil C pool (CRAAQ 2010):

$$C_{is} = C_i \times 12\,\% \quad \text{to} \quad C_i \times 20\,\%$$

As one of the main goals of this work is the calculation of the carbon credits eventually generated from a different crop management, the Carbon input to the soil must be converted in terms of CO_2-eq with the following relationship:

$$CO_{2-eq} = C_{is} \text{ x } \frac{44}{12}$$

Where 44 and 12 are referred to the Carbon Dioxide molecular mass and the Carbon atomic mass, respectively.

Table 1: Comparison of some features of the presented Carbon sequestration methodologies.

	AQUINO ET AL.	POPP ET AL.	WINANS ET AL
YEAR OF PUBLICATION	2017	2011	2015
PLANT CARBON SEQUESTRATION	Yes	Yes	Yes
ABOVE GROUND SEQUESTRATION	Yes	Yes	Yes
BELOW GROUND SEQUESTRATION	Yes	Yes	Yes
SOIL CARBON SEQUESTRATION	Yes	Yes	Yes
NEED FOR DIRECT LABORATORY TESTS	Yes	No	No
CONTAINS EACH PLANT PORTION	No	No	Yes

In this work the choice is to use the methodology proposed by Winans et al. (2015) for the calculation of the carbon sequestration in the corn field, based on the previous Net Primary Productivity methodology proposed by Bolinder et al. (2007). From a comparison with other methodologies, briefly resumed in table 1, this choice relies on the criteria satisfied by the method, which are consistent with the goal of this work, based on: accuracy, comparability, consistency with easily accessible data, direct and simple estimation of the annual C inputs to the soil for use in simulations of the dynamics of soil C in response to crop type and management methods.

2.3.GHG calculation

UNFCCC, in the **Afforestation and reforestation project activities implemented on lands other than wetlands** document states that any property that does not qualify as a wetland may be planted or replanted using this process. The technique limits the level of soil disturbance in the project to no more than 10% where the land's baseline land-use has a soil organic carbon (SOC) content that is anticipated to be higher than that under the land-use of "forestry". The higher SOC content in the baseline may be due to anthropogenic activity or the makeup of the soils, such as the fact that they are organic soils (e.g. soils are not tilled and external organic matter is added as inputs). The approach has a wide range of applications aside from this restriction on the severity of soil disturbance in specific types of soils and land-use practises. For instance, the land that will be replanted or afforested must not be degraded.

Small-scale afforestation and reforestation (A/R) project activities covered by the clean development mechanism (CDM) are appropriate for this methodology. Large-scale A/R CDM project activities are not covered by it. The carbon pools selected for accounting of carbon stock changes are shown in the following table 2.

Table 2: Carbon Pools considered in the A/R to account for carbon stock changes.

Carbon pool	*Whether selected*	*Justification/Explanation*
Above-ground biomass	Yes	This is the major carbon pool subjected to project activity
Below-ground biomass	Yes	Carbon stock in this pool is expected to increase due to the implementation of the project activity
Deadwood and litter	Optional	Carbon stock in these pools may increase due to implementation of the project activity

2.3.1. Identification of the baseline scenario and demonstration of additionality

The pre-project land use is continued in the baseline scenario for a small-scale A/R CDM project activity executed under this methodology. Participants in the project (PPs) prove that the project activity is additional by setting a realistic baseline scenario.

2.3.1.1. Methodology

Baseline net GHG removals by sinks

The baseline net GHG removals by sinks shall be calculated as follows:

$$\Delta C_{BSL,t} = \Delta C_{TREE\_BSL,t} + \Delta C_{SHRUB\_BSL,t} + \Delta C_{DW\_BSL,t} + \Delta C_{LI\_BSL,t}$$

where:

$\Delta C_{BSL,t}$	Baseline net GHG removals by sinks in year t; t CO_2-eq.

$\Delta C_{TREE\_BSL,t}$ — Change in carbon stock in baseline tree biomass within the project boundary in year t, as estimated in the tool "Estimation of carbon stocks and change in carbon stocks of trees and shrubs in A/R CDM project activities"; t CO_2-eq

$C_{SHRUB\_BSL,t}$ — Change in carbon stock in baseline shrub biomass within the project boundary, in year t, as estimated in the tool "Estimation of carbon stocks and change in carbon stocks of trees and shrubs in A/R CDM project activities"; t CO_2-eq

$\Delta C_{DW\_BSL,t}$ — Change in carbon stock in baseline dead-wood biomass within the project boundary, in year t, as estimated in the tool "Estimation of carbon stocks and change in carbon stocks in dead wood and litter in A/R CDM project activities"; t CO_2-eq

$\Delta C_{LI\_BSL,t}$ — Change in carbon stock in baseline litter biomass within the project boundary, in year t, as estimated in the tool "Estimation of carbon stocks and change in carbon stocks in dead wood and litter in A/R CDM project activities"; t CO_2-eq

2.3.2. Actual net GHG removals by sinks

GHG emissions resulting from removal of herbaceous vegetation, combustion of fossil fuel, fertilizer application, use of wood, decomposition of litter and fine roots of N-fixing trees, construction of access roads within the project boundary, and transportation attributable to the project activity shall be considered insignificant and therefore accounted as zero

The actual net GHG removals by sinks is calculated as follows:

$$\Delta CACTUAL,t = \Delta CP,t - GHGE,t$$

where:

$\Delta C_{ACTUAL,t}$	=	Actual net GHG removals by sinks, in year *t*; t CO_2-eq
$\Delta C_{P,t}$	=	Change in the carbon stocks in project, occurring in the selected carbon pools, in year *t*; t CO_2-eq
$G_{HGE,t}$	=	Increase in non-CO_2 GHG emissions within the project boundary as a result of the implementation of the A/R CDM project activity, in year *t*, as calculated in the tool "Estimation of non-CO_2 GHG emissions resulting from burning of biomass attributable to an A/R CDM project activity"; t CO_2-eq.

Change in the carbon stocks in project, occurring in the selected carbon pools, in year *t* is calculated as follows:

$$\Delta C_{P,t} = \Delta C_{TREE\_PROJ,t} + \Delta C_{SHRUB\_PROJ,t} + \Delta C_{DW\_PROJ,t} + \Delta C_{LI\_PROJ,t} + \Delta SOC_{AL,t}$$

where:

$\Delta C_{P,t}$	=	Change in the carbon stocks in project, occurring in the selected carbon pools, in year *t*; t CO_2-eq
$\Delta C_{TREE\_PROJ,t}$	=	Change in carbon stock in tree biomass in project in year *t*, as estimated in the tool "Estimation of carbon stocks and change in carbon stocks of trees and shrubs in A/R CDM project activities"; t CO_2-eq

$\Delta C_{SHRUB\_PROJ,t}$	=	Change in carbon stock in shrub biomass in project in year *t*, as estimated in the tool "Estimation of carbon stocks and change in carbon stocks of trees and shrubs in A/R CDM project activities"; t CO_2-eq
$\Delta C_{DW\_PROJ,t}$	=	Change in carbon stock in dead-wood biomass in project in year *t*, as estimated in the tool "Estimation of carbon stocks and change in carbon stocks in dead wood and litter in A/R CDM project activities"; t CO_2-eq
$\Delta C_{LI\_PROJ,t}$	=	Change in carbon stock in litter biomass in project in year *t*, as estimated in the tool "Estimation of carbon stocks and change in carbon stocks in dead wood and litter in A/R CDM project activities"; t CO_2-eq
$\Delta SOC_{AL,t}$	=	Change in carbon stock in SOC in project, in year *t*, as estimated in the tool "Tool for estimation of change in soil organic carbon stocks due to the implementation of A/R CDM project activities"; t CO_2-eq

2.3.3. Leakage

Leakage emissions shall be estimated as follows:

$$LK_t = LK_{AGRIC,t}$$

where:

LK_t	=	GHG emissions due to leakage, in year *t*; t CO_2-eq

$LK_{AGRIC,t}$	=	Leakage due to the displacement of agricultural activities in year *t*, as calculated in the tool "Estimation of the increase in GHG emissions attributable to displacement of pre-project agricultural activities in A/R CDM project activity"; t CO_2-eq

2.3.4. Net anthropogenic GHG removals by sinks

The net anthropogenic GHG removals by sinks is calculated as follows:

$$\Delta C_{AR-CDM,t} = \Delta C_{ACTUAL.t} - \Delta C_{BSL,t} - LK_t$$

where:

$\Delta C_{AR-CDM,t}$	=	Net anthropogenic GHG removals by sinks, in year *t*; t CO_2-eq
$\Delta C_{ACTUAL.t}$	=	Actual net GHG removals by sinks, in year *t*; t CO_2-eq
$\Delta C_{BSL,t}$	=	Baseline net GHG removals by sinks, in year *t*; t CO_2-eq
LK_t	=	GHG emissions due to leakage, in year *t*; t CO_2-eq

2.3.5. Calculation of tCERs and lCERs

The *tCERs* and *lCERs* for a verification period $T = t_2 - t_1$, where t_1 and t_2 are the years of the start and the end, respectively, of the verification period, are calculated as follows:

$$tCER_{t_2} = \sum_{1}^{t_2} \Delta C_{AR-CDM,t}$$

$$lCER_{t_2} = \sum_{t_1+1}^{t_2} \Delta C_{AR-CDM,t}$$

where:

$tCER_{t_2}$	=	Number of units of temporary certified emission reductions (tCERs) issuable in year t_2
$lCER_{t_2}$	=	Number of units of long-term certified emission reductions (lCERs) issuable in year t_2
$\Delta C_{AR-CDM,t}$	=	Net anthropogenic GHG removals by sinks, in year t; t CO_2-eq
t_1, t_2	=	The years of the start and the end, respectively, of the verification period

If $lCER_{t_2} < 0$ then $lCER_{t_2}$ represents the number of *lCERs* that shall be replaced because of a reversal of net anthropogenic GHG removals by sinks since the previous certification.

2.3.6. Assessment of additionality

Project participants (PPs) shall demonstrate that the project activity would not have occurred anyway due to at least one of the following barriers:

- Investment barriers, other than economic/financial barriers
- Institutional barriers
- Institutional barriers
- Barriers relating to local tradition
- Barriers due to prevailing practice
- Barriers due to local ecological conditions
- Barriers due to social conditions

3. CASE STUDY

According to the objective of the study, the methodologies described in Chapter 2 were applied to crops and finished products of one of the leading companies in the agri-food sector at European level. In the following subchapters there is a description of the company, of the analyzed crops, of the finished products of Conserve Italia and of the collection and analysis of data for implementation on the SimaPro software and for carbon sequestration algorithm.

3.1. Sweet Corn

The choice of studying corn derives from the necessity of producing food for human consumption and increasing awareness that agriculture, especially on a large scale, must become more sustainable. The corn processed by Conserve Italia is all of Italian origin. The cultivations, coming from strictly "No GMO" seeds, are planned and carried out in Emilia-Romagna, in the province of Piacenza, and in Lombardy in particular in the “cremonese” and “lodigiano” areas. Conserve Italia itself defines the time of harvest, choosing the ideal stage of maturation, that is when the corn is crunchy and still sweet: an excess of maturation would bring the corn to an excessive content of starches causing a decrease in its quality. After the harvesting, the cobs are transported to the factory where they are first deprived of the leaves that wrap them and then are shelled with special machines that preserve the grains despite their extreme delicacy. The sweet corn grains are first washed in running water, then they pass to the first sorting stage carried out by electronic optical reading machines, followed by the manual one with which the defective or stained grain residues are eliminated. The double sorting is an operation that concerns all the products processed by Conserve Italia, which for this process relies on the one hand to absolute avant-garde technologies and, on the other, to the experience and preparation of specialized personnel who perform manual selections. The selected and carefully washed corn is canned with the addition of a modest amount of water, salt and a small component of sugar. The boxes are hermetically sealed under vacuum, i.e without air inside, to then pass to the sterilization phase in large containers that carry out the so-called "steam cooking" [41].

The analysis that will be carried out for two commercial products.

- Steamed Valfrutta sweetcorn (Figure 9): the first chosen format is the cluster box of 3 boxes of 160gr each. In 2021, with the SAP code 027212, 50.861 packages were produced, while of the product with SAP 043068, 323.609 were produced.

Figure 9: Steamed Valfrutta sweetcorn, 160 g box.

- Cirio WAKU sweetcorn (Figure 10): The second one is the cluster box of 6 boxes of 2100gr each. In 2021, with the SAP code 041134, 93.131 packages were produced.

Figure 10: Cirio WAKU sweetcorn, 2100 g box.

In terms of production volumes, the first covered 13,58% while the second 86,42%. The bills of materials of the two products do not present differences in terms of input used.

3.2. Life Cycle Inventory

In accordance with the purpose of the study, in this chapter, the analysis of the data used for the LCA methodology. In particular, the two most representative and impacting phases of the product life cycle were analyzed: process phase and cultivation phase.

The analysis was carried out with the support of the SimaPro 9.4 software, which facilitated the modeling of material and energy flows of the various analyzed products and the calculation of the respective potential impacts on the environment and on human health.

The ISO 14040 [30] compliant LCA was performed following the specific rules defined in the Product Category Rules (PCR 2019:10) document on “arable and vegetal crops” [42] [43] published in the framework of the International Environmental Product Declaration (EPD) System [44] and according to ISO 14025 [45]. PCR 2019:10 states in that the system boundaries the upstream, the core and the downstream phases should be included, in this work the boundaries of the system are divided into the following two phases of the life cycle:

- Upstream processes (from cradle-to-gate);
- Core processes, manufacturing processes (from gate-to-gate).

Table 3: System diagram illustrating the processes that are included in the product system, divided into upstream and core processes

UPSTREAM	CORE
• Cultivation phase • Semi-product manufacturing • Emission from fertilizer application • Production of agricultural inputs and ingredients additives, auxiliary products • Generation of energy wares used in agriculture, at the farm, and in production • Production of packaging materials	• Transportation to food processing plant • Food processing • Packaging processing • Storage • Wastewater treatment

The General Program Instructions (GPI) of the International EPD® System and the PCR of reference were used to determine the system's boundaries. Everything is recorded during the inventory phase, including entering and exiting material and energy flows, air and water emissions. The farms and production facilities participating in the foreground inventory data collection along the whole supply chain, from the agricultural to the distribution phase, have given their data directly. The "I.O. Life Cycle Analysis and Environmental Product Declaration" and the General Program Instruction (GPI 3.0) of the International EPD System from an EPD Process perspective are followed for the gathering and processing of data.

The information gathered comes primarily from credible reliable sources, including the following:

- Bills of Materials (BOMs) for products;
- Invoices and bills;
- Direct measures;
- Counters.

These basic data have undoubtedly been supplemented with secondary data from the software databases and data generated using models. It combines all widely used life cycle inventory (LCI) data sources, such as the sector-specific Ecoinvent v3.8 and the Agri-footprint database. The next chapters include descriptions of the data and the assumptions made.

3.2.1. Inventory analysis of the cultivation phase-Business-As-Usual

The cultivation phase has been evaluated by studying the contribution of different farmlands (table 4), and by accounting finally for all contributions together from the tillage phase to the transportation of the harvested corn to the processing plant.

Table 4: Area, region, province, size and type of farmland for sweet corn.

No.	Culture	Area	Region	Province	Dimension(ha)	Type of soil
1	Sweet corn	NORD ITALIA	EMILIA ROMAGNA	PIACENZA-PARMA-REGGIO EMILIA	17,3	Heavy
2	Sweet corn	NORD ITALIA	EMILIA ROMAGNA	PIACENZA-PARMA-REGGIO EMILIA	8,1	Light
3	Sweet corn	NORD ITALIA	EMILIA ROMAGNA	PIACENZA-PARMA-REGGIO EMILIA	21,6	Heavy
4	Sweet corn	NORD ITALIA	EMILIA ROMAGNA	PIACENZA-PARMA-REGGIO EMILIA	46	Light
5	Sweet corn	NORD ITALIA	EMILIA ROMAGNA	PIACENZA-PARMA-REGGIO EMILIA	12,3	Heavy
6	Sweet corn	NORD ITALIA	EMILIA ROMAGNA	PIACENZA-PARMA-REGGIO EMILIA	13,5	Heavy
7	Sweet corn	NORD ITALIA	EMILIA ROMAGNA	PIACENZA-PARMA-REGGIO EMILIA	19	Heavy
8	Sweet corn	NORD ITALIA	LOMBARDIA	CREMONA-LODI	14,7	Light
9	Sweet corn	NORD ITALIA	LOMBARDIA	CREMONA-LODI	18,9	Light
10	Sweet corn	NORD ITALIA	LOMBARDIA	CREMONA-LODI	13,3	Light
11	Sweet corn	NORD ITALIA	LOMBARDIA	CREMONA-LODI	18,1	Light
12	Sweet corn	NORD ITALIA	LOMBARDIA	CREMONA-LODI	23,9	Light
13	Sweet corn	NORD ITALIA	EMILIA ROMAGNA	FERRARA	26	Light
14	Sweet corn	NORD ITALIA	EMILIA ROMAGNA	FERRARA	14,5	Light
15	Sweet corn	NORD ITALIA	EMILIA ROMAGNA	BOLOGNA	7	Heavy
16	Sweet corn	NORD ITALIA	EMILIA ROMAGNA	MANTOVA-VERONA	6,2	Light

Table 5 shows the processes carried out for each type of cultivation and, since they vary according to the company in question, the number of companies that have adopted this type of processing for the reference year is indicated.

Table 5: Number of companies that carry out every type of processing for sweet corn

Field Operation	**Number of companies**
Plowing	11
Sowing	16
Harrowing	15
Milling	0
Rolling	2
Chemical Protection	16
Irrigation	16
Fertilisation	8
Harvesting	16
Weeding	16
Grubbing	10
Transplant	0

The data concerning agricultural production are all referred to a cultivated hectare and are all primary data or calculated from data provided directly by the cooperative and by far Crop yield can vary because of conditions such as weather, soil, location, input intensity, irrigation, and rotation.

All specific data refer to the year 2021, reported in table 6. The average crop yields of the studied farms account for 14,86 t sweet corn/ha.

The amount of water used, both to dilute herbicides and to irrigate, have been provided for each company, specifying the numbers of irrigation interventions and the methodology used. The water used for irrigation and treatments is taken from the drainage channel. Water use varies with species, climatic and soil conditions, and with the growth period. In the performed analysis, it averagely amounts to 1301.39 m^3/ha for sweet corn. There are different types of irrigation used by the various companies for the crops in question. For irrigation methods, the systems used are the hose-reel irrigation machines and the pivot. The first type has an efficiency of 75% while the second of 85%. In particular, their diffusion in the Conserve Italia companies is that the hose-reel machine is used 90% of times with corn.

Direct energy use from agricultural inputs comes from on-farm diesel consumption for machinery operations and includes irrigation and fertirrigation. Each selected company has provided agricultural diesel consumption for each processing phase. For the fuel it was considered an agricultural gas oil with a density of 0,84 kg / L and a calorific value of 42,877 MJ / kg. For the sweetcorn, a total Diesel consumption of 328,91 l/ha has been estimated.

As nitrogen fertilizers, urea (NPK 46-0-0) or ammonium nitrate (28% of N) are applied. For sweet corn 140,36 kgN /ha of urea. In a farm producing sweet corn, a certain amount of nitrogen is administered in the form of ternary fertilizer (NPK) and organic fertilizer. For the purposes of software simulation, a 50% administration of the two fertilizers was hypothesized. In particular, for both types of nitrogen fertilizers, sweet corn was given an average of 1,69 kgN /ha. Phosphoric anhydride (P_2O_5) and potassium oxide (K_2O) are used as phosphoric and potassium fertilizer respectively.

Urea was used along with ternary or organic fertilizer so that total nitrogen amounts to 158,96. Phosphoric anhydride is applied only to corn on average 8,63 kg P_2O_5 / ha. No ammonium nitrate or potassium oxide are employed for sweet corn cultivation. Chemical treatments amount to 13,96 kgl/ha. As far as chemical treatments are concerned, selected herbicides are used for pre and post emergence against weeds. The maximum number of their applications is set by the applicable Regional Integrated Production specifications. As for the packaging, i.e. the sacks of seeds, fertilizers and chemical treatments, the number was calculated using the quantities used in the field and the weight was calculated effectively measuring the various plastic packaging. The average of plastic packaging of the studied farms account 0,42 t / ha sweet corn.

For the processing on SimaPro, polypropylene was used as a plastic material using the Ecoinvent process “Polypropylene, granulate {RER} | production | cut off”. An equal quantity was considered as waste using the "Packaging waste, plastic" process.

Table 6: Inventory data for the cultivation phase for the year 2021.

Inventory data for cultivation phase	
Crop gross yield [t/ha year]	14,86
Seeds/seedings [kg-No/ha]	7,78
Water [m3/ha]	1301,39
Fertilizers	
Urea [kgN /ha]	140,36
Ammonium nitrate [kgN /ha]	0
Organic fertilizer [kgN /ha]	1,69
Ternary fertilizer [kgN /ha]	1,69
Phosphorous pentoxide [kgP2O5/ha]	8,63
Potassium Oxide [kgK2O/ha]	0
Chemical treatments [kg/ha]	22,86
Diesel [MJ/ha]	11010
Packaging [t/ha]	0,42

Crop yield, seeds, water, fertilizers, chemical treatments, diesel consumption and packaging are all primary data collected during the reference period.

The air emissions caused by the use of nitrogen fertilizers, used for cultivation operations, have been calculated according to the PCR 2020: 07 Arable and vegetable crops. The emissions in the case under study concern chemical and organic fertilizers, both nitrogenous and phosphate: in the first case they are represented by urea, organic manure and ternary fertilizer and in the second case from phosphorus pentoxide P_2O_5. Obviously, we always consider the nitrogen content inside the fertilizer: 28% for ammonium nitrate and 46% for urea.

The emissions in air considered are as follows:

- Ammonia volatilized;
- N_2O, NO– direct emission;
- N_2O –indirect emission

The emission factor for ammonia volatilized emissions (0,0220 t-N2O/t-N) as well as N2O direct emissions were estimated using the EMEP/CORINAIR [45] emission factors (0,142 kg-NH_3 /kg-N for urea, 0,210 kg- NH_3 /kg-N for organic manure and 0,030 kg- NH_3 /kg-N for ammonium nitrate and ternary fertilizer) defined by the PCR of arable crops [46], as well as NO direct emissions (emission factors used: 0,007 kg-NO/kg-N for urea, 0,005 kg-NO/kgN for organic manure and 0,006 kg-NO/kg-N for ammonium nitrate and ternary fertilizer). Instead N_2O indirect emission factors (0,01 kg-N_2O/kg-N per kg NH_3-N volatilized from fertilizers applied and 0,0075 kg-N_2O/kg-N per kg of NO_3-N lost by leaching/runoff) come from IPCC 2006 Guidelines [47]. The IPPC emissions factor (i.e. 0,3 kg-NO_3/kg-N) were used also for emissions of nitrate to water [48]. Emissions to water from phophates fertilizers are obtaine through Prasuhn methodology (2006) [49]. Table 7 shows the values of the emissions calculated as shown in the paragraph for each type of crop analyzed.

Table 7: Values of the calculated emissions used in SimaPro. Data referred to 1 ha for crop yield.

Emissions	
Air	
NH3 (kg/ha)	23,58
N2O- direct and indirect emissions (kg/ha)	3,52
NO- direct emissions (kg/ha)	4,60
Water	
Nitrate (NO3-) (kg/ha)	170,12
Phosphorous (kg/ha)	1,27

Direct and indirect N and P emissions are secondary data calculated starting from nitrogen fertilizer application.

Land use affects biodiversity. The size of the surface and the type of land use have an impact on biodiversity. The damage to be attributed to the Land use derives from both the conversion and the occupation of the land, and both regional and local consequences are taken into consideration in this impact category. Therefore, this damage is given in m^2 year: “Land occupation recorded as m^2 times year per unit output”.

The indicator was calculated using the following expression:

$$Land\ use = Total\ area \times Years\ Yield$$

The starting year for sweet corn is considered to be 1980. The total years considered in the calculation are 41, the period between 1980 and 2021. A total area of 10.000 [m^2] has been considered. The resulting land use value amounts to 27.59 m^2yr/kg.

3.2.2. Inventory analysis of process phase Business-As-Usual

3.2.2.1. The products

This part provides the inventory analysis and the production-related fundamental process assumptions for the product under examination. The inputs and outputs, specific for the product in question as well as the facilities where the processing and packaging phase is carried out, have been taken into consideration.

Data relating to the production and packaging plants, regarding the bill of materials (BOM) of the considered product are referred to a package consisting of 24 pieces with a total weight of 3,84 kg of Steamed Valfrutta sweet corn. The following Table 8 shows the results that were used in the implementation on the SimaPro software, subdivided by category and referring to a package.

Table 8: Values entered on SimaPro. The data refer to a pack of 24 Steamed Valfrutta sweet corn.

Input	**Quantity**	**Unit**
Sweet corn	9,74	kg
Salt	0,035	kg
Water	0,4	kg
Electricity	0,898	kWh
Fuel	11,03	MJ
Primary packaging		
Can	0,042	m^2
Lid	0,011	m^2
Label	0,028	kg
Secondary/tertiary package		
Pallet	0,200	kg
Interlayer	0,038	kg
Cluster	0,16	kg
Glue	0,012	kg
Film/Sheet	0,025	kg

According to Table 8, almost of 10 kg of sweet corn for agriculture and 0,0354 kg of salt are needed to produce a package of steamed sweet corn weighing 3,84 kg in total. 11,0304 MJ of methane, 0,8980 kWh of electricity, and 0,4446 kg of water are used. Water is not added to the product in this instance therefore consumption is far reduced. For 24 tin cans weighing 160 gr, the primary package, which includes the container, lid, and label, weighs 0,8504 kg per pack. There is a total weight of 0,430 kg per pack for secondary (cluster, layer, and plastic film) and tertiary packaging (cardboard interlayer, external plastic film, label, and pallet).

Analogously for Cirio WAKU Corn is available in a box of 6 tinplate boxes of 2100g each. Regarding agriculture and plant information there are no substantial differences in those life cycle stages.

Table 9: Values entered on SimaPro. The data refer to a package of 6 Cirio WAKU sweet corn.

Input	**Quantity**	**Unit**
Sweet corn	30.876	kg
Salt	0,11	kg
Water	1,84	kg
Electricity	2,28	kWh
Fuel	27,11	MJ
Primary packaging		
Can	0,008	m^2
Lid	0,017	m^2
Label	0,036	kg
Secondary/tertiary package		
Pallet	0	kg
Interlayer	0,125	kg
Cluster	0	kg
Glue	0,0112	kg
Film/Sheet	0,0492	kg

3.2.2.2. The plant

This section shows the input and output data relating to the production plants. For each of these, management data for the year 2021 were collected. Sweet corn is produced in the Alseno plant. The data relating to electricity and fuel consumption do not require any allocation starting from the plant data, as specific data are already present for each product and reported in the various bill of materials. The transport of the cultivated product from the field to the production plants takes place by means of a 12t truck. For fresh products the average distance travelled is 70 km.

The following table, table 10, shows the input data used in SimaPro software to study the food processing at production plant considering one year of corn produced, all data are referred to one t of corn produced.

Table 10: input data used in SimaPro software to study the food processing at production plant

Inventory data for food processing at production plant	**Alseno, PC**	**Unit**
Processed material		
Sweet corn	23.663	t
Byproducts		
Byproducts for zootechnical use	0.53	t/t
Raw materials		
Nitrogen for production		
Caustic soda (Sodium Hydroxide) 30%-50%	0,29	kg/t
Hydrochloric acid 8% -33%	2,33	kg/t
Sodium chlorite 7.5% -10%	0,56	kg/t
Other reagents, detergents, sanitizers (NALCO, Hypofoam, ...)	0,7167	kg/t
Lubricants, fats	0,064	kg/t
Paints, inks	0,013	kg/t
Refrigerants	0	kg/t
Fuels		
Diesel for forklift	6,27	MJ/t
Water		
Water from aqueducts (drinking water)	277	kg/t
Well water	7,23	m^3/t
Wastewater		
Water discharged in surface water (after purification plant)	4,20	m^3/t
Waste		
Waste for disposal (hazardous or not)	0,0010	kg/t
Electricity		
Electricity consumed from the grid	0,0883	kWh/kg

3.3. Carbon sequestration potential

As already mentioned, the chosen methodology from Winans et al. (2015) [39] to be carried out needs a quantity of parameters. Some of those can be directly obtained from measurements on field as well as from literature. In particular, for this analysis the only parameter that has been taken from companies is the Yield [t/ha] while other parameters are obtained as an average from different scientific reports. The data have been considered reliable since many studies report the same average values for corn. The first parameter necessary for the application of the methodology is the dry matter yield which is obtained from the actual yield to which it is subtracted the moisture content of the stover, which according to Li et al. (2020) on average amounts to the 30% of the total mass [52].

The following tables show average county averages gathered rather than specific county yield information. No matter the yield, the same assumptions about C content, harvest index, and root/shoot ratios were made.

The quantity of biomass still present on the field after harvest was calculated using the harvest index, which is the ratio of the harvested grain mass to the total aboveground plant biomass. The model employed an average value published from the literature as indicated in Table 11 because harvest index values can vary greatly by seed cultivar, planting season, production technique, growth circumstances, and location.

Table 11: Harvest index according to different literature references.

Harvest Index [-]	Reference
0,50	Graham et al. (2007)
0,38	Wilts et al. (2008)
0,42	Cox and Cherney (2001)
0,42	Adhikari et al. (2021) [58]
0,52	Ordonez et al. (2020) [59]
0,45	**Average**

In order to estimate the yield-dependent belowground C content of the roots, it was first essential to determine the yield-dependent BGB production using the root/shoot ratio. Root material and the AGB were modelled independently since they have slightly differing C concentrations. Root/shoot ratios reported in the literature vary widely, similar to harvest indices, hence a mid-range estimate was employed in this investigation (Table 12).

Table 12: Root Shoot Ratio according to different literature references.

Root/shoot ratio [-]	Reference
0,18	Prince et al. (2001)
0,24	Herbert et al. (2001)
0,19	**Average**

It is well recognised that agronomic techniques have a significant impact on plant development and output. Tillage is a typical agronomic technique used to manage agricultural waste, prepare a seedbed for sowing, and suppress weeds. Water infiltration, storage, and transport through a soil profile are all impacted by tillage. Tillage has a direct impact on the generation of above- and below-ground biomass as well as plant establishment and soil compaction. Crop leftovers, which are frequently seen as a barrier to planting a crop, are actually a valuable source of organic matter and nutrients that help to preserve the fertility of soil. Tillage offers a way to physically combine crop residues with the soil and speed up the breakdown of crop residues. It also breaks down soil-born roots. This improves how plant waste interacts with the microorganisms in the soil that mineralize organic materials and reuse vital nutrients from the waste for use by succeeding crops. A portion of the more easily accessible carbon from cellulose and hemicellulose is respired back to the environment as CO_2, whereas lignin, a more resilient source of carbon in the plant waste, remains in the soil as humus because soils can only absorb a fixed amount of carbon. In conclusion, tillage decreases the amount of carbon that may be stored in the soil by increasing the potential for soil erosion, incorporating residue, and stimulating microbial activity, which increases soil respiration and CO_2 leakage. Producers have gradually reduced tillage to mitigate soil loss since it is detrimental to long-term sustainability, even if doing so may result in less effective short-term nutrient recycling due to the absence of residue absorption. In order to simulate the aforementioned impacts, the parameter SP, which is the fraction of the C from plant that enters the soil, ranges from 0 to 1, representing 0–100 % of a plant fraction incorporated into the soil at the end of a growing season.

However, not all of the carbon (C) present in the roots and aboveground waste can be regarded as sequestered until it has been integrated into the soil. Sequestered carbon is the portion of crop residue that stays in the soil after the microbes have been successful in mineralizing the more readily available C fractions that are ultimately respired to the atmosphere as CO_2 because many types of crop residues contain roughly 50% lignin.

In general, the top 15 to 30 cm of the soil profile, which is the layer primarily impacted by tillage, has demonstrated the most dramatic changes in C content in most long-term C sequestration investigations. However, with time, carbon can travel to lower soil layers, maintaining a soil's ability to store carbon for a while in the future. The initial C content of the soil has a significant impact on soil C sequestration in addition to the depth and duration of sampling. More C can often be stored in soils with a relatively low initial C level than in soils with a relatively high initial C content. Due to the typically low soil organic matter and C contents, the soil C sequestration potential (i.e., the annual accumulations of C in the soil) may not be depleted for decades on cropland. This implies that soil C accumulation dynamics should not be taken into account when using a model that just calculates annual sequestration. The model does not use initial C concentration data, which are not available to the spatial detail needed here, nor does it take into account C-holding limits for that soil because a soil in a specific county can accumulate a significant amount of C per hectare for decades without becoming saturated.

The effects of tillage are hence taken into account with the parameters reported in table 5, which are a summary of the experimental results obtained by Y. Gao et al. (2015) [51] shown in figure 11.

Table 13: Carbon content in aboveground and belowground biomass

Tillage option	**Below Ground Biomass [-]**	**Above Ground Biomass [-]**	**Reference**
Conservational tillage	0,45	0,55	Y. GAO ET AL. (2015)
Conventional tillage	0,30	0,45	Y. GAO ET AL. (2015)

:

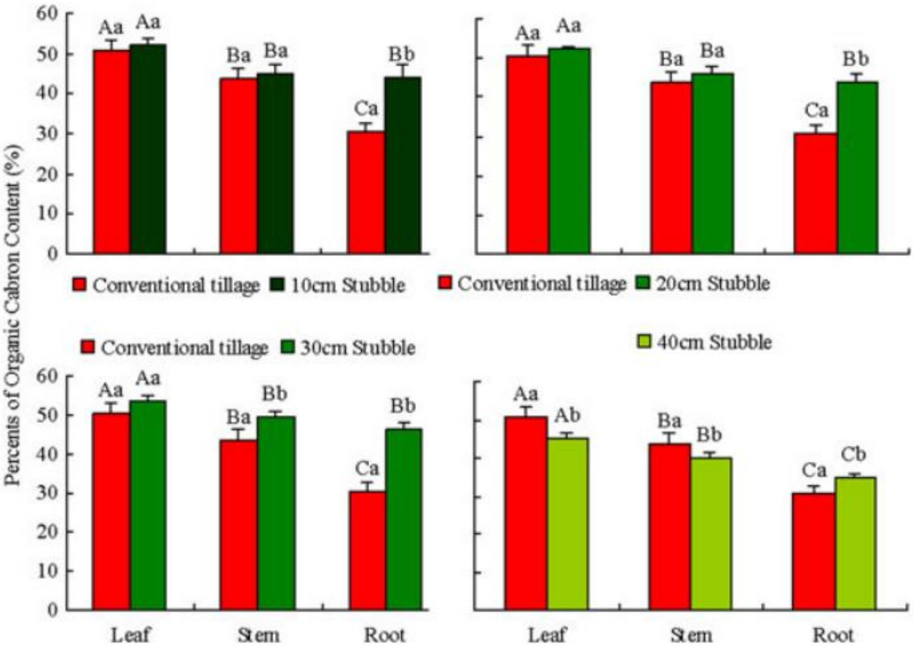


Figure 11: Percentages of organic Carbon content under different tillages (Y. Gao et al.)

The effects of tillage on soil C sequestration and soil C sequestration itself are both affected by soil texture (i.e., the relative mixture of sand, silt, and clay that makes up a soil). Soil texture affects soil aggregation, which in turn affects soil water content and the degree to which the soil water content fluctuates. In general, frequent wet and dry fluctuations will enhance the breakdown of soil organic matter by physical, chemical, and biological means. In other words, a soil that holds water longer will generally experience less frequent and less intense wetting and drying cycles, which occurs more with fine-textured (i.e., clayey) soils.

The effects of tillage and the amount of the Carbon from plant that enters the soil are represented by extreme values in a range of possible values, in this work different practices and methods will be presented and studied and these parameters will be varied to model different scenarios.

4. RESULTS AND DISCUSSION

The aim of this thesis is to calculate the net carbon footprint of the production process of the two maize products of the company Conserve Italia previously presented, an important phase is the cultivation phase which is accounted using 1 t of corn produced as functional unit and also the reference for the calculation of eventual carbon credits. This is done by calculating the CO_2 emissions equivalent and the uptake of carbon dioxide which is carried out by the corn plant. Another objective is to propose alternative carbon farming scenarios, which are intentionally aimed at increasing uptake of carbon dioxide and quantifying it, while assessing the environmental impact related to their implementation through LCA. In this way it is possible to calculate a net carbon footprint of the different practices to identify a better scenario and possible limitations.

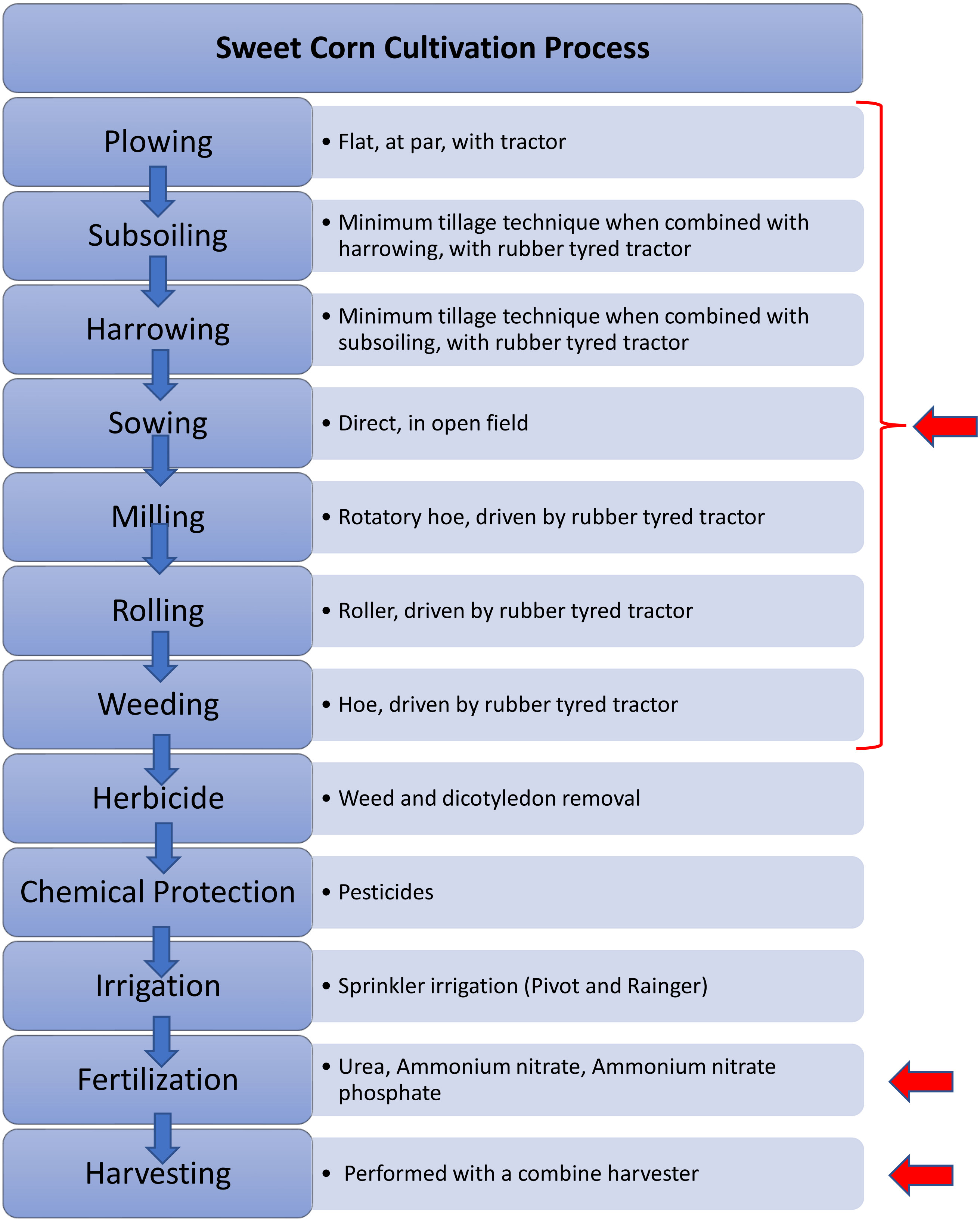
The impact category was identified in order to pave the way for environmental impact quantification by means of LCA tool and carbon sequestration. The choice is to pay more attention to one parameter that is the most representative for the purpose of this thesis: the Carbon Footprint (CF), the indicator of climate change GWP (Global Warming Potential) [kg CO_2-equivalent, 100 years]. The GWP of a substance is given by the ratio between the contribution to the absorption of the hot radiation that is provided by the instantaneous release of 1 kg of this substance and that provided by the emission of 1 kg of CO_2. The impact assessment factors are those defined by the IPPC (Sixth Assessment Report - Climate Change 2021 [50]) and reported in the CML 2001 method.

The results that will be presented are about the Carbon Footprint and the sequestered amount of CO_2 for the cultivation phase of four different scenarios, starting from the Business-As-usual scenario. These two results allow for the calculation of a Net Carbon Footprint and consequently the eventual generation of carbon credits.

4.1. Scenarios

Concerning the cultivation phase, where carbon farming practices can be applied, it is interesting to see where it is possible to intervene to apply such practices.

The cultivation process can be studied to understand where some possible actions can be implemented, the specific processes are highlighted with a red arrow.



In the following section, several scenarios related to different agricultural techniques, changing tillage methods, and harvesting procedures will be presented.

- Scenario 1: Business-As-Usual.
- Scenario 2: Application of biochar and substituting inorganic fertilizers with organic fertilizers.
- Scenario 3: Reduced tillage.
- Scenario 4: Application of biochar and substituting inorganic fertilizers with organic fertilizers under Reduced tillage.

The goal of this work is to define the carbon uptake carried out by the crop under study and determine how it can be improved through more appropriate carbon farming techniques, evaluating what benefits they can bring. Four different scenarios will be compared.

Each scenario has some characteristics that entail the use of different values for the parameters necessary to apply the methodology presented in the previous chapter. More specifically the input data that can vary in the ranges previously reported (Tables 11 to 13) and are related to tillage techniques, yield consequent to different fertilizations, carbon content of the biomass and the amount of the biomass left on the field after harvesting.

For given yield, the actual productivity of the case study, the methodology introduced by Bolinder et al. (2007) [40] used gives the range of results shown in figure 12:

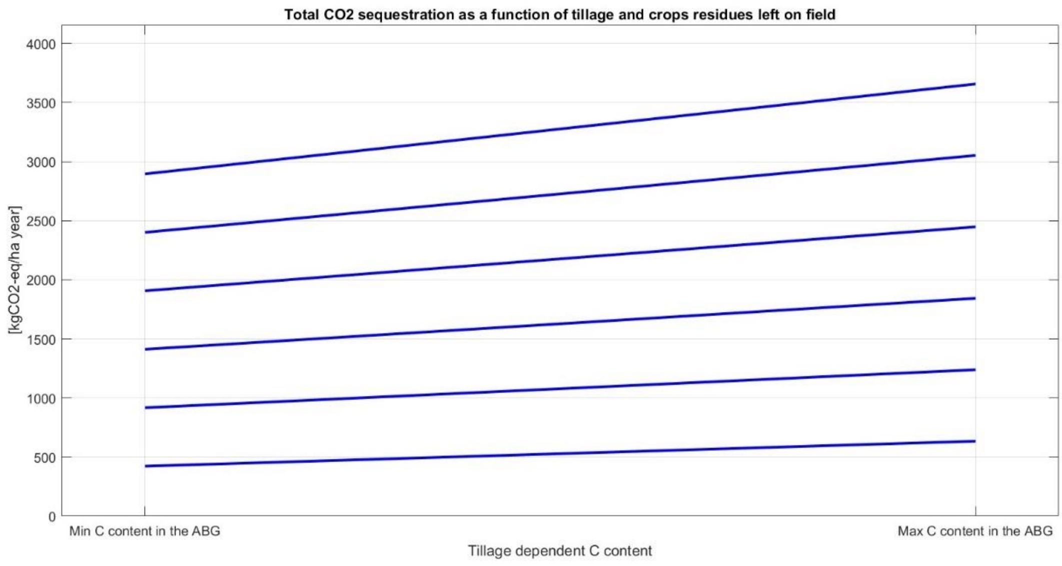


Figure 12: Total CO_2-eq sequestration as a function of tillage techniques and the amount of crop left on field after harvesting according to the methodology by Bolinder et al. (2007), for given yield.

Where, as already mentioned, Ss is the amount of crop residue left on field after harvesting (0 to 1) and the tillage dependent carbon content is referred both to Above Ground Biomass (0,45 to 0,55) and to the Below Ground Biomass (0,30 to 0,45).

For actual yield conditions the minimum value for carbon sequestration, where tillage is very intense and no crop residues are left on field, is about 422 kg CO_2-eqha^{-1}yr^{-1}. While the best scenario sequestration, where soil disturbance is at the lowest and all crop residues are left on field, amounts to 3657 kg CO_2-eqha^{-1}yr^{-1}.

4.1.1. Business As-Usual-Scenario

4.1.2. LCA results of the cultivation phase in BAU Scenario

Table 14 shows the results obtained for the indicator considered, referring to the cultivation of 1 t of sweet corn.

Table 14: CF results referred to 1 t of corn, B-A-U Scenario

	Carbon Footprint (kg CO_2-eq/t)	**[%]**
Emissions	64,72	36,3
Maize seeds	0,69	0,4
Urea	33,50	18,8
Ammonium Nitrate	5,13	2,9
Nitrogen Fertiliser	8,36	4,7
Pesticide	7,19	4,0
Polyethylene	0,052	0,0
Diesel	58,83	33,0
Total	**178,49**	100,0

With regard to the CF emissions have the greatest impact with a contribution of 36%, followed by the diesel consumption is the phase of life, with an impact of 33% and the use of Urea which impacts to the 18,8% of the total (figure 13).

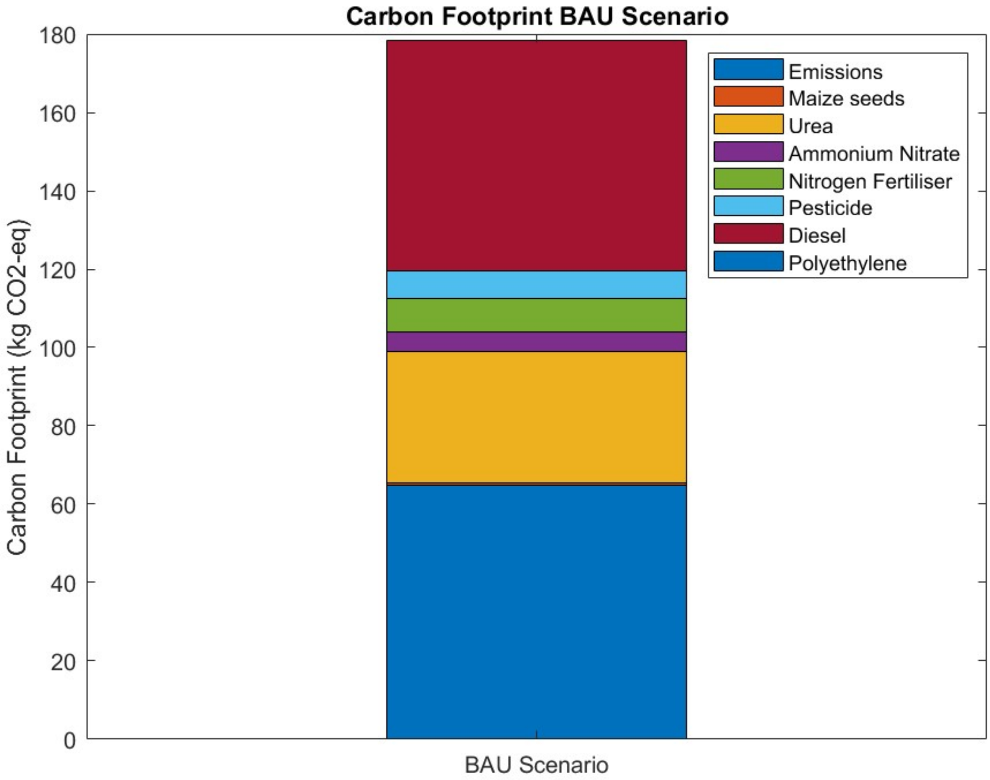


Figure 13: Cultivation CF specific contributions in BAU scenario. The results are referred to 1 t of sweet corn.

4.1.3. Carbon sequestration in the BAU Scenario

The first scenario studied is the so-called Business as Usual (BAU). The data reported in the case study chapter refer to the business-as-usual scenario.

It represents the baseline condition to which every other data will be compared to. As reported in the previous section the level of tillage is high and the use of inorganic fertilizers is widespread in all the companies in the case study. Actually, specific information about some features of the tillage methods is not available because it was not given, such as the amount of biomass left on the field or removed after the harvest.

It is possible to associate present conditions with the "Conventional Tillage" which typically includes a sequence of soil tillage, such as plowing and harrowing, to produce a fine seedbed, and the removal of most of the plant residue from the previous crop. In this context, the terms cultivation and tillage are synonymous, with an emphasis on soil preparation. Conventional tillage is any system that attempts to cover most of the residue, leaving around 20% of the soil surface covered with residue after planting. Usually, a variety of tillage implements are used, bringing some advantages in terms of labour but also some disadvantages:

- Equipment, fuel, and labour costs associated with seedbed preparation are high;

- Field traffic is significant, increasing the risk of compaction and weeds spreading in the field;
- Risk of soil erosion by wind and water as well as crusting are greater with inadequate surface residue;
- Tillage reduces organic matter levels.

The value of the parameters employed for the CO_2-eq uptake in this scenario are summed in table 16.

Table 15: Values for NPP methodology in conventional tillage scenario

Plant Carbon Content	Roots Carbon Content	Amount of residue crop left on field after harvesting
C_{cp} [-]	C_{cr} [-]	S_s [-]
0,48	0,345	0,20

The result of the calculation model shows that in this case the carbon sequestration is equal to 1013,99 kg CO_2-eqha^{-1}yr^{-1}.

And the results are also shown in figure 14:

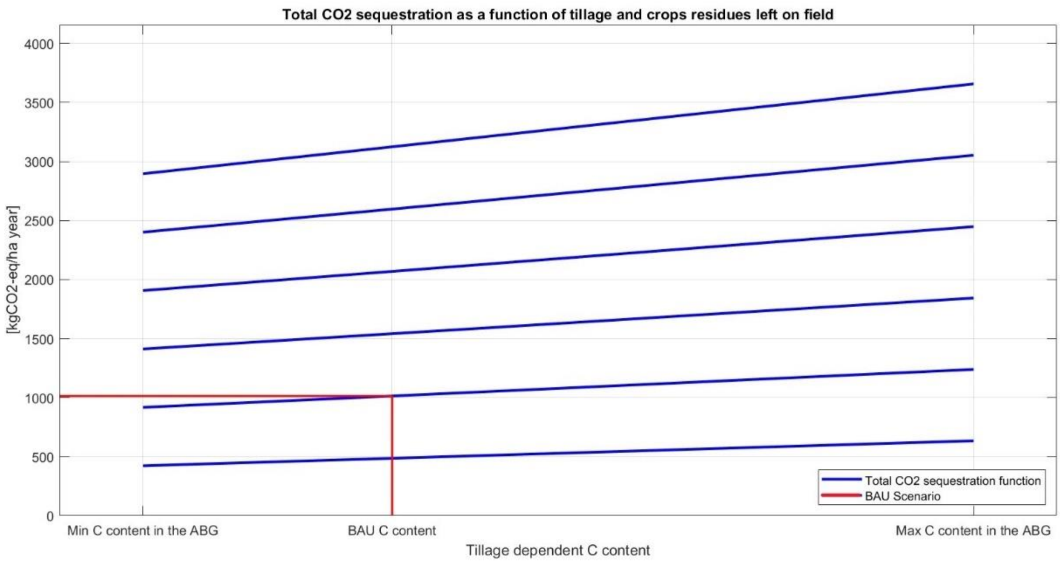


Figure 14: Total CO_2 sequestration in BAU Scenario compared to the spectrum of potentiall CO_2 sequestration as a function of tillage techniques and the amount of crop left on field after harvesting according to the methodology by Bolinder et al. (2007), for given yield.

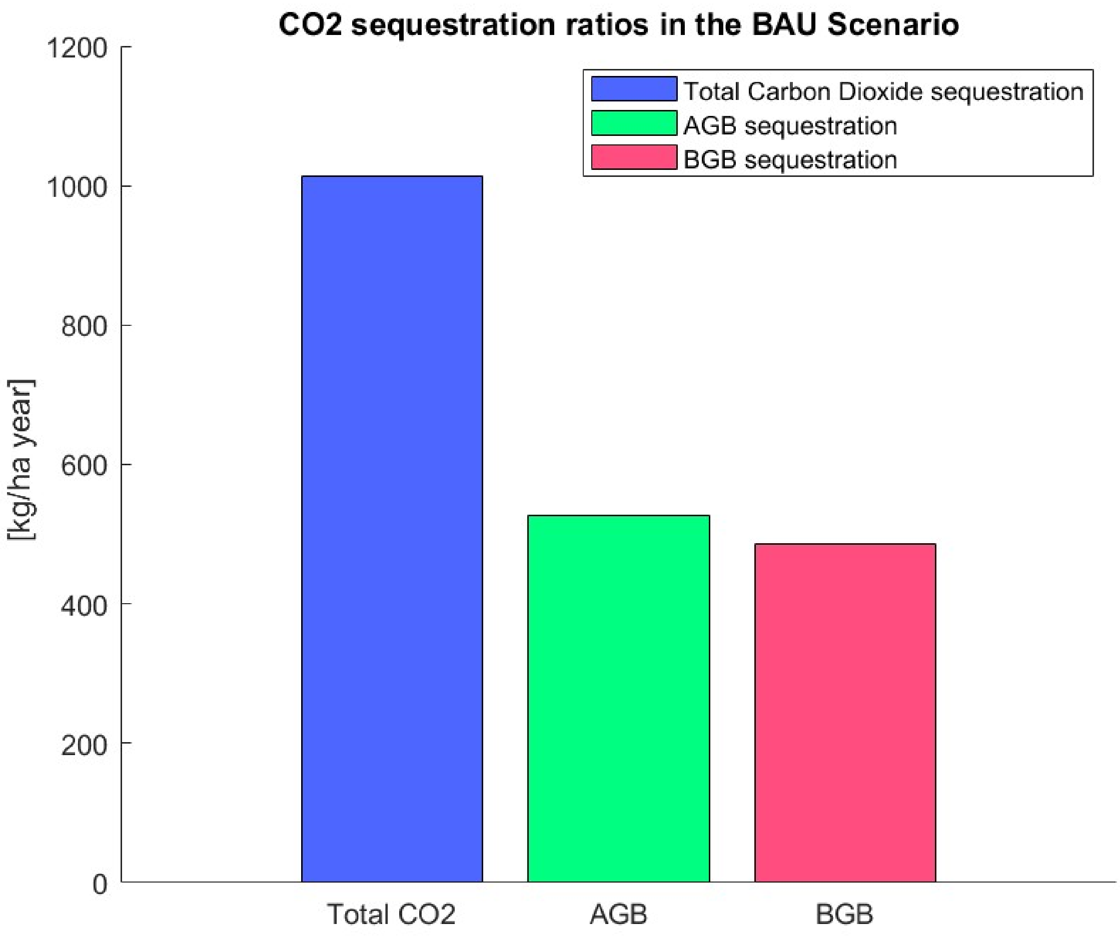


Figure 15: Fraction of CO_2 sequestered in AGB and BGB compared to the total in BAU Scenario

It is also interesting to observe the contribution for carbon uptake given respectively by the ABG and the BGB, which rates are shown in figure 15, AGB is responsible for 52% of the total sequestration while the remaining 48% is to be attributed to the BGB.

4.2.Scenario 2: Substituting inorganic fertilizer with organic fertilizers and application of biochar

Bandhari et al. (2014) [53] reported that the utilization of biochar can be considered as a long wave geoengineering option for climate change mitigation as it plays a role into the removal of CO_2 from the atmosphere and enhances the level of long wave radiation leaving from the planet. A biochar system is a carbon sink, where agricultural crops are grown and is subsequently pyrolyzed to produce biochar, which is then applied to soil. This means that CO_2 from atmosphere is sequestered as carbohydrates in the growing plants and that conversion of the plant biomass to biochar stabilizes the carbon. The stabilization of carbon in biochar delays its decomposition and ensures that carbon remains locked away from the atmosphere for hundreds to thousands of years. In carbon cycle, plants remove CO_2 from atmosphere via photosynthesis and convert it into biomass. Almost all that carbon (99%) is returned to atmosphere as CO_2 when plants die and decay, or immediately if biomass is burned as a renewable substitute for fossil fuels. In biochar cycle, half (50%) of that carbon is removed and sequestered as biochar and the rest half (50%) is converted to renewable energy co-products before being returned to the atmosphere.

Application of higher amounts of biochar to the soil may increase the carbon credit benefit to the farmers. Carbon which is applied to the field in the form of biochar could provide the farmer carbon credits that could be sold in a C credit market for additional income.

Major et al. (2013) (54) have showed that biochar sprinkled on the soil every three years at a rate of 20 t ha-1 gives a yield increase of 0% in the first year, a yield increase of 28% in the second year and 30% at the end of the third year.

Syuhada et al. (2016) [55] demonstrated that the application of biochar alone is not able to supply enough nutrients for the healthy growth of corn, so the proposed scenario involves the use of biochar as soil amendment and a switch to a mix of organic fertilizers and urea. Organic fertilizers are derived from biological or living materials. These fertilizers take longer time to release the nutrient in the soil. Organic fertilizers come in the different forms such as: manure derived from livestock such as cows, chickens, goats and others. Green manure is obtained from young plants, especially different type of legumes. Compost derived from agricultural that is waste organic material such as straw, corn stalks or decomposed waste. In contrast, inorganic fertilizers are classified as those fertilizers that are synthesized artificially or mined from non-living materials. Also known as chemical fertilizers, inorganic fertilizers are absorbed by the plants relatively fast. Urea is a chemical fertilizer. Nitrogen is a major element required for successful plant growth and development. Farmers often cultivate sweet corn with excessive nitrogen, which will damage soil fertility. Also, a reduced amount of nitrogen in the soil leads to a higher C:N ratio, which is recommended for a successful Carbon Farming implementation.

Pangaribuan et al. (2018) [56] studied the effect of organic fertilizer and urea fertilizer on growth, yield, and quality of sweet corn (Zea mays L. saccharata) and soil health. The results showed that application of integrated use of organic fertilizer (poultry manure), at a rate of 15 t ha^{-1}, and urea fertilizer would decrease the use of urea of 25% and be recommended for sweet corn cultivation. Organic fertilizer gives a better postharvest quality of sweet corn and a better soil health with respect to soil respiration as well as fungi and bacterial population.

In this scenario the choice is then to sprinkle both biochar and the mix of organic fertilizer and urea on the field for harvesting.

4.3.1. LCA results of the cultivation phase in Scenario 2

As reported in this scenario Urea will be decreased by 25%, organic manure will be applied at a rate of 15-t ha^{-1} and biochar will be sprinkled at a rate of 20-t ha^{-1}. The use of biochar will be divided in the three years to allocate its impact on the three years of its studied effects. The results here are referred to 1 t of corn produced. The data for the production of biochar have been taken from the studies carried out by Hamedani et al. (2016) [65].

For what concerns the first year after the application of biochar, when no increase in yield is observed:

Table 16: CF results referred to 1 t of corn, Scenario 2, first year after the application of biochar

	Carbon Footprint (kg CO_2-eq/t)	**[%]**
Emissions	70,18	22,6
Maize seeds	0,69	0,2
Urea	25,12	8,1
Pesticide	7,19	2,3
Poultry Manure	0	0,0
Polyethylene	0,052	0,0
Biochar	148,7	47,8
Diesel	58,83	18,9
Total	**310,84**	100,0

With regard to the CF, from table 16 it is possible to notice that the application of biochar is the phase of life with the greatest impact with a contribution of 48%, followed by the emissions, which impact amounts to the 23% and the diesel consumption which impacts to the 18,9% of the total (figure 16).

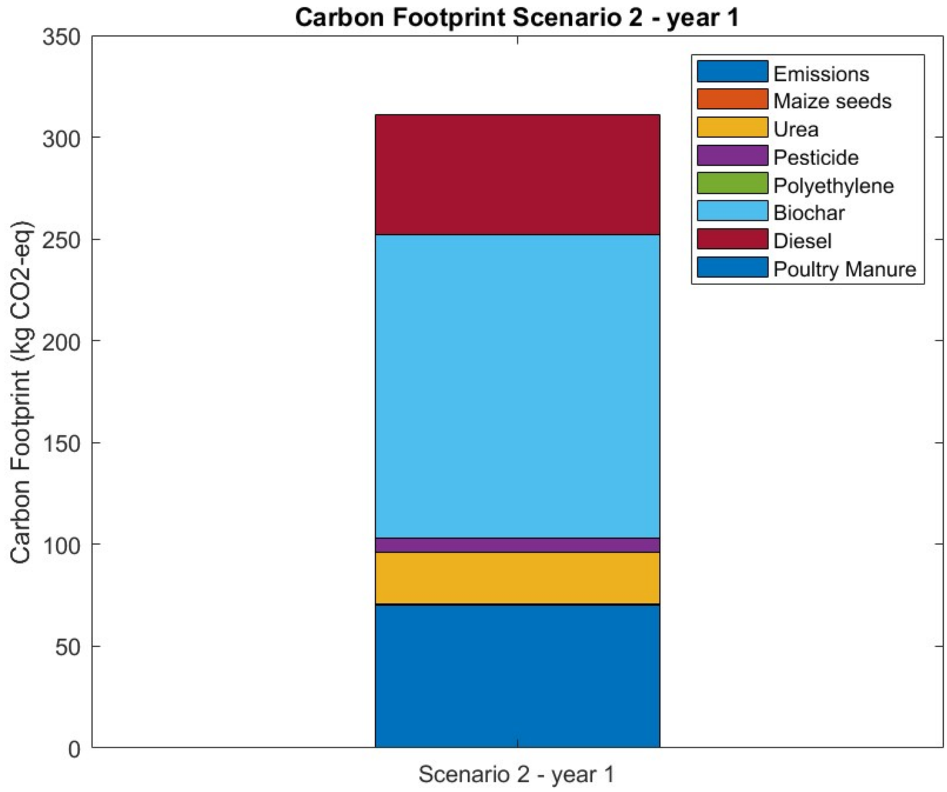


Figure 16: Cultivation CF specific contributions in scenario 2 - year 1. The results are referred to 1 t of sweet corn.

For what concerns the second year after the application of biochar, when an increase in yield of 28% is observed:

Table 17: CF results referred to 1 t of corn, Scenario 2, second year after the application of biochar

	Carbon Footprint (kg CO_2-eq/t)	**[%]**
Emissions	53,98	22,2
Maize seeds	0,69	0,3
Urea	19,32	8,0
Pesticide	5,64	2,3
Poultry Manure	0	0,0
Polyethylene	0,052	0,0
Biochar	116,32	47,9
Diesel	45,90	18,9
Total	**242,84**	100,0

With regard to the CF, table 17 shows that the application of biochar is the phase of life with the greatest impact with a contribution of 47,9%, followed by emissions accounting for 22% of the total and the diesel consumption which impacts to the 18,9% of the total (figure 17).

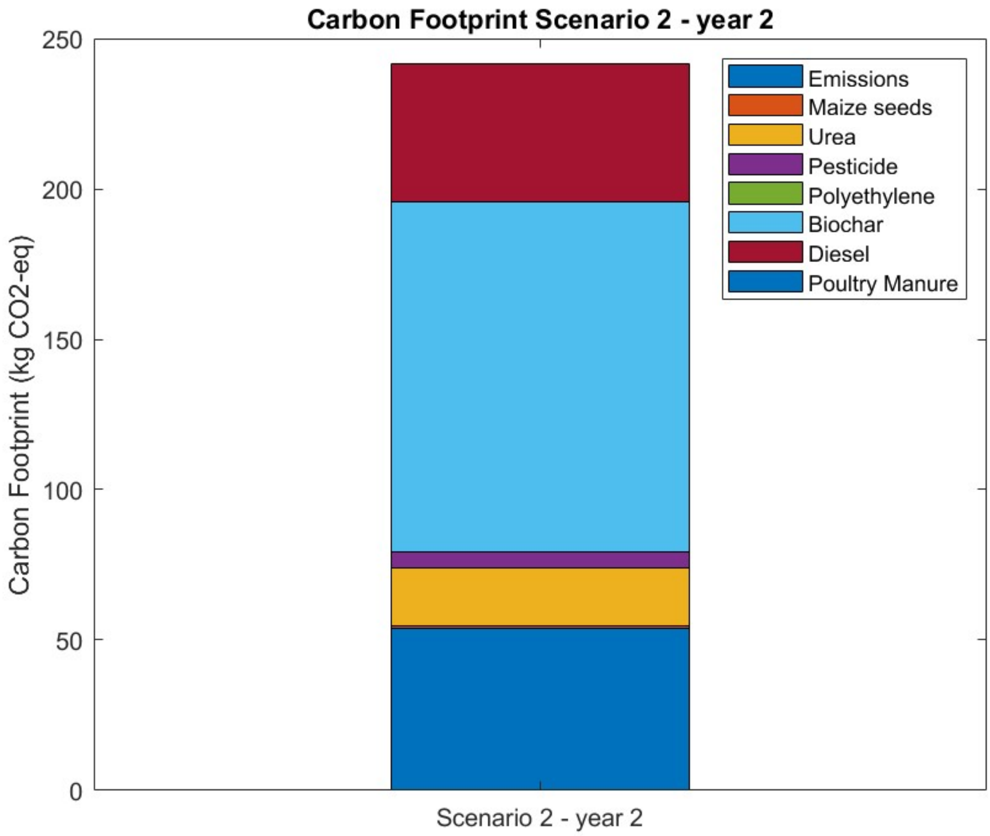


Figure 17: Agriculture CF specific contributions in scenario 2 - year 2. The results are referred to 1 t of sweet corn.

For what concerns the third year after the application of biochar, when an increase in yield of 30% is observed:

Table 18: CF results referred to 1 t of corn, Scenario 2, third year after the application of biochar

	Carbon Footprint (kg CO_2-eq/t)	**[%]**
Emissions	53,98	22,6
Maize seeds	0,53	0,2
Urea	19,32	8,1
Pesticide	5,53	2,3
Poultry Manure	0	0,0
Polyethylene	0,040	0,0
Biochar	114,43	47,9
Diesel	45,25	18,9
Total	**239,11**	100,0

With regard to the CF, from table 18 it is possible to notice that the application of biochar is the phase of life with the greatest impact with a contribution of 48%, followed by the diesel consumption which impacts to the 18,9% of the total (figure 18).

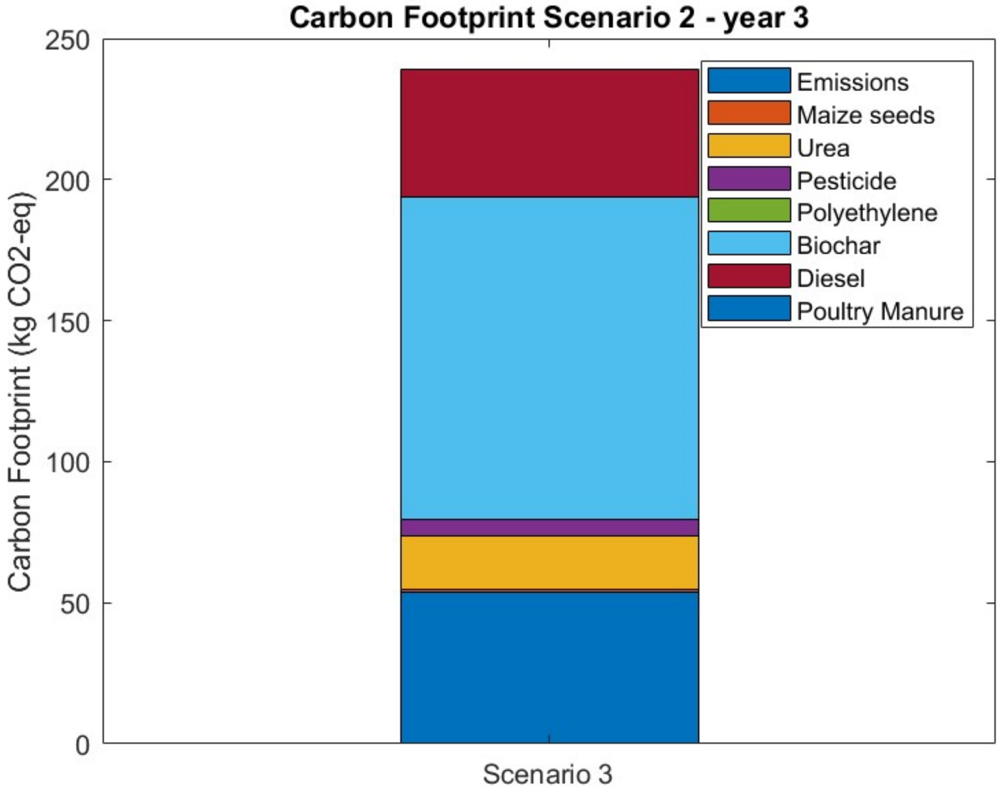


Figure 18: Agriculture CF specific contributions in scenario 2 - year 3. The results are referred to 1 t of sweet corn.

4.3.2. Carbon Sequestration in Scenario 2

Carbon Content and the amount of residue crop left on field after harvesting are left unchanged with respect to the BAU scenario, what changes is the dry matter yield assumed to be on average 20% higher than in the BAU scenario but evaluated for each year separately.

For what concerns the first year after the application of biochar, when no increase in yield is observed, the amount of carbon sequestered is the same of the BAU scenario and amounts to 1013,99 kg CO_2-eqha^{-1}yr^{-1}.

For what concerns the second year after the application of biochar, when an increase in yield of 28% is observed, the parameters employed for the calculation of Carbon sequestered are as follows (table 19):

Table 19: Values for NPP methodology in conventional tillage substituting fertilizers and using biochar scenario, second year after application of biochar

Plant Carbon Content	Roots Carbon Content	Amount of residue crop left on field after harvesting	Dry Matter Yield
C_{cp} [-]	C_{cr} [-]	S_s [-]	Y_p [t $ha^{-1}year^{-1}$]
0,48	0,345	0,20	13,08

The result of the calculation model shows that in this case the carbon sequestration is equal to 1297,9 kg CO_2-eq$ha^{-1}yr^{-1}$.

For what concerns the second year after the application of biochar, when an increase in yield of 30% is observed, the parameters employed for the calculation of Carbon sequestered are as follows (table 20):

Table 20: Values for NPP methodology in conventional tillage substituting fertilizers and using biochar scenario, third year after application of biochar

Plant Carbon Content	Roots Carbon Content	Amount of residue crop left on field after harvesting	Dry Matter Yield
C_{cp} [-]	C_{cr} [-]	S_s [-]	Y_p [t $ha^{-1}year^{-1}$]
0,48	0,345	0,20	13,29

The result of the calculation model shows that in this case the carbon sequestration is equal to 1318,2 kg CO_2-eq$ha^{-1}yr^{-1}$.

Total carbon dioxide sequestered from the atmosphere, each year after the application of biochar, is shown in figure 19.

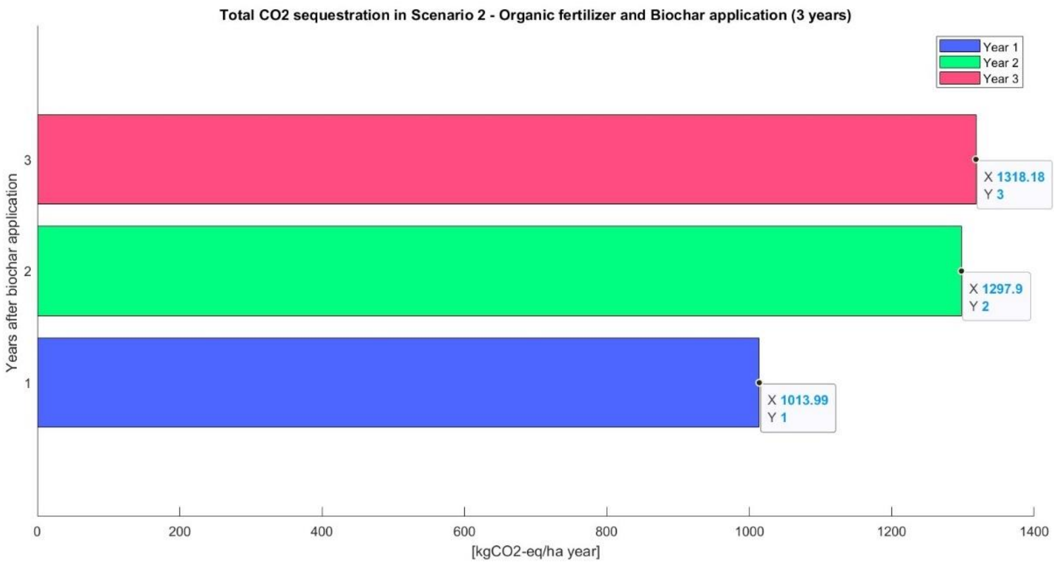


Figure 19: Carbon sequestration in scenario 2 for each year after the application of biochar.

4.4. Scenario 3: Reduced tillage

Dachraoui et al. (2020) [57] reported that a result of the interaction between residue at the soil surface during No Tillage (NT) management and the lack of soil disturbance is enhancing Soil Organic Carbon contents (SOC) at/or near the soil surface. Actually, the primary factor limiting the stabilisation of soil carbon within microaggregates is tillage disturbance. Tillage treatments change aggregate distributions dramatically; more macro- and micro-aggregates can be identified after NT treatment than under CT system, Huang et al. (2010) [61] found that under long-term maize monoculture in Northeast China, NT encouraged soil C accumulation inside micro-aggregates, which increased total SOC by 18.1% in comparison to CT treatment.

Basing on the previous observations the second possible scenario analyzed is about "Reduced Tillage". You, Debao, et al. (2017) [60] showed how short-term reduced tillage (rotary-till and no-till) and residue incorporation promoted soil properties and maize growth. Compared with plow-till, rotary-till and no-till decreased soil bulk density and compaction below the plough layer (30 cm). The soil organic carbon (SOC) increased under the rotary-till (0–20 cm) and no-till (0–10 cm), which were higher in 0–30 cm soil layers for residue incorporation.

Reduced tillage practices minimize soil disturbance with targeted and appropriate tillage based on farm goals. Reduced tillage means less intensity, shallower depth, and less area disturbed, either in the bed, field or across the farm. It can mean less frequent tillage and lead to successful adoption of no-till practices.

Practices take many forms. They may be system-wide, applied across the whole farm, or only fit in a part of the rotation for specific crops. They often maintain the benefits of some tillage for managing weeds, making a better seed bed for crop establishment, or incorporating residues. How they take shape on a farm can depend on farm size and soil characteristics, access to equipment or materials, farm skill sets, and labour availability.

4.4.1. LCA results of the cultivation phase in Scenario 3

Afshar et al. (2022) [64] performed a Sustainability assessment of corn production in conventional and conservation tillage systems using LCA methodology. From this study it is possible to notice that in conservational tillage diesel consumption for machineries is about 53% lower than in conventional tillage, while the amount of fertilizers employed is unchanged.

Table 21: CF of the cultivation phase of 1 t of sweet corn in Scenario 3

	Carbon Footprint (kg CO_2-eq/t)	[%]
Emissions	64,72	43,9
Maize seeds	0,70	0,5
Urea	33,50	22,7
Ammonium Nitrate	5,13	3,5
Nitrogen fertilizer	8,36	5,7
Pesticide	7,19	4,9
Polyethylene	0,052	0,0
Diesel	27,65	18,8
Total	**147,30**	100,0

With regard to the CF (figure 20) the use of Urea is the phase of life with the greatest impact with a contribution of 22,7%, followed by the diesel consumption which impacts to the 18,8% of the total (Table 21).

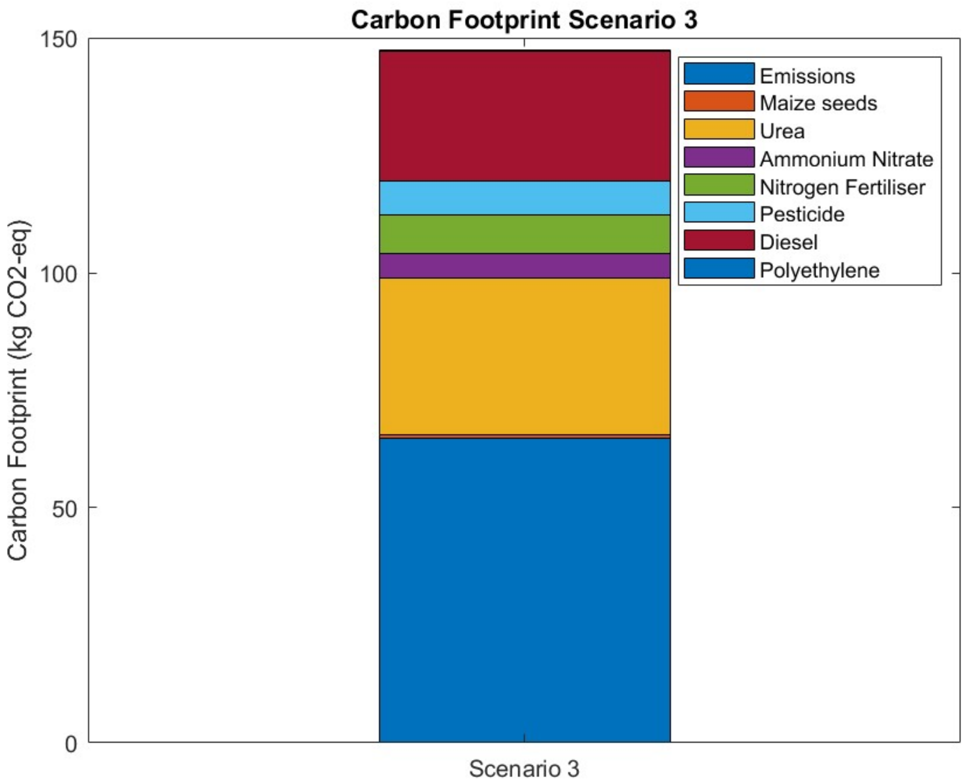


Figure 20: Agriculture CF specific contributions in scenario 3. The results are referred to 1 t of sweet corn.

4.4.2. Carbon Sequestration results in Scenario 3

The aforementioned study of Gao et al. (2015) [51] showed how Biomass carbon content changes in relation with tillage practices, in this analysis, in addition to the increase in carbon content, the practice of RT has been combined with a higher amount of crop residue left on field, about 80% (Table 22).

Table 22: Values for NPP methodology in reduced tillage scenario

Plant Carbon Content	**Roots Carbon Content**	**Amount of residue crop left on field after harvesting**
C_{cp} [-]	C_{cr} [-]	S_s [-]
0,53	0,42	0,80

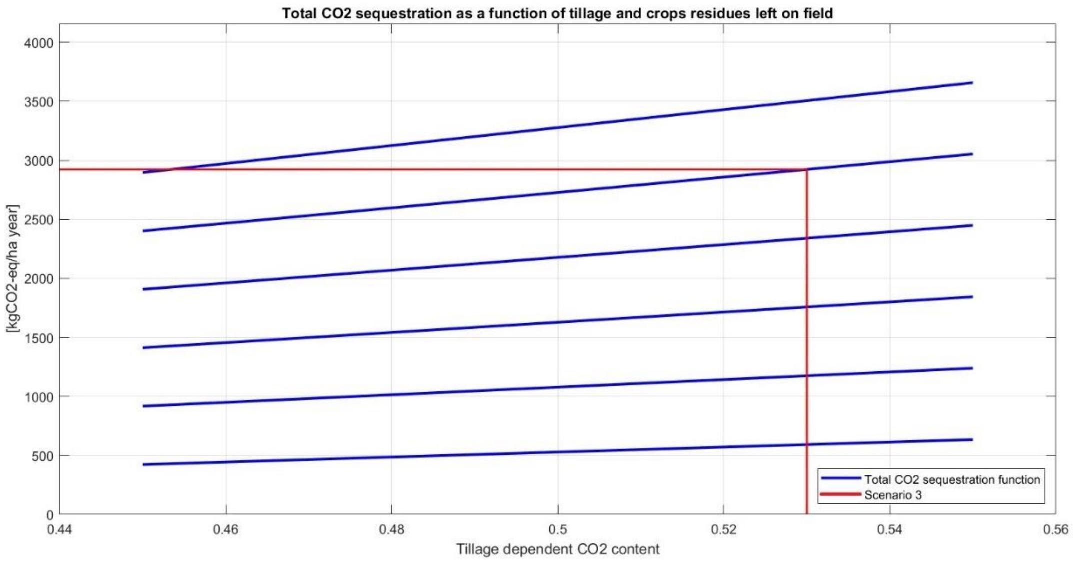


Figure 21: Fraction of CO_2 sequestered in AGB and BGB compared to the total in Scenario 3

The result of the calculation model (figure 21) shows that in this case the carbon sequestration is equal to 2922,4 kg CO_2-eqqha^{-1}yr^{-1}.

It is also interesting to observe the contribution for carbon uptake given respectively by the ABG and the BGB, which rates are shown in the following figure 22:

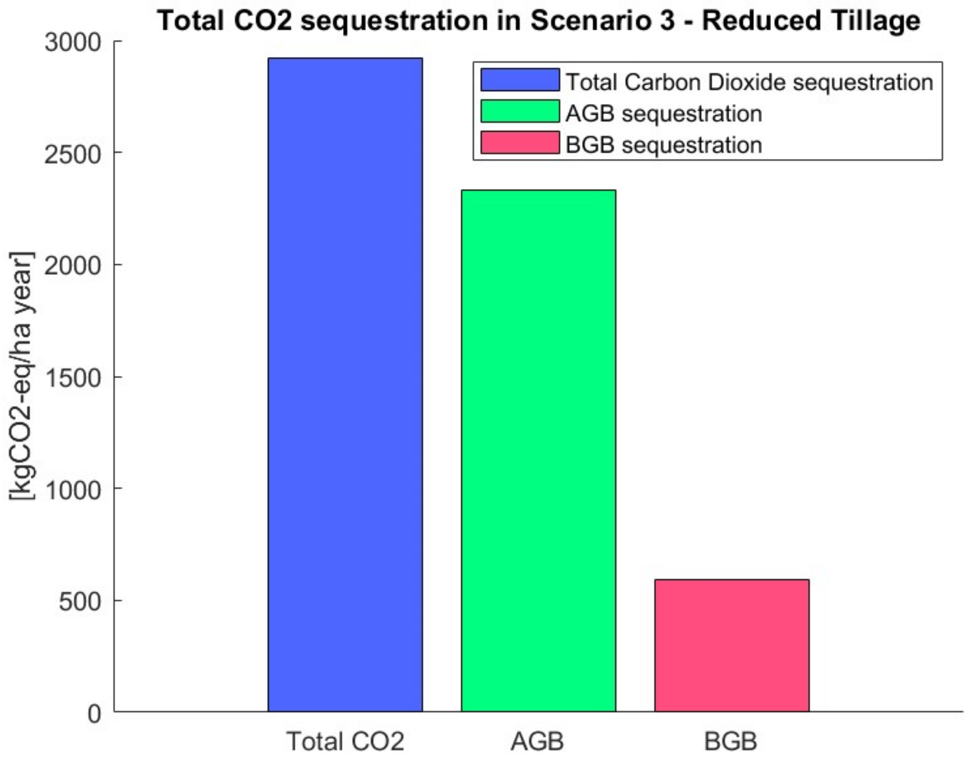


Figure 22: Fraction of CO_2 sequestered in AGB and BGB compared to the total in Scenario 3

this scenario AGB is responsible for 75% of the total sequestration while the remaining 25% is to be attributed to the BGB.

4.5. Scenario 4: Reduced Tillage, application of biochar and use of organic manure as a fertilizer

Almagro et al. (2016) [62] have compared different scenarios about Conventional Tillage, Reduced Tillage and Reduced Tillage combined with manure and have been able to show that when compared to reduced- and no-tillage regimes, the incorporation of manure implied a higher stock of carbon in the soil by the combination of conservational tillage and the use of organic fertilizers such as manure. Khorramdel et al. 2013 [63] have showed that the effect of crop management practices on carbon sequestration rate in soil is significant and in particular that no-tillage with application of organic fertilizers increased soil sequestered carbon.

Therefore, in this analysis reduced tillage has been combined with the application of biochar and organic fertilizer. Also, a higher amount of crop residue left on field, about 80% has been assumed. These are the justifications for which the values in table 4 have been in used to model Scenario 4.

4.5.1. LCA results of the cultivation phase in Scenario 4

As reported, in this scenario Urea will be decreased by 25%, organic manure will be applied at a rate of 15-t ha^{-1} and biochar will be sprinkled at a rate of 20-t ha^{-1}. The use of biochar will be divided in the three years to allocate its impact on the three years of its studied effects. The results here are referred to 1 t of corn produced.

In addition, reduced tillage practices can decrease diesel consumption by 53%.

For what concerns the first year after the application of biochar, when no increase in yield is observed:

Table 23: CF results referred to 1 t of corn, Scenario 4, first year after the application of biochar

	Carbon Footprint (kg CO_2-eq/t)	**[%]**
Emissions	70,18	25,1
Maize seeds	0,69	0,2
Urea	25,12	9,0
Pesticide	7,19	2,6
Poultry Manure	0	0,0
Polyethylene	0.052	0,0
Biochar	148,7	53,2
Diesel	27,65	9,9
Total	**279,65**	100,0

With regard to the CF (Table 23) the application of biochar is the phase of life with the greatest impact with a contribution of 53,2%, followed by emissions which account about 25% of emissions and the diesel consumption which impacts to the 9,9% of the total (figure 23).

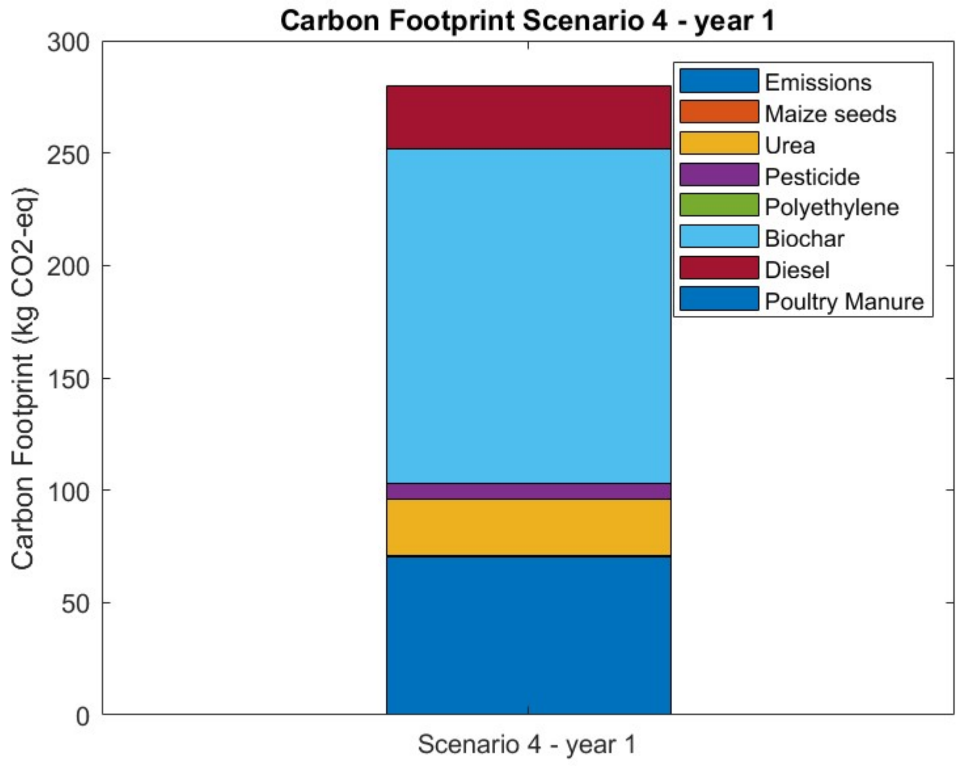


Figure 23: Agriculture CF specific contributions in scenario 4 - year 1. The results are referred to 1 t of sweet corn.

For what concerns the second year after the application of biochar, when an increase in yield of 28% is observed:

Table 24: CF results referred to 1 t of corn, Scenario 4, second year after the application of biochar

	Carbon Footprint (kg CO_2-eq/t)	**[%]**
Emissions	53,98	24,7
Maize seeds	0,6	0,3
Urea	19,32	8,8
Pesticide	5,64	2,6
Poultry Manure	0	0,0
Polyethylene	0,052	0,0
Biochar	116,32	53,2
Diesel	21,60	9,9
Total	**218,48**	100,0

With regard to the CF (Table 24) the application of biochar is the phase of life with the greatest impact with a contribution of 53,2%, followed by the diesel consumption which impacts to the 9,9% of the total (figure 24).

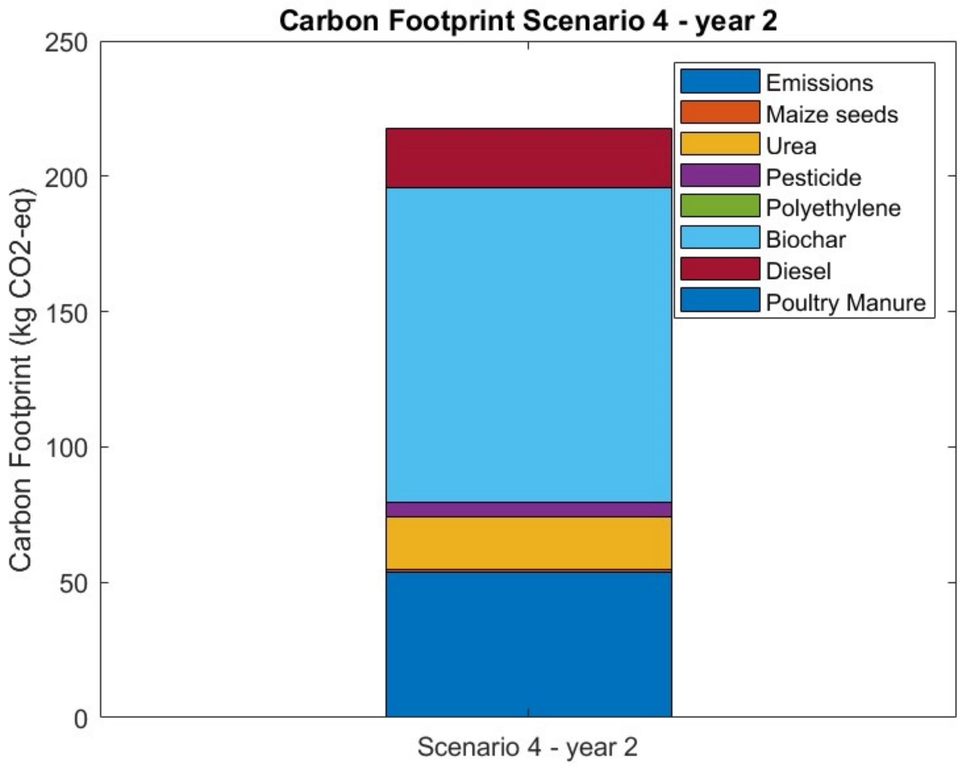


Figure 24: Agriculture CF specific contributions in scenario 4 - year 2. The results are referred to 1 t of sweet corn.

For what concerns the third year after the application of biochar, when an increase in yield of 30% is observed:

Table 25:CF results referred to 1 t of corn, Scenario 4, third year after the application of biochar

	Carbon Footprint (kg CO_2-eq/t)	**[%]**
Emissions	53,98	25,1
Maize seeds	0,53	0,2
Urea	19,32	9,0
Pesticide	5,53	2,6
Poultry Manure	0	0,0
Polyethylene	0,040	0,0
Biochar	114,43	53,2
Diesel	21,27	9,9
Total	**215,13**	100,0

With regard to the CF (Table 25) the application of biochar is the phase of life with the greatest impact with a contribution of 48%, followed by the diesel consumption which impacts to the 18,9% of the total (figure 25).

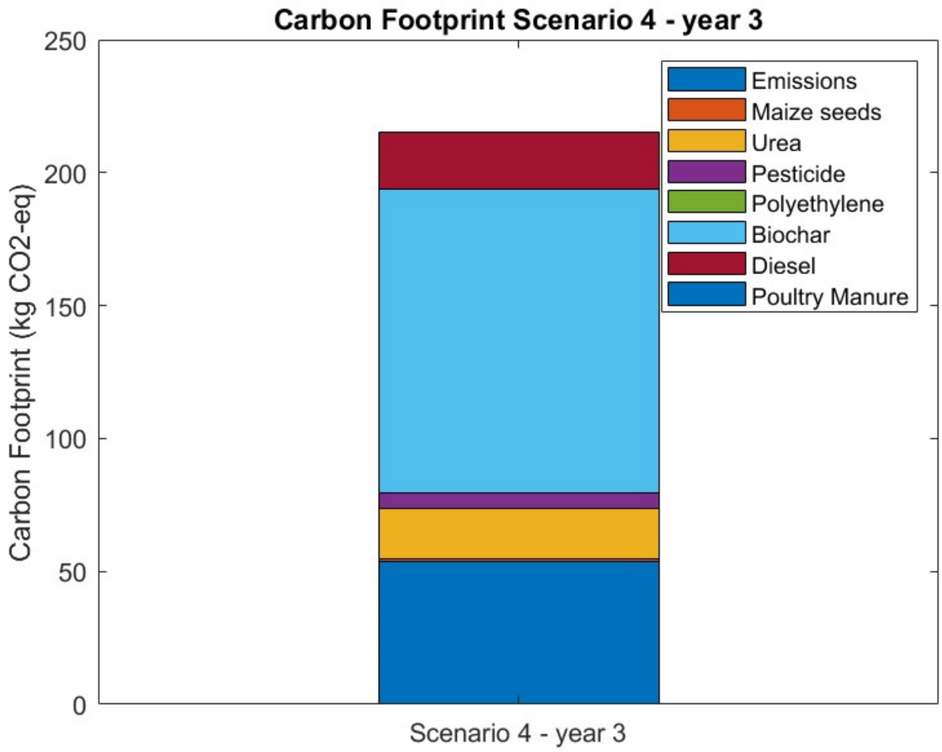


Figure 25: Agriculture CF specific contributions in scenario 4 - year 3. The results are referred to 1 t of sweet corn.

4.5.2. Carbon Sequestration results of Scenario 4

Carbon Content and the amount of residue crop left on field after harvesting are left unchanged with respect to the scenario 3, reduced tillage, what changes is the dry matter yield assumed to be on average 20% higher than in the BAU scenario but evaluated for each year separately.

For what concerns the first year after the application of biochar, when no increase in yield is observed, the amount of carbon sequestered is the same of the reduced tillage scenario and amounts to 2922,4 kg CO_2-eqha^{-1}yr^{-}. The parameters used in the calculation model are reported in table 26.

Table 26: Values for NPP methodology scenario 4, first year

Plant Carbon Content	Roots Carbon Content	Amount of residue crop left on field after harvesting	Dry Matter Yield
C_{cp} [-]	C_{cr} [-]	S_s [-]	Y_p [t ha^{-1}year^{-1}]
0,53	0,42	0,80	12,27

For what concerns the second year after the application of biochar, when an increase in yield of 28% is observed, the parameters employed for the calculation of Carbon sequestered are as follows (Table 27):

Table 27: Values for NPP methodology scenario 4, second year

Plant Carbon Content	Roots Carbon Content	Amount of residue crop left on field after harvesting	Dry Matter Yield
C_{cp} [-]	C_{cr} [-]	S_s [-]	Y_p [t $ha^{-1}year^{-1}$]
0,53	0,42	0,80	13,08

The result of the calculation model shows that in this case the carbon sequestration is equal to 3740,7 kg CO_2-eq$ha^{-1}yr^{-1}$.

For what concerns the second year after the application of biochar, when an increase in yield of 30% is observed, the parameters employed for the calculation of Carbon sequestered are as follows (Table 28):

Table 28: Values for NPP methodology scenario 4, third year

Plant Carbon Content	Roots Carbon Content	Amount of residue crop left on field after harvesting	Dry Matter Yield
C_{cp} [-]	C_{cr} [-]	S_s [-]	Y_p [t $ha^{-1}year^{-1}$]
0,53	0,42	0,80	13,29

The result of the calculation model shows that in this case the carbon sequestration is equal to 3799,2 kg CO_2-eq$ha^{-1}yr^{-1}$.

Total carbon dioxide sequestered from the atmosphere, each year after the application of biochar, is shown in figure 26.

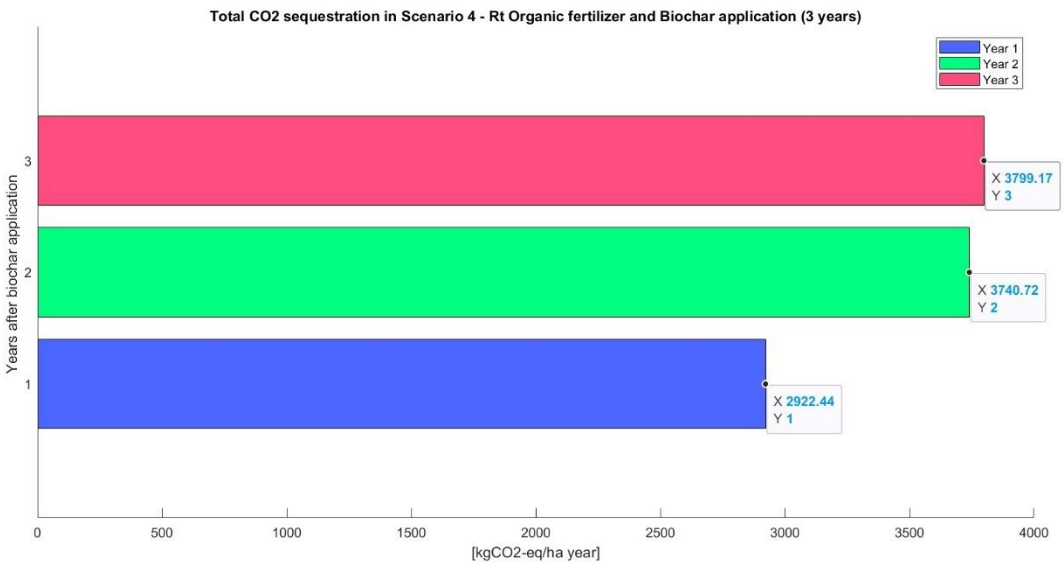


Figure 26: Carbon sequestration in scenario 4 for each year after the application of biochar.

4.6. *The products environmental impact*

Each environmental impact reported in this section, since it is referred to the single finished product, is reported in terms of annual impact. So BAU scenario and scenario 3, which do not have yearly variability will be reported as calculated while Scenario 2 and Scenario 4, which impacts change depending on the year considered, will be here reported as an average of the three years.

4.6.1. *BAU Scenario*

STEAMED VALFRUTTA SWEET CORN

Table 29 shows the results obtained for the indicator considered, referring to 1 kg of Steamed Valfrutta sweet corn.

Table 29: CF results referred to 1 kg of steamed Valfrutta sweet corn, BAU Scenario.

Indicator	Upstream	Core	Total
Carbon Footprint (kg CO_2 eq/kg)	1,75	0,26	2,01

With regard to the CF the upstream is the phase of life with the greatest impact with a contribution of 87,3%, while the core phase is responsible for the 12,7% of the total, as figure 27 shows:

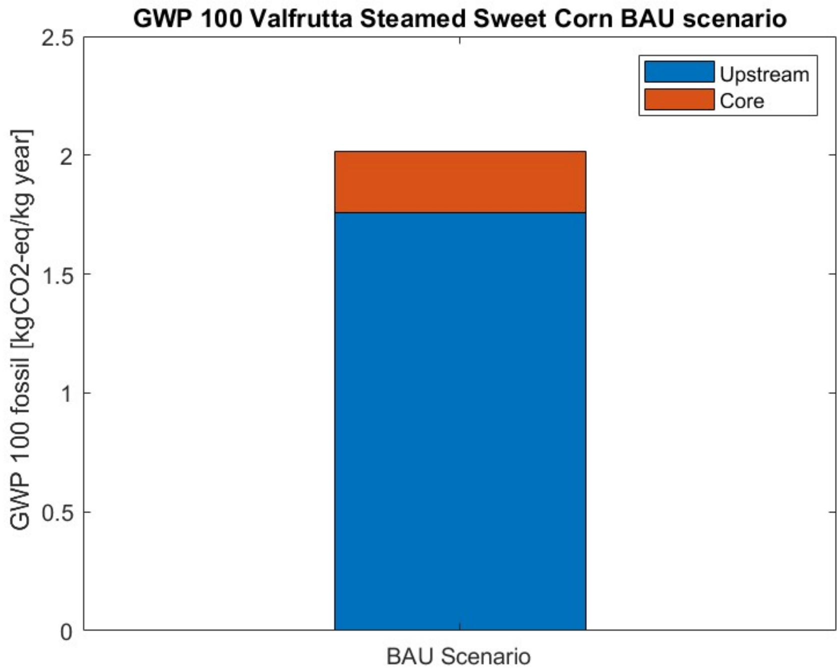


Figure 27: Total CF divided in the upstream and core phase. The results are referred to 1 kg of Steamed Valfrutta sweet corn, in BAU scenario.

The most significant impact is related to the production of the tin-plated cans with a contribution of 58,7% followed by the corn cultivation phase with a contribution of 22,6% and the corn processing phase (also in this case the main contribution is attributable to the consumption of natural gas) with a contribution of 10,7%. as shown by the tree diagram in figure 28.

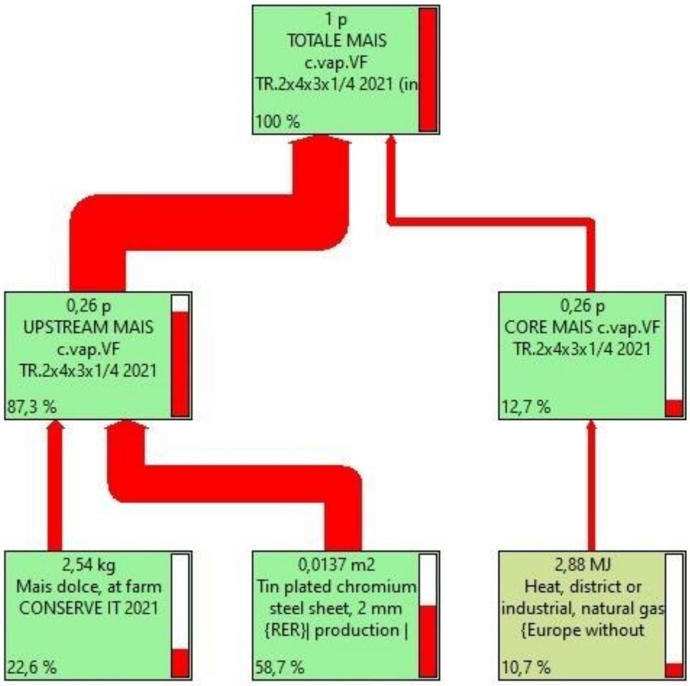


Figure 28: Tree diagram of the results of the Carbon Footprint for the steamed Valfrutta sweet corn.

CIRIO WAKU SWEET CORN

Table 30 shows the results obtained for the indicator considered, referring to 1 kg of Cirio WAKU sweet corn

Table 30:CF results referred to 1 kg of Cirio WAKU sweet corn.

Indicator	Upstream	Core	Total
Carbon Footprint (kg CO_2 eq/kg)	1,32	0,18	1,50

With regard to the CF the upstream is the phase of life with the greatest impact with a contribution of 78,8%, while the core phase is responsible for the 21,2% of the total, as figure 29 shows:

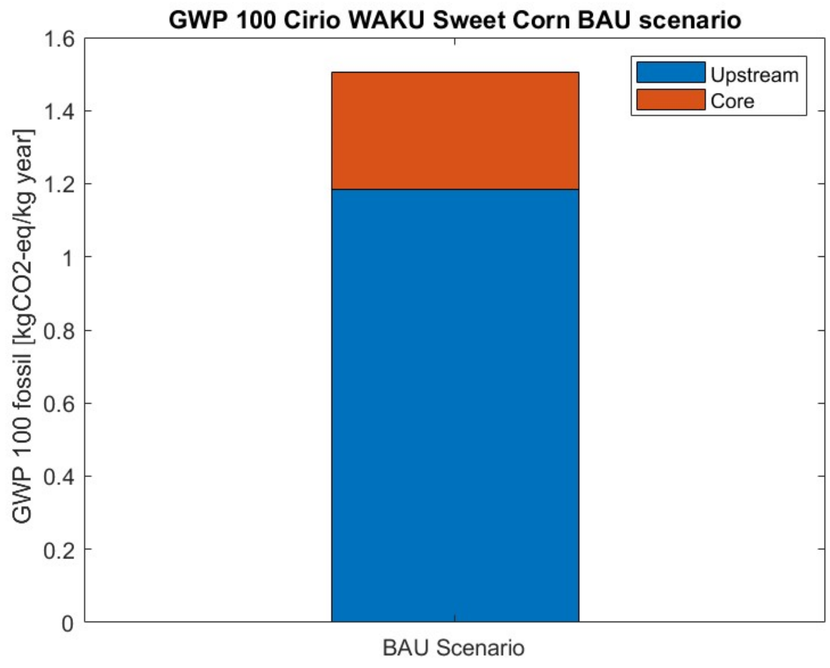


Figure 29: total CF divided in the upstream and core phase. The results are referred to 1 kg of Cirio WAKU sweet corn, in BAU scenario.

The most significant impact is related to the production of the tin-plated cans with a contribution of 46,4% followed by the corn cultivation phase with a contribution of 29,1% and the corn processing phase (also in this case the main contribution is attributable to the consumption of natural gas) with a contribution of 10,7% as shown by the tree diagram in figure 30.

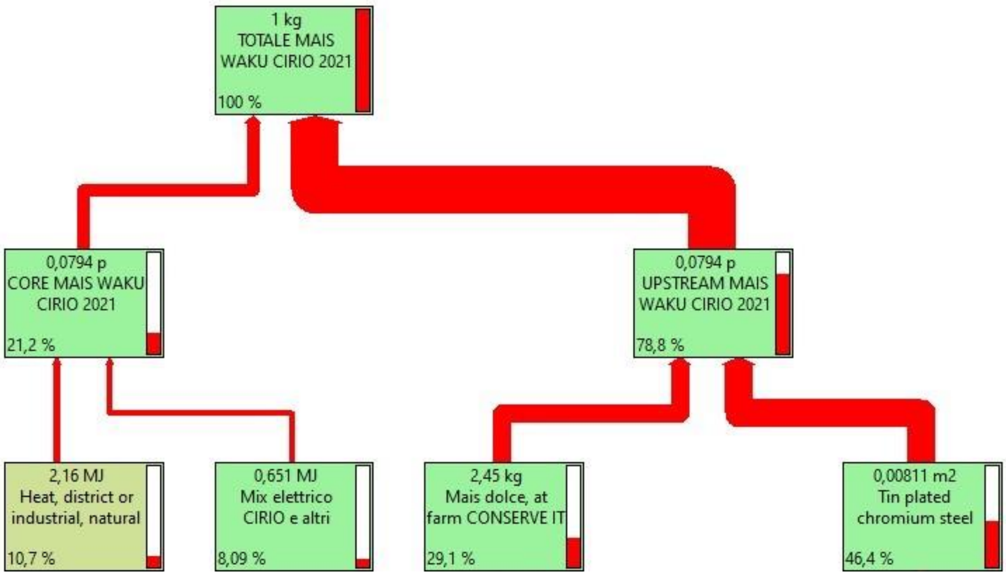


Figure 30: Tree diagram of the results of the Carbon Footprint for the Cirio WAKU sweet corn.

4.6.2. Scenario 2

STEAMED VALFRUTTA SWEET CORN

Table 31 shows the results obtained for the indicator considered, referring to 1 kg of Steamed Valfrutta sweet corn.

Table 31: CF results referred to 1 kg of steamed Valfrutta sweet corn in Scenario 2.

Indicator	Upstream	Core	Total
Carbon Footprint (kg CO_2 eq/kg)	1,95	0,26	2,21

With regard to the CF the upstream is the phase of life with the greatest impact with a contribution of 88,2%, while the core phase is responsible for the 11,8% of the total, as figure 31 shows:

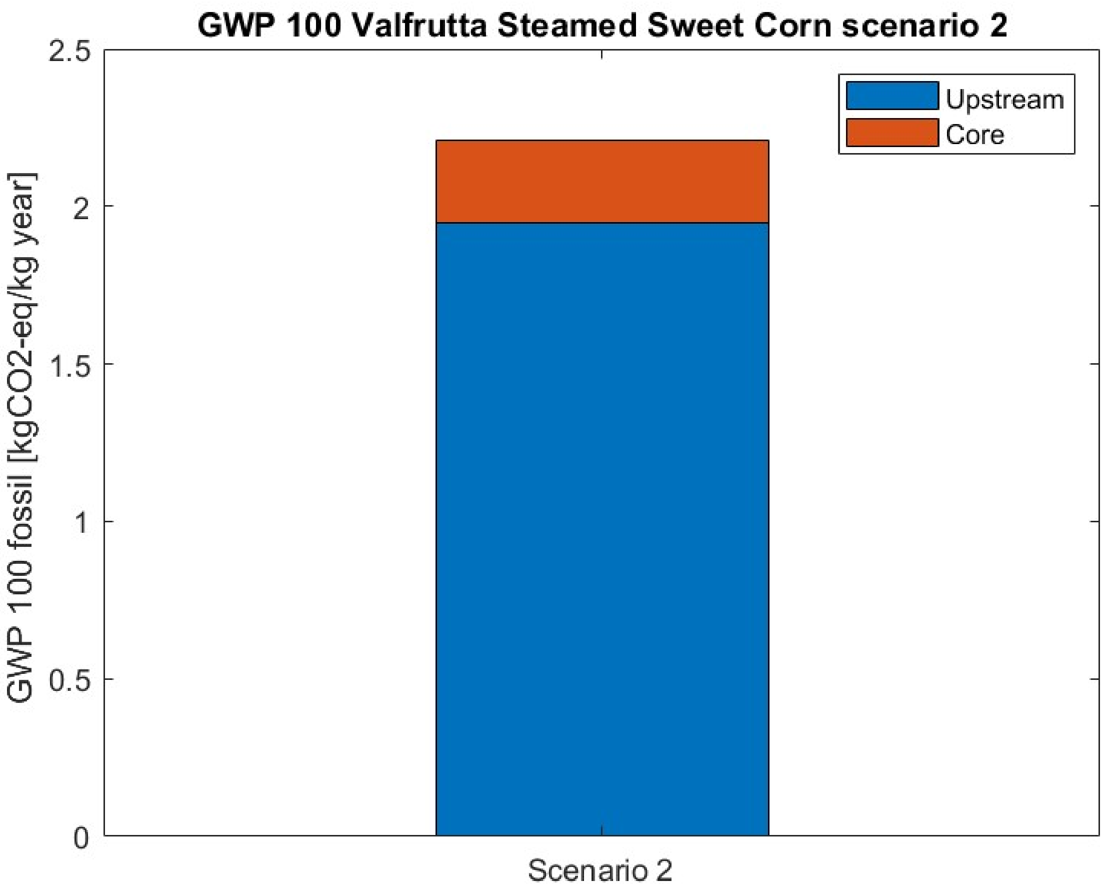


Figure 31: Total CF divided in the upstream and core phase. The results are referred to 1 kg of Steamed Valfrutta sweet corn, in scenario 2.

The most significant impact is related to the production of the tin-plated cans with a contribution of 53,2% followed by the corn cultivation phase with a contribution of 29,7% and the corn processing phase (in this case the main contribution is attributable to the application of biochar) with a contribution of 14,3%. as shown by the tree diagram in figure 32.

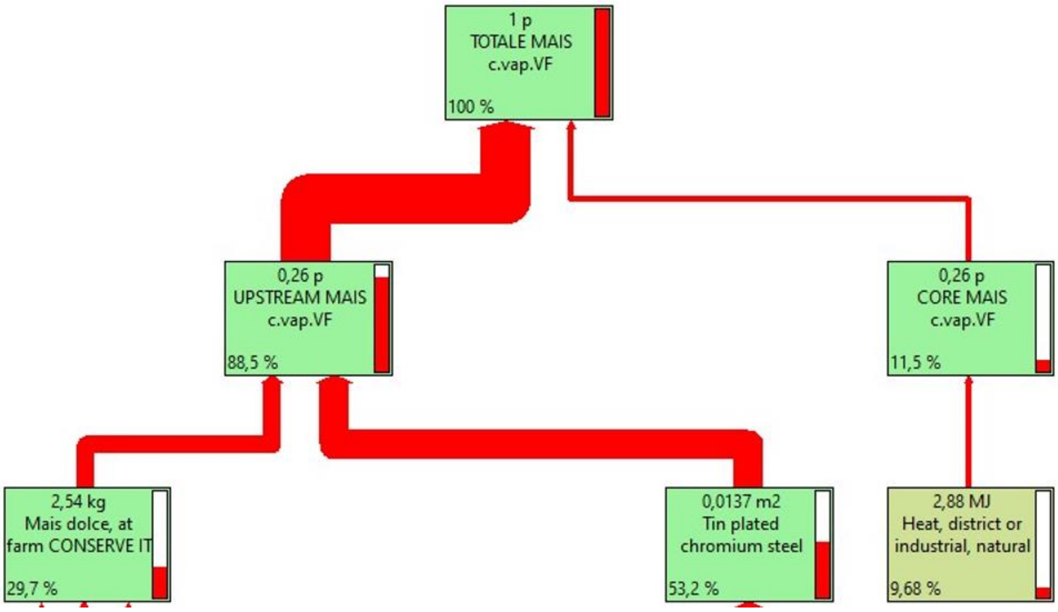


Figure 32: Tree diagram of the results of the Carbon Footprint for the steamed Valfrutta sweet corn.

CIRIO WAKU SWEET CORN

Table 32 shows the results obtained for the indicator considered, referring to 1 kg of Cirio WAKU sweet corn

Table 32:CF results referred to 1 kg of Cirio WAKU sweet corn.

Indicator	Upstream	Core	Total
Carbon Footprint (kg CO_2 eq/kg)	1,38	0,32	1,70

With regard to the CF the upstream is the phase of life with the greatest impact with a contribution of 81,2%, while the core phase is responsible for the 18,8% of the total, as figure 33 shows:

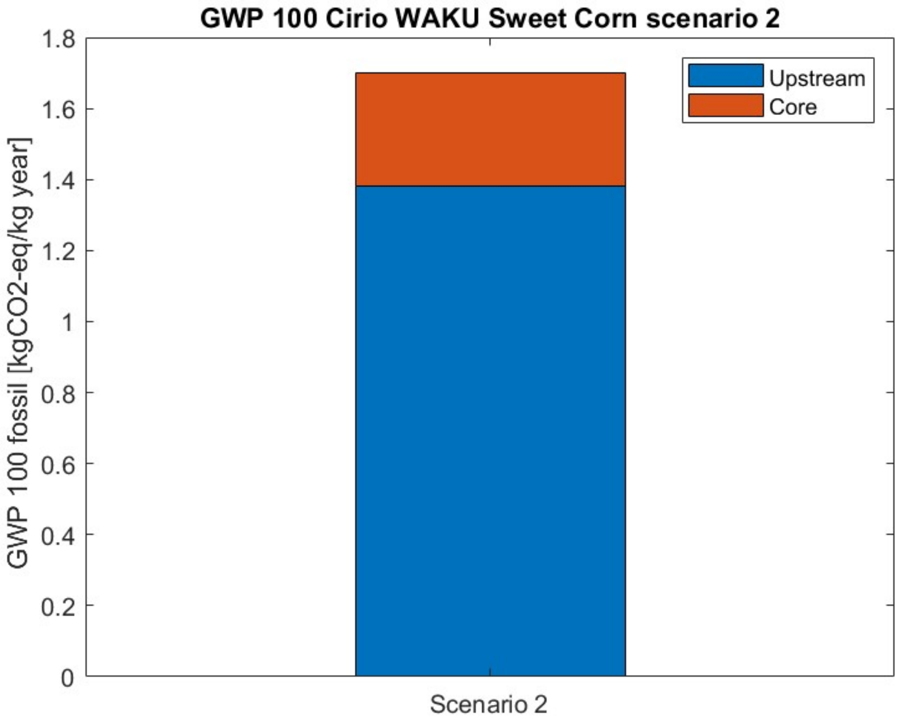


Figure 33: Total CF divided in the upstream and core phase. The results are referred to 1 kg of Cirio WAKU sweet corn, in scenario 2.

The most significant impact is related to the production of the tin-plated cans with a contribution of 40,9% followed by the corn cultivation phase with a contribution of 29,1% and the corn processing phase (also in this case the main contribution is attributable to the application of biochar) with a contribution of 17,9% as shown by the tree diagram in figure 34.

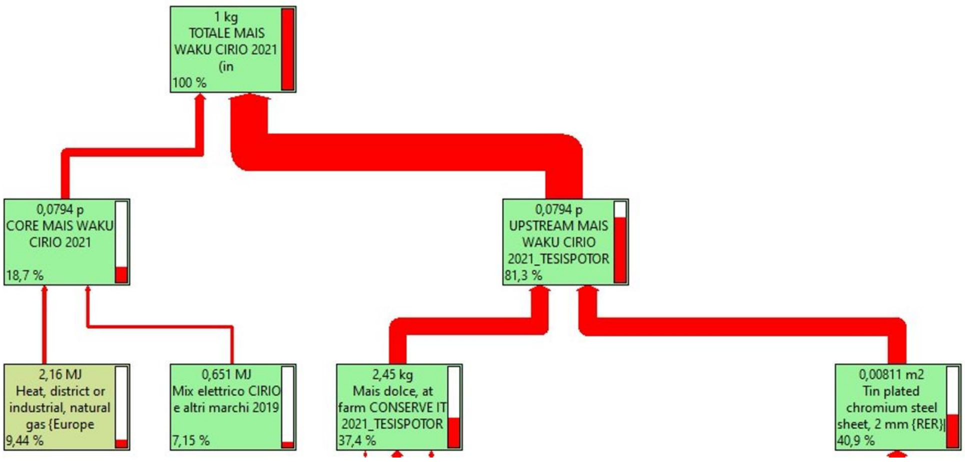


Figure 34: Tree diagram of the results of the Carbon Footprint for the Cirio WAKU sweet corn.

4.6.3. Scenario 3

STEAMED VALFRUTTA SWEET CORN

Table 33 shows the results obtained for the indicator considered, referring to 1 kg of Steamed Valfrutta sweet corn

Table 33: CF results referred to 1 kg of steamed Valfrutta sweet corn in Scenario 3.

Indicator	Upstream	Core	Total
Carbon Footprint (kg CO_2 eq/kg)	1,66	0,26	1,92

With regard to the CF, also in this case the upstream is the phase of life with the greatest impact with a contribution of 86,8%, while the core phase is responsible for the 13,2% of the total, as figure 35 shows:

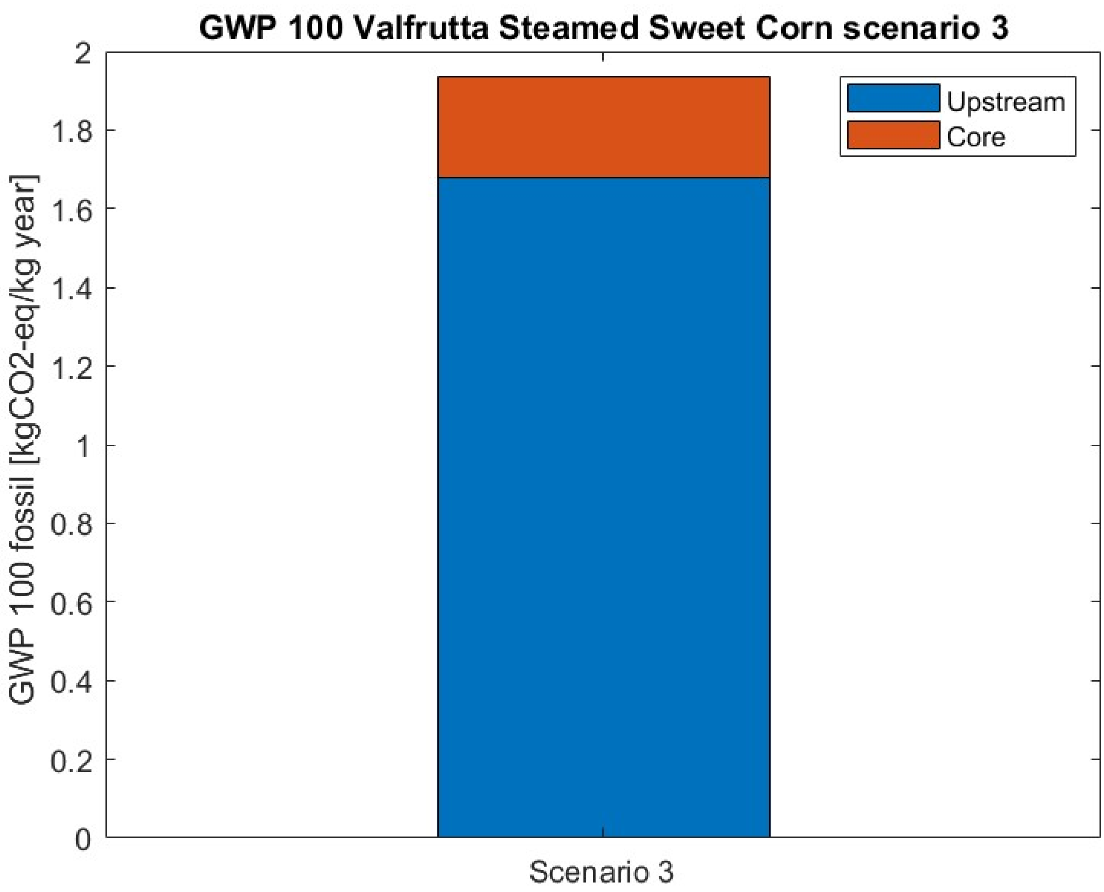


Figure 35: Total CF divided in the upstream and core phase. . The results are referred to 1 kg of Steamed Valfrutta sweet corn, in scenario 3.

The most significant impact is still related to the production of the tin-plated cans with a contribution of 61% followed by the corn cultivation phase, which decreases its importance, with a contribution of 19,3% and the corn processing phase (also in this case the main contribution is attributable to the consumption of natural gas) with a contribution of 11%, as shown by the tree diagram in figure 36.

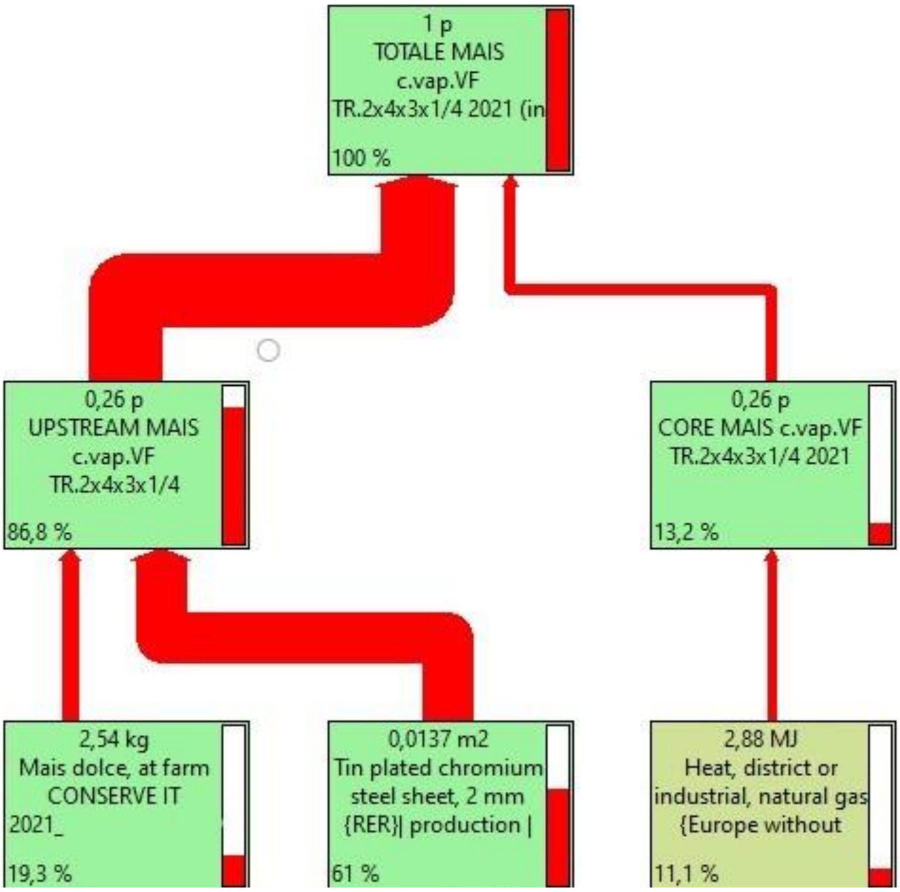


Figure 36: Tree diagram of the results of the Carbon Footprint for the steamed Valfrutta sweet corn in Scenario 3.

CIRIO WAKU SWEET CORN

Table 34 shows the results obtained for the indicator considered, referring to 1 kg of Cirio WAKU sweet corn

Table 34: CF results referred to 1 kg of Cirio WAKU sweet corn in Scenario 3.

Indicator	Upstream	Core	Total
Carbon Footprint (kg CO_2 eq/kg)	1,11	0,32	1,43

With regard to the CF the upstream is the phase of life with the greatest impact with a contribution of 77,6%, while the core phase is responsible for the 22,4% of the total, as figure 37 shows:

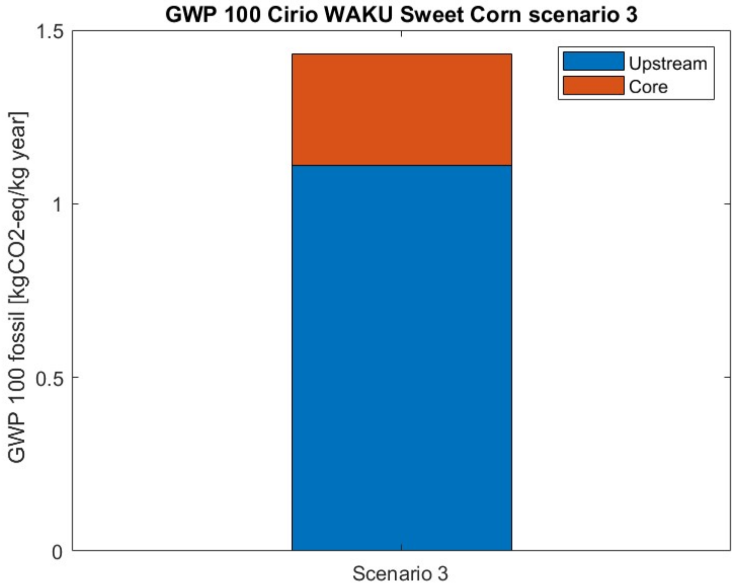


Figure 37: Total CF divided in the upstream and core phase in Scenario 3. The results are referred to 1 kg of Cirio WAKU sweet corn, in scenario 3.

The most significant impact is related to the production of the tin-plated cans with a contribution of 48,8% followed again by the corn cultivation phase with a contribution of 25,3%, reduced with respect to the BAU scenario, and the corn processing phase (also in this case the main contribution is attributable to the consumption of natural gas) with a contribution of 11,3%, as shown in the tree diagram reported in figure 38.

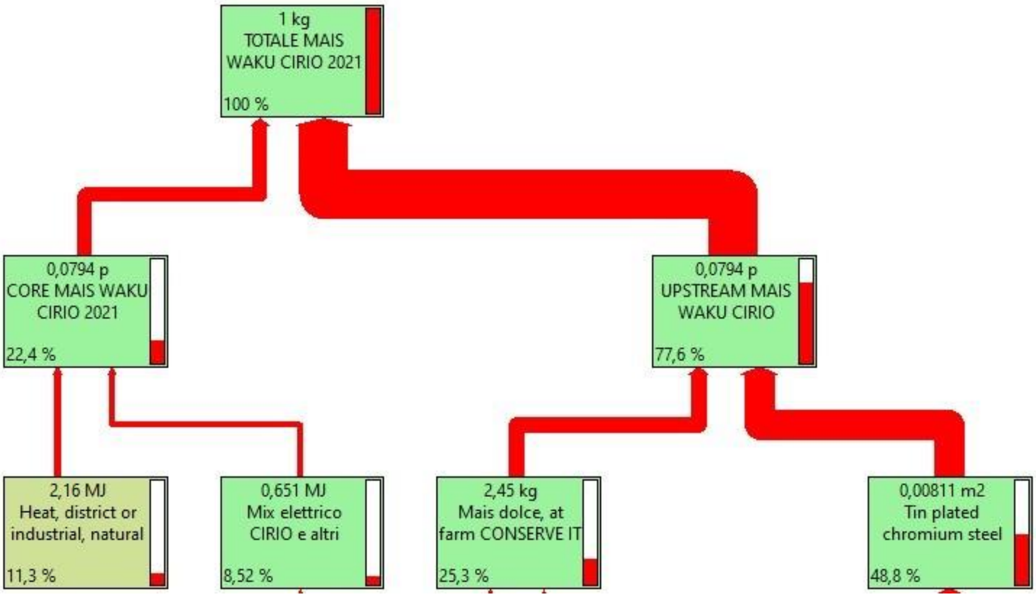


Figure 38:: Tree diagram of the results of the Carbon Footprint for the Cirio WAKU sweet corn.

4.6.4. Scenario 4

STEAMED VALFRUTTA SWEET CORN

Table 35 shows the results obtained for the indicator considered, referring to 1 kg of Steamed Valfrutta sweet corn

Table 35: CF results referred to 1 kg of steamed Valfrutta sweet corn in Scenario 4.

Indicator	**Upstream**	**Core**	**Total**
Carbon Footprint (kg CO_2 eq/kg)	2,00	0,26	2,26

With regard to the CF, also in this case the upstream is the phase of life with the greatest impact with a contribution of 88,5%, while the core phase is responsible for the 11,5% of the total, as figure 39 shows:

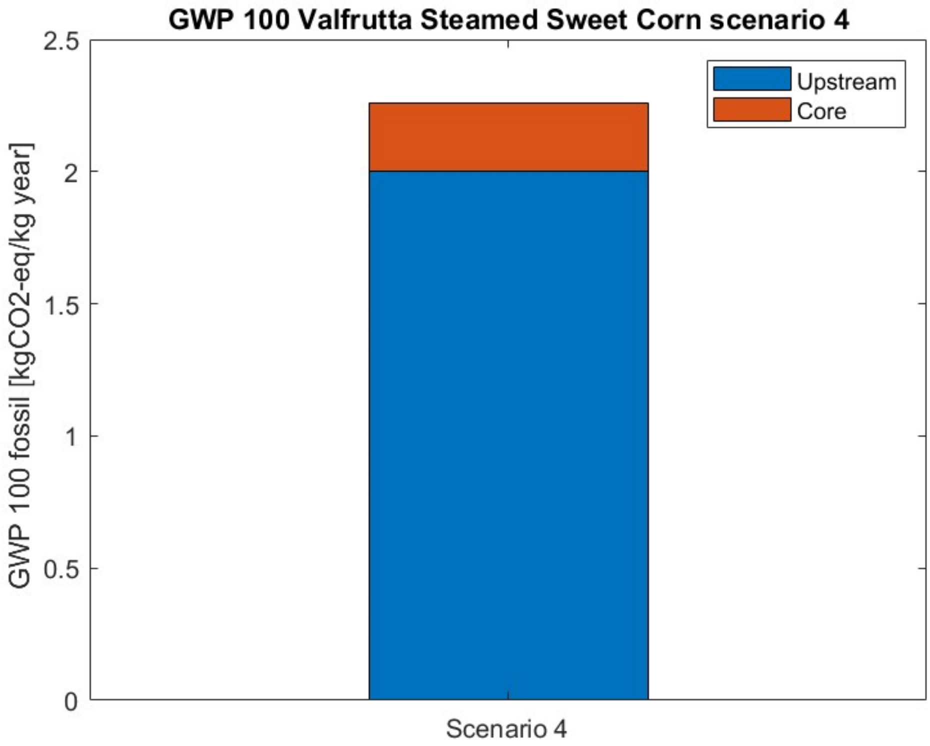


Figure 39: total CF divided in the upstream and core phase. The results are referred to 1 kg of Steamed Valfrutta sweet corn, in scenario 4.

The most significant impact is still related to the production of the tin-plated cans with a contribution of 53,2% followed by the corn cultivation phase, slightly higher than in the BAU scenario accounting for the 29,7% of total emissions and then the corn processing phase (also in this case the main contribution is attributable to the consumption of natural gas) with a contribution of 11%, as shown by the tree diagram in figure 40.

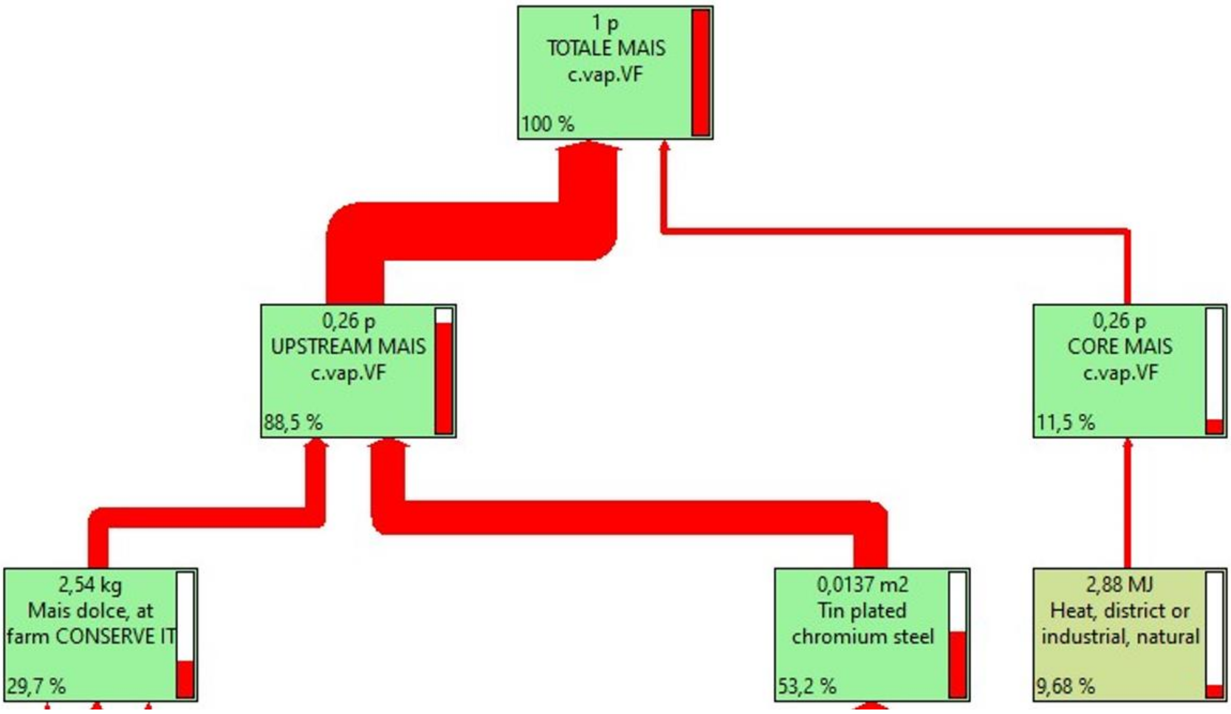


Figure 40: Tree diagram of the results of the Carbon Footprint for the steamed Valfrutta sweet corn in Scenario 4.

CIRIO WAKU SWEET CORN

Table 36 shows the results obtained for the indicator considered, referring to 1 kg of Cirio WAKU sweet corn.

Table 36: CF results referred to 1 kg of Cirio WAKU sweet corn in Scenario 4.

Indicator	Upstream	Core	Total
Carbon Footprint (kg CO_2 eq/kg)	1,38	0,32	1,70

With regard to the CF the upstream is the phase of life with the greatest impact with a contribution of 81,3%, while the core phase is responsible for the 18,7% of the total, as figure 41 shows:

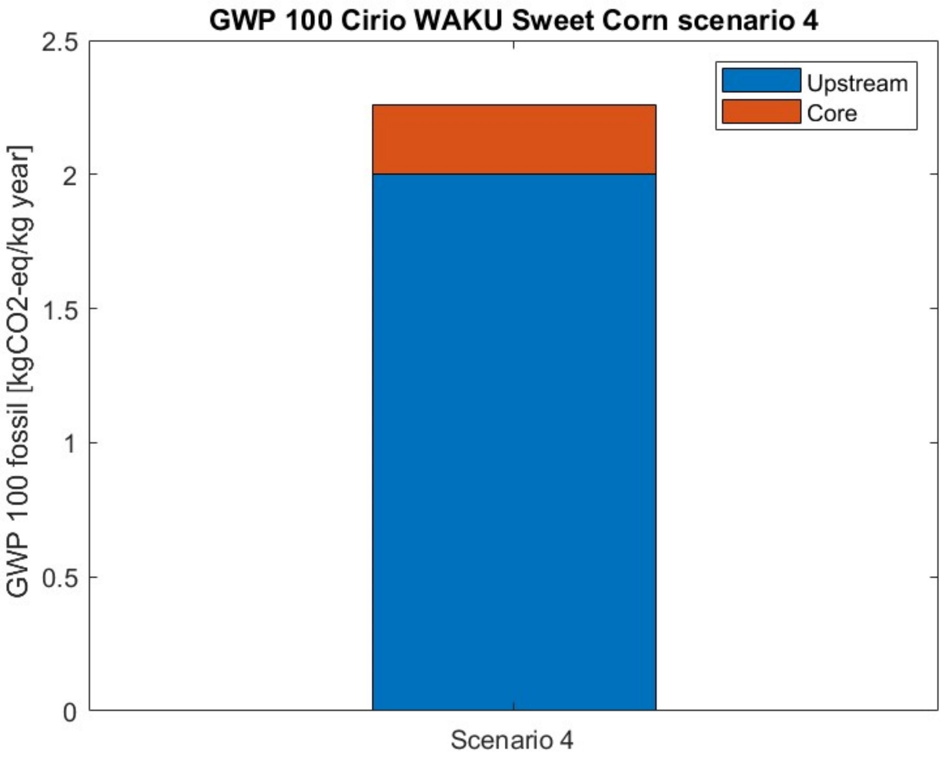


Figure 41: Total CF divided in the upstream and core phase in Scenario 4. The results are referred to 1 kg of Cirio WAKU sweet corn, in scenario 4.

The most significant impact is related to the production of the tin-plated cans with a contribution of 40,9% followed again by the corn cultivation phase with a contribution of 37,4%, higher than in the BAU scenario, and then the corn processing phase (also in this case the main contribution is attributable to the consumption of natural gas) with a contribution of 18,7%, as shown in the tree diagram reported in figure 42.

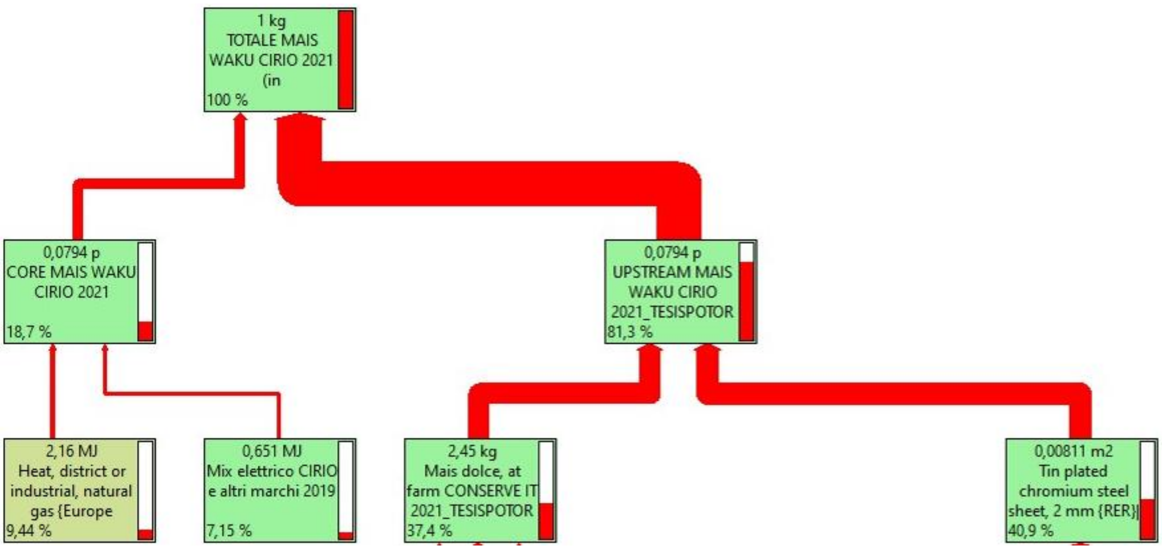


Figure 42: Tree diagram of the results of the Carbon Footprint for the Cirio WAKU sweet corn in Scenario 4

4.7. Net Carbon Footprint

Once carbon footprint and carbon sequestration have been evaluated, it is possible to get the net carbon footprint because it is the difference between the total emissions and the uptake.

It is necessary to have a common reference between the impact assessment, measured in terms of kg CO_2-eq, and the sequestration, measured as well in terms of CO_2-eq. The cultivation phase has been evaluated for 1 t of sweet corn production, the carbon sequestration instead for the yield production per hectare and the products for 1 kg of finished product.

In this analysis the net carbon footprint will be evaluated for both the cultivation phase and the finished product, to do so carbon sequestration will be referred to 1 t of sweet corn produced for the cultivation phase and for 1 kg of finished product for the products.

Concerning the cultivation phase, carbon sequestration for 1 t of corn is obtained by dividing the total CO_2 sequestration got from the calculation model for the specific total yield of the scenario considered, expressed in t (Table 37).

Table 37: Carbon sequestration for 1 t of corn.

	Yield [t ha^{-1}]	**CO_2 seq for 1 ha [kg CO_2-eq/ha]**	**CO_2 seq for 1 ha [kg CO_2-eq/t]**
BAU Scenario	14,86	1014,00	68,2
Scenario 2 – year 1	14,86	1014,00	68,2
Scenario 2 – year 2	19,02	1297,9	68,3
Scenario 2 – year 3	19,32	1318,2	68,3
Scenario 3	14,86	2922,4	196,7
Scenario 4 – year 1	14,86	2922,4	196,7
Scenario 4 – year 2	19,02	3740,7	196,9
Scenario 4 – year 3	19,32	3799,2	196,7

Concerning the finished product, carbon sequestration for 1 t of corn is obtained by dividing the total CO_2 sequestration got from the calculation model for the specific total yield of the scenario considered, expressed in kilogram, to obtain the uptake given by 1 kg of sweetcorn and then by multiplying the result just got for the amount of sweetcorn necessary to have 1 kg of finished product, which are 2,54 kg for steamed Valfrutta sweetcorn and 2,45 kg for Cirio WAKU sweetcorn (Table 38).

Table 38: carbon sequestration for 1 kg of Valfrutta and Cirio WAKU sweetcorn

	CO_2 seq for 1 ha [kg CO_2-eq/ha]	**CO_2 seq for 1 kg of corn (Valfrutta) [kg CO_2-eq/kg]**	**CO_2 seq for 1 kg of corn (WAKU) [kg CO_2-eq/kg]**
BAU Scenario	1014,00	0,170	0,176
Scenario 2 – average	1210,0	0,170	0,175
Scenario 3	2922,4	0,482	0,500
Scenario 4 – average	3487,4	0,482	0,499

4.7.1. Cultivation phase

Now the net carbon footprint of the cultivation phase will be calculated for 1 t of sweetcorn produced, table 39 shows the difference between the emissions and sequestration.

Table 39: Net Carbon Footprint of 1 t of corn produced in each scenario

	Carbon footprint [kg CO_2-eq/t]	**CO_2 seq for 1 t of corn [kg CO_2-eq/t]**	**Net Carbon Footprint 1 t of corn [kg CO_2-eq/t]**	**Percentual decrease [%]**
BAU Scenario	178,49	68,2	110,29	38,9
Scenario 2 – year 1	310,84	68,2	241,8	22,4
Scenario 2 – year 2	242,84	68,3	174,54	28,1
Scenario 2 – year 3	239,11	68,3	170,81	28,6
Scenario 3	147,30	196,7	-49,40	133,5
Scenario 4 – year 1	279,65	196,7	82,95	70,3
Scenario 4 – year 2	218,48	196,9	21,58	90,1
Scenario 4 – year 3	215,13	196,7	18,43	91,4

The same values of table 39 are graphically reported in figure 43.

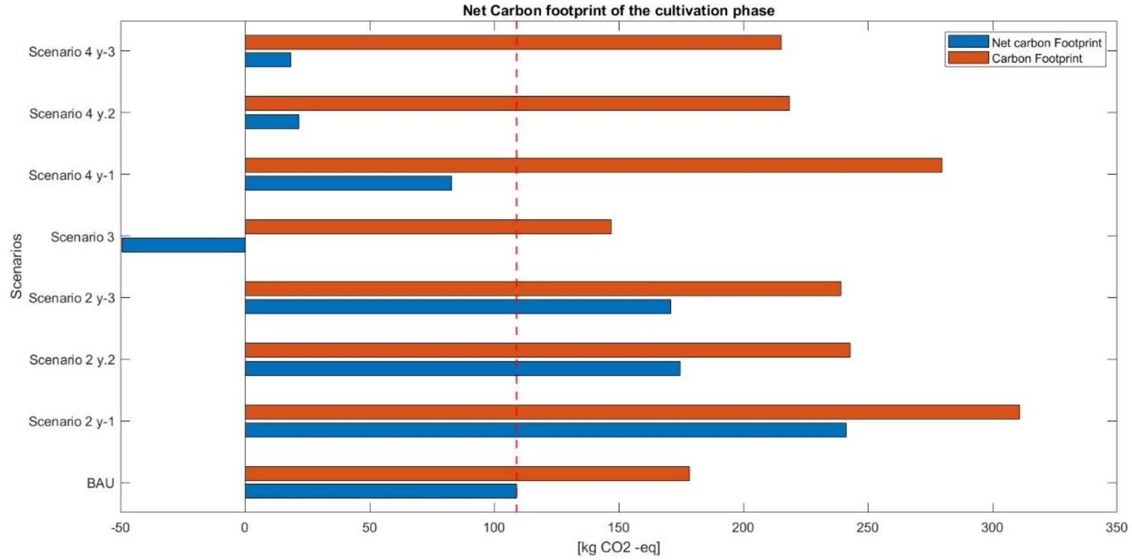


Figure 43: Net Carbon Footprint of 1 t of sweetcorn produced in each scenario

4.7.2. Steamed Valfrutta sweetcorn

Now the net carbon footprint of the product will be calculated for 1 kg of sweetcorn produced, table 40 shows the difference between the emissions and sequestration.

Table 40: Net Carbon Footprint of 1 kg of steamed Valfrutta sweetcorn in each scenario

	Carbon footprint 1 kg of corn [kg CO_2-eq]	**CO_2 seq for 1 kg of Steamed Valfrutta sweetcorn [kg CO_2-eq]**	**Net Carbon Footprint 1 kg of Cirio WAKU sweetcorn [kg CO_2-eq]**	**Percentual decrease [%]**
BAU Scenario	2,01	0,170	1,84	8,5
Scenario 2 – average	2,21	0,170	2,04	7,7
Scenario 3	1,92	0,482	1,438	25,1
Scenario 4 – average	2,26	0,482	1,758	22,2

The same values of table 40 are graphically reported in figure 44.

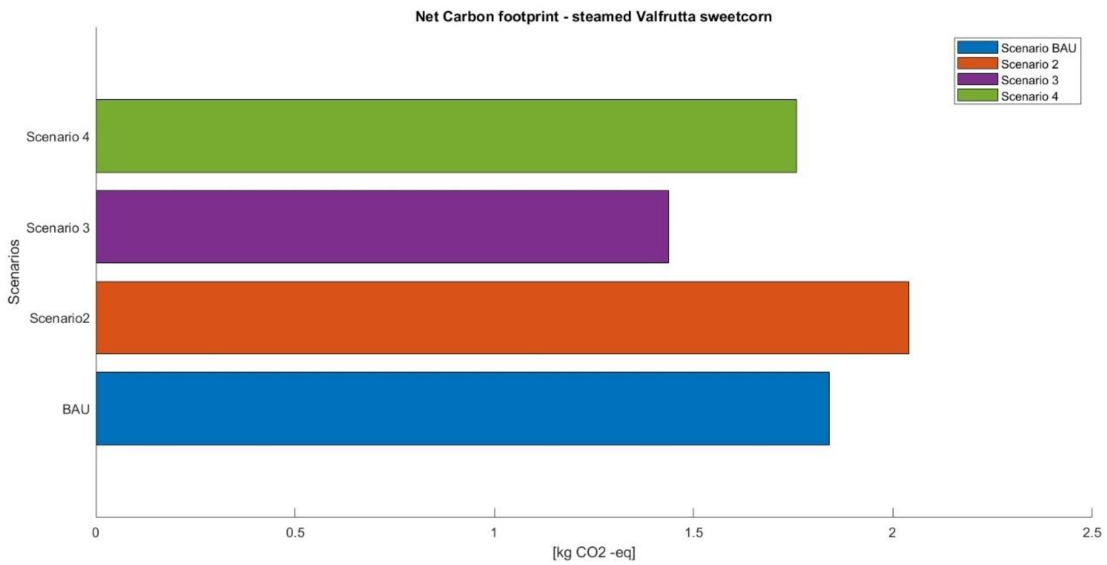


Figure 44: Net Carbon Footprint of 1 kg of steamed Valfrutta sweetcorn in each scenario

4.7.3. Cirio WAKU sweetcorn

Now the net carbon footprint of the product will be calculated for 1 kg of sweetcorn produced, table 41 shows the difference between the emissions and sequestration.

Table 41: Net Carbon Footprint of 1 kg of Cirio WAKU sweetcorn in each scenario

	Carbon footprint 1 kg of corn [kg CO_2-eq]	CO_2 seq for 1 kg of corn [kg CO_2-eq]	Net Carbon Footprint 1 kg of corn [kg CO_2-eq]	Percentual decrease [%]
BAU Scenario	1,50	0,176	1,324	11,7
Scenario 2 – average	1,70	0,175	1,625	4,4
Scenario 3	1,43	0,500	0,93	35
Scenario 4 – average	1,70	0,499	1,201	29,4

The same values of table 41 are graphically reported in figure 45.

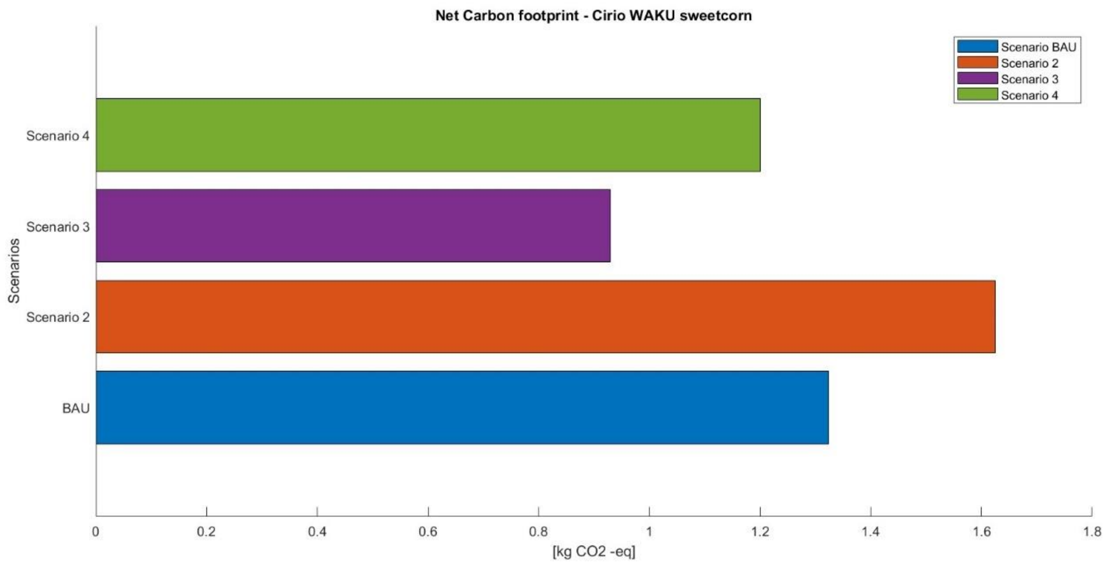


Figure 45:Net Carbon Footprint of 1 kg Cirio WAKU sweetcorn in each scenario

4.8. Emissions Reductions and Sequestration

In this closing section the possibility of generating carbon emission reductions and sequestration potential from the cultivation phase will be explored, since it is the only one affected by the proposed scenarios of carbon farming practices both in terms of emissions and, naturally, uptake. As mentioned in the introductory chapter of this thesis, voluntary emissions reductions measure and track the quantity of additional carbon sequestered in the soil and GHG emissions reduced.

A possible way to deal with the evaluation of emissions reductions is the comparison between the BAU scenario net carbon footprint and the proposed scenarios net carbon footprint.

An important feature to consider when the topic is emissions reduction and sequestration is the period: The Project Crediting Period is the period of time for which net GHG emissions reductions or removals can be verified, which may be equivalent to the project lifetime. In this case the chosen crediting period is of 10 years according to VCS Standards for Agriculture, Forestry and Other Land Use (AFOLU) projects [66], in particular for the case study which is in the category of ALM: Agricultural Land Management. All data here are referred one hectare of land.

4.8.1. Scenario 2

The first scenario analyzed is about the application of biochar along with the substitution of part of inorganic fertilizers with organic fertilizers such as poultry manure. As observed in the previous chapters the application of biochar, which is repeated every three years, has a significative effect on the emissions generated, which are by far higher, the subsequent increase in yield, when normalized back to the production of 1 t of sweetcorn, does not have such positive effects on the carbon uptake. These are the reasons that stand behind the results shown in table 42.

Table 42: Difference between Net carbon footprint in the BAU scenario and in scenario 2

Years	**Net Carbon Footprint 1 t of corn [kg CO_2-eqq]**		
	BAU Scenario	**Scenario 2**	**Difference**
0	108,99	108,99	0
1	108,99	241,34	-132.35
2	108,99	174,54	-65.55
3	108,99	170,81	-61.82
4	108,99	241,34	-132.35
5	108,99	174,54	-65.55
6	108,99	170,81	-61.82
7	108,99	241,34	-132.35
8	108,99	174,54	-65.55
9	108,99	170,81	-61.82
10	108,99	241,34	-132.35
Total	**1198,89**	**2110,40**	**-911,51**

The same results of table 42 are graphically reported in figure 46.

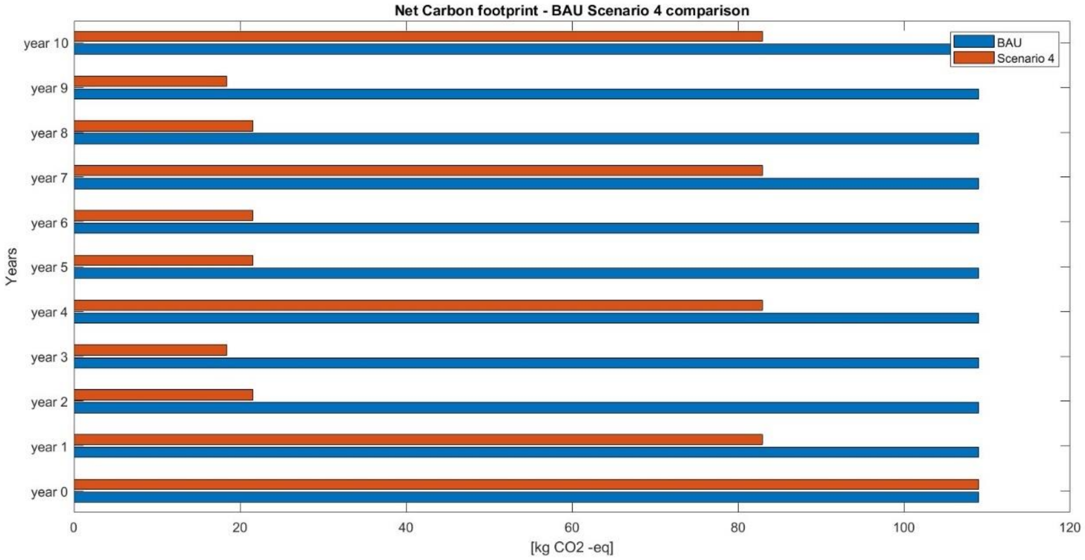


Figure 46: Difference between Net carbon footprint in the BAU scenario and in scenario 2

From this analysis it is possible to state that scenario 2 would not be carbon negative and, as an obvious consequence, does not generate emissions reductions nor carbon sequestration.

4.8.2. Scenario 3

The second scenario analyzed is about reduced tillage. As observed in the previous chapters the decrease of mechanical work brought by machinery has an important effect both on the emissions generated, which are significatively lower, and the increase in biomass carbon content along with a greater amount of biomass left on field after harvesting have a positive effect on the carbon uptake. These are the motivations that stand behind the results shown in table 43.

Table 43: Difference between Net carbon footprint in the BAU scenario and in scenario 3

Years	**Net Carbon Footprint 1 t of corn [kg CO_2-eqq]**		
	BAU Scenario	**Scenario 3**	**Difference**
0	108,99	108,99	0
1	108,99	-49,40	148,39
2	108,99	-49,40	148,39
3	108,99	-49,40	148,39
4	108,99	-49,40	148,39
5	108,99	-49,40	148,39
6	108,99	-49,40	148,39
7	108,99	-49,40	148,39
8	108,99	-49,40	148,39
9	108,99	-49,40	148,39
10	108,99	-49,40	148,39
Total	**1198,89**	**-385,01**	**1483,9**

The same results of table 43 are graphically reported in figure 47.

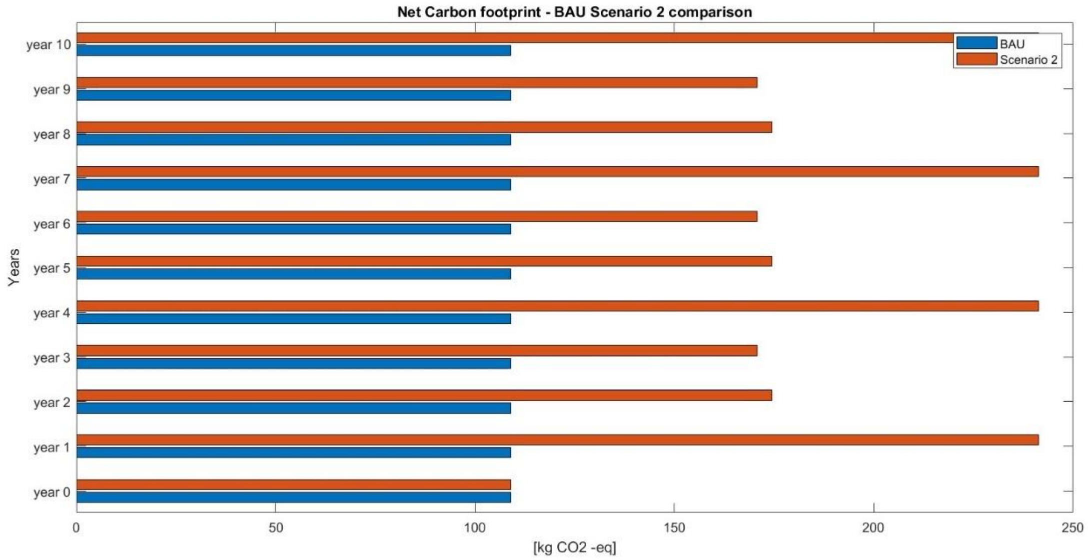


Figure 47: Difference between Net carbon footprint in the BAU scenario and in scenario 3

From this analysis it is possible to state that scenario 3 would be carbon negative and, as a consequence, could be generating up to 1,483 [t CO_2-eq] of carbon emission reductions and sequestration potential on the crediting period for one tonne of sweetcorn produced.

4.8.3. Scenario 4

The last scenario analyzed is about the combination of the previous two. As observed in the previous chapters the decrease of mechanical work brought by machinery has an important effect both on the emissions generated, which are significatively lower, and the increase in biomass carbon content along with a greater amount of biomass left on field after harvesting have a positive effect on the carbon uptake while the application of biochar, which is repeated every three years, has a significative effect on the emissions generated, which are by far higher, the subsequent increase in yield, when normalized back to the production of 1 t of sweetcorn, does not have such positive effects on the carbon sequestration. These are the motivations that stand behind the results shown in table 44.

Table 44: Difference between Net carbon footprint in the BAU scenario and in scenario 4

Years	**Net Carbon Footprint 1 t of corn [kg CO_2-eq]**		
	BAU Scenario	**Scenario 4**	**Difference**
0	108,99	108,99	0
1	108,99	82,95	26,04
2	108,99	21,58	87,41
3	108,99	18,43	90,56
4	108,99	82,95	26,04
5	108,99	21,58	87,41
6	108,99	18,43	90,56
7	108,99	82,95	26,04
8	108,99	21,58	87,41
9	108,99	18,43	90,56
10	108,99	82,95	26,04
Total	**1198,89**	**560,82**	**638,07**

The same results of table 44 are graphically reported in figure 48.

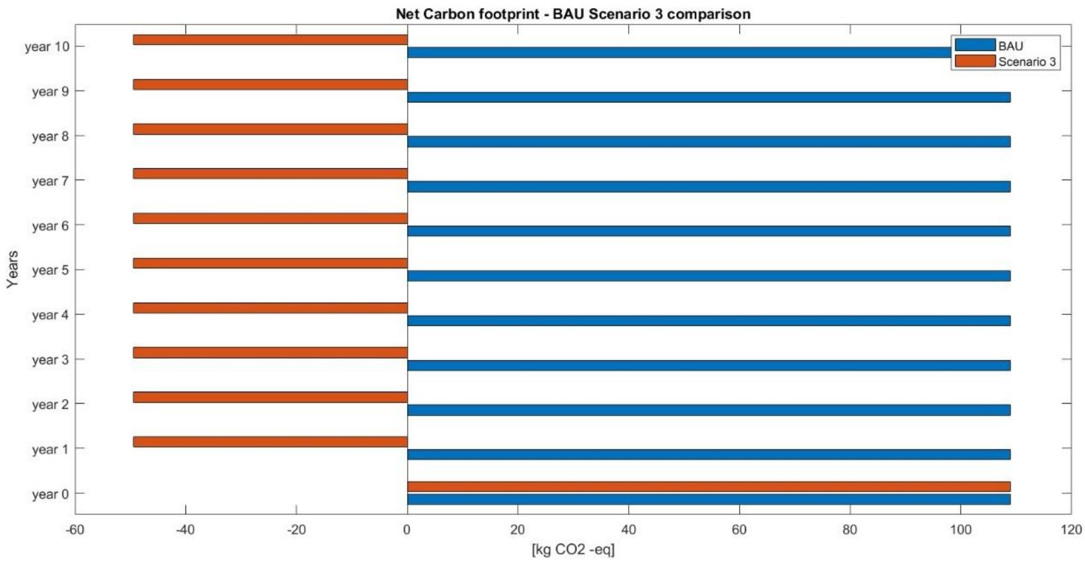


Figure 48: Difference between Net carbon footprint in the BAU scenario and in scenario 4:

From this analysis it is possible to state that scenario 4 is not climate negative but could be still generating up to 0,639 [t CO_2-eq] of carbon emission reductions and sequestration potential on the crediting period for one ton of sweetcorn produced, because it has a lower environmental impact due to practices that satisfy the requirements for emissions reductions and sequestration potential generation.

5. CONCLUSIONS

The aim of this study has been to calculate the carbon emission reductions and sequestration potential generated through a more sustainable management of agricultural land to improve the environmental performances in the Agri-food sector. One of the most important techniques at the moment is carbon farming. Carbon farming is a practice that is catching on, anyway there are still many limitations to overcome for its stable implementation in the regulatory framework at international level and on the field. In particular nowadays some specific recommendations and rules are not present for annual crops, among which is present the cultivation object of this work: sweet corn. The lack of uniformity has been one of the main reasons that has caught the interest and brought to deepen the knowledge on the state of the art.

The study is based on data gathered from one of the most important companies in the Agri-food sector at European level: Conserve Italia. On the basis of these data, it has been possible to evaluate the so-called Business-As-Usual scenario in terms of environmental burden for the production of sweetcorn products, with a particular interest on the cultivation phase which is the one affected by the implementation of carbon farming practices and accounts for around the 25% of the Carbon Footprint of the finished products. In order to get these results, the Life Cycle Assessment methodologies have been used, with a particular focus on the calculation of the Carbon Footprint.

Through the implementation of carbon farming techniques, it is possible to increase the carbon sequestration potential of the crops, this is one of the necessary requirements to demonstrate additionality for the generation of carbon credits. Anyway, from the study carried out in this thesis work, it is possible to notice how not all the practices aimed to improve environmental performances of the cultivation phase and of the overall finished product succeed at the intended purpose.

Scenario 2 clearly shows how a better management of the cultivation field, in terms of nutrients, quality of the harvest and increased productivity, does not bring the expected benefits in terms of environmental burden after its implementation. In facts, in terms of Net Carbon Footprint, this scenario over 10 years brings to, for what concerns the cultivation phase, to an increase of GHG emissions to the atmosphere which amounts to 911,51 kgCO_2-eq per t of sweetcorn produced.

Scenario 3 instead turned out to be the most profitable in terms of effects on the atmosphere, the cultivation phase in this case is carbon negative, over a 10-year period there would be the possibility to sequester up to 1483,9 kgCO_2-eq per t of sweetcorn produced into soil and biomass.

Scenario 4, as a combination of the previous two, is less profitable in terms of environmental performances than scenario 3 but has the advantage to maintain scenario 2 positive features such as: good supply of nutrients, quality of the harvest and increased productivity. This scenario is not carbon negative as scenario 3 but it is beneficial in terms of Net carbon Footprint, when compared to the BAU scenario, because it can save up to 638,07 kgCO_2-eq per t of sweetcorn produced.

Results for the cultivation phase of the different scenarios are summed up in the graph of figure 49.

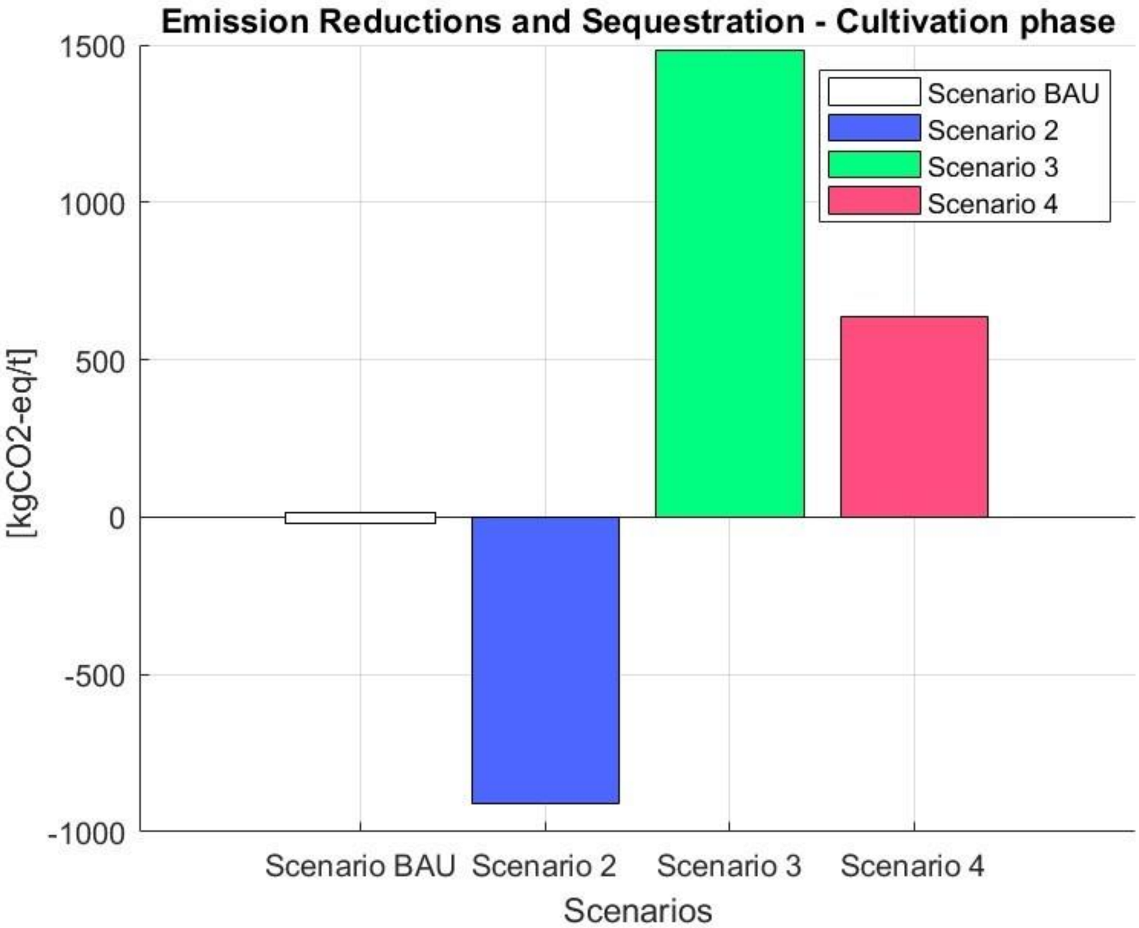


Figure 49: Emissions Reduction and Sequestration for a t of sweetcorn produced in 10 years

One of the open questions left by this analysis is that a better environmental performance can bring to the generation of emission reductions and sequestration, satisfying the present regulatory framework about additionality, legitimacy and durability over time, but there are not methods universally recognized for an accurate and unquestionable evaluation of carbon sequestered into the soil by crops, especially concerning annual crops such as sweet corn.

One of the future prospects and challenges would be to set a clear methodology to define support for accountability and certifications, calculating net emissions for the products object of the research study. Anyways, avoiding and reducing GHG emissions should be the first and main priority of climate mitigation efforts in the land use sectors. This avoidance and reduction of emissions first principle should be reflected in the carbon farming initiative. The development of a robust, transparent, and science-based certification system for carbon removals is essential to ensure the environmental integrity of possible carbon farming initiatives. A possible goal would be to define an indicator able to describe the different aspects of the footprint of the agricultural phase quantifying greenhouse gas emissions, water consumption, energy and soil requirements, and carbon absorption of crops.

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