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MASTER THESIS

Carbon Capture and Storage Technologies and the Potential of Tree Planting to Increase CO_2 Sequestration

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I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Name Surname: İpek Öztürk
Signature:

DEDICATION

I would like to dedicate this thesis to my parents, Ayşe and Mehmet Öztürk, and my sister, Ece Öztürk Uludağ, who always devoted their love to me, made me feel their support at every moment, and stood behind me under all circumstances. You have been my source of inspiration, support, and guidance. Thank you for being by my side on this adventure.

ABSTRACT

The increase in global temperatures mostly due to anthropogenic greenhouse gas emissions, particularly carbon dioxide (CO_2), presents a critical challenge for humanity. This thesis investigates methodology, effectiveness and cost analysis of different strategies to counteract global warming and focusing on the potential of reducing carbon emissions and enhancing negative emissions through tree planting.

The first part of the thesis delves into the main sources of CO_2 in atmosphere. Fossil fuels, cement production, refineries, iron and steel industry, petrochemical industry and biomass are discussed in terms of their emissions. In addition, it examines different countries' CO_2 emissions. Thesis also contextualizes its findings within the framework established by the Intergovernmental Panel on Climate Change (IPCC), synthesizing key reports and assessments to underscore the urgency of action in mitigating climate change. It also examines the outcomes of the 21st Conference of the Parties (COP21) to the United Nations Framework Convention on Climate Change (UNFCCC), particularly the Paris Agreement, and its implications for global efforts to address carbon emissions and promote sustainable development.

Next, the thesis investigates the concept of negative carbon emissions, which involves removing CO_2 from the atmosphere through existing technological solutions like bioenergy with carbon capture and storage (BECCS), direct air capture (DAC); nature-based solutions like afforestation and reforestation. Moreover, thesis is dedicated to analyzing the potential of tree planting as a scalable and cost-effective method for carbon sequestration. It evaluates the carbon sequestration capacity of forests, the factors influencing tree growth and survival, and the socio-economic benefits associated with afforestation and reforestation projects, offset carbon emissions and mitigate climate change impacts. It considers factors such as land availability, ecosystem restoration, biodiversity conservation in designing and implementing tree planting.

By synthesizing insights from scientific research, policy analysis, and case studies, this thesis provides valuable insights into the potential of tree planting to contribute to global efforts in combating climate change, and it underscores the need for integrated approaches that combine emissions reduction strategies with negative emissions technologies to achieve long-term climate resilience and sustainability.

Keywords: Carbon Capture, Carbon dioxide, Tree Planting, Global Warming, Negative Emissions

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INTRODUCTION

Climate change, driven by the increasing concentration of greenhouse gases in the atmosphere, is one of the most pressing challenges of our time. Carbon dioxide (CO_2), a major greenhouse gas, has significantly contributed to global warming. Understanding the sources of CO_2 emissions and exploring effective mitigation strategies are critical to reducing the impacts of climate change and achieving a sustainable future. Climate change, driven predominantly by CO_2 emissions from fossil fuel combustion and industrial processes, poses a severe threat to our planet. To combat this, various regulations like the Intergovernmental Panel on Climate Change (IPCC)'s special report on Global Warming and Paris Agreement have been implemented globally, aiming for significant emissions reductions and promoting carbon pricing mechanisms. Achieving negative emissions, where CO_2 is actively removed from the atmosphere, is crucial for meeting these climate goals. Negative CO_2 emissions refer to the process of removing more CO_2 from the atmosphere than is emitted. Technologies such as Bioenergy with Carbon Capture and Storage (BECCS) and Direct Air Capture (DAC) play vital roles in this effort. BECCS combines biomass energy production with CO_2 capture and storage, offering both energy production and carbon sequestration, although its costs and efficiency vary depending on the technology and biomass type. DAC involves the extraction of CO_2 directly from the ambient air using chemical processes. There are two primary types of DAC technologies: solid sorbent DAC and liquid solvent DAC. The costs of DAC technologies change with capital, operational and energy source costs. Natural solutions like afforestation and reforestation also contribute significantly by sequestering carbon in biomass and soils, with additional benefits such as biodiversity enhancement and ecosystem services. Policies and incentives are critical to support these initiatives, while accurate calculation methodologies for CO_2 sequestration by trees are essential for effective planning and economic analysis, as the cost-effectiveness of tree planting involves considerations of initial investment and long-term carbon storage benefits. The efficiency of CO_2 sequestration varies by tree species, age, and site conditions, with mature forests generally having higher carbon sequestration rates than younger plantations. The methodology involves measuring tree diameter at breast height (DBH), height, and bulk density, and applying specific or generalized equations to estimate biomass. The costs include site preparation, planting, maintenance, and opportunity costs of land use.

1. MAIN SOURCES OF CO_2 IN ATMOSPHERE

Carbon dioxide (CO_2) enters the atmosphere from a multitude of sources, both natural and anthropogenic. While the anthropogenic sources include steel and cement industries, deforestation, and the consumption of fossil fuels such as coal, oil, and natural gas, natural sources include respiration, ocean release and decomposition. Global CO_2 emissions from burning fossil fuels and industrial processes totaled roughly 24.6 gigatons (Gt) in 2000; this number increased to 36.5 Gt in 2021, a 48.4% rise (El-Moneim, Rashed, & Eldesouki, 2023).

Human activities such as the burning of oil, coal and gas, as well as deforestation are the primary cause of the increased carbon dioxide concentrations in the atmosphere. As shown in the Figure 1, 87% of all human-produced CO_2 emissions come from the burning of fossil fuels like coal, natural gas and oil. The remainder results from the clearing of forests and other land use changes (9%), as well as some industrial processes such as cement manufacturing (4%).

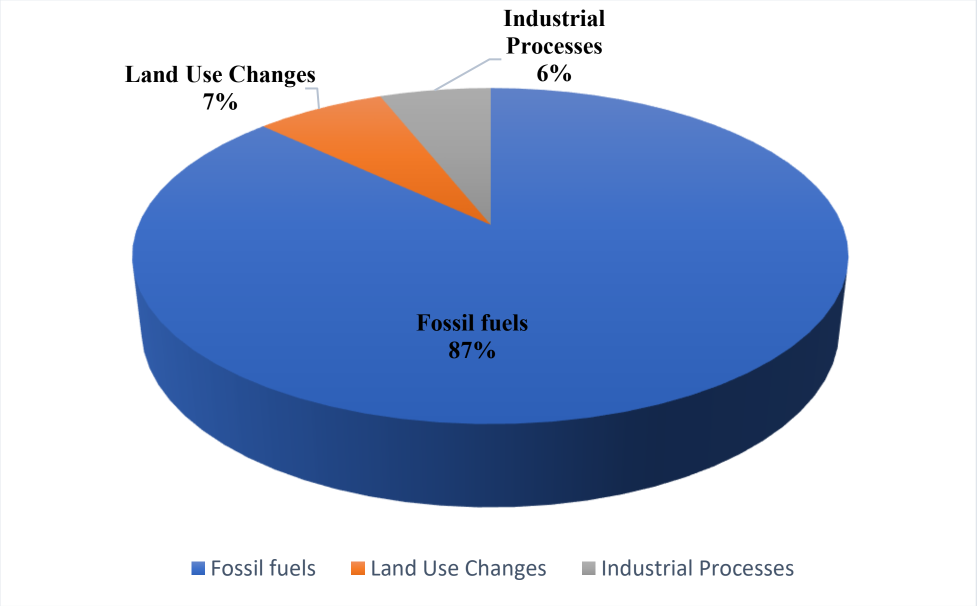

Figure 1. The percentages of CO_2 emissions from different sectors (Main sources of carbon dioxide emissions, n.d.)

The comparison of the emissions from the different energy sectors in the years 2000 and 2021 is shown in Figure 2. In comparison to the other energy sectors—natural gas, crude oil, and biomass, coal has the highest emissions in both of the years. Over the previous 20 years, coal emissions have doubled to a total of 15 Gt CO_2. As it can be seen from the Figure 2., in both 2000 and 2021, energy combustion and industrial operations are the primary sources of CO_2 emissions into the environment.

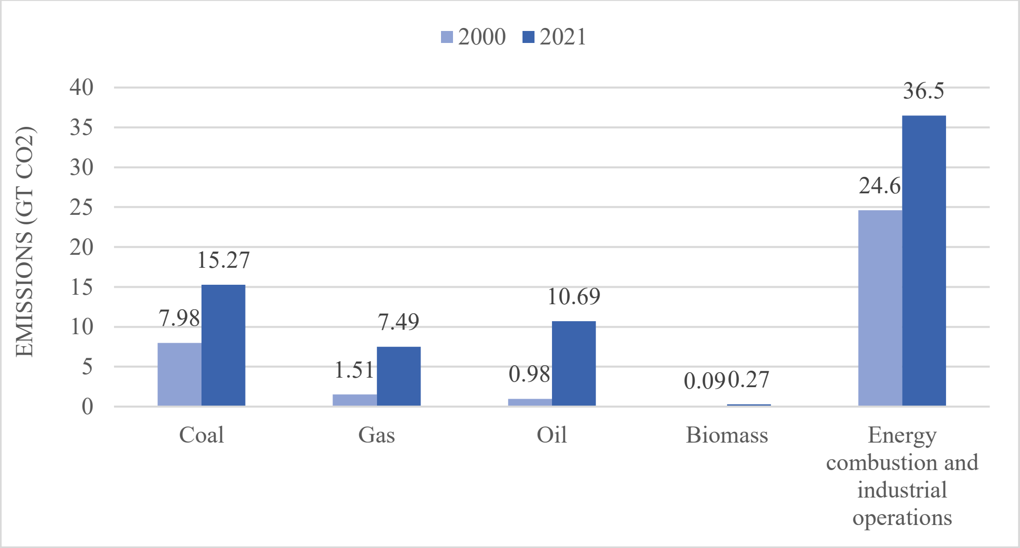

Figure 2. Illustration of global CO_2 emissions from energy sources in 2000 and 2021 (Metz et al. 2005; IEA 2021)

The sectors of transportation, electricity generation, and industry are among the sectors that consume the most fuel and therefore emit the most carbon dioxide, especially in industrialized countries. Table 1. represents the amount of emissions per capita in the countries that emit the most carbon dioxide during the past thirty years, but it should be taken into account that population differs from country to country, and population varies over the years in the same country (Crippa, 2022).

Table 1. CO_2 emission per capita in the top emitter countries (Crippa, 2022)

	1990	***2000***	***2010***	***2021***
EU 27	9.09	8.35	7.77	6.25
China	2.07	2.89	6.84	8.73
USA	20.07	21.29	18.05	14.24
India	0.69	0.94	1.41	1.9
Russia	16.23	11.43	12.11	13.52
Japan	9.41	9.82	9.54	8.6
Germany	12.88	10.78	10.11	8.06
South Korea	6.32	10.21	12.09	12.13
Iran	3.64	5.33	7.72	8.43
Indonesia	0.89	1.4	1.8	2.19
Canada	16.01	17.73	16.52	14.86

For instance, America's population ranked third in the world in 2010 with 309 million, compared to approximately 252 million in 1990. When comparing the amount of CO_2 emitted, it was 5.0 Gt in 1990 and 5.5 Gt in 2010 (El-Moneim, Rashed, & Eldesouki, 2023). Therefore, although the amount of emissions per capita decreased by about 2%, the actual emitted quantities increased by approximately 0.5 Gt CO_2.

As part of the Earth's carbon cycle, CO_2 is naturally present in the atmosphere due to the movement of carbon between the atmosphere, oceans, soils, plants, and animals. Even though natural processes like wildfires, plant and animal respiration, the decomposition of organic materials, and volcanic eruptions also release CO_2, their contributions smaller in compared to human activities. Due to logging, urbanization, and agricultural growth, deforestation and changes in land use release carbon dioxide into the atmosphere that was previously stored in vegetation and soils. CO_2 emissions are also a result of agricultural practices such fertilizer use, livestock digestion, and soil degration. Furthermore, CO_2 is released into the environment during waste management procedures such as waste incineration and landfill decomposition. Together, these various sources raise the atmospheric concentrations of CO_2, intensifying climate change and its related effects. In order to slow down climate change and maintain stable CO_2 amounts in the atmosphere, these sources must be controlled. The implementation of certain economic policies is crucial in mitigating the energy consumption resulting from the combustion of fossil fuels, particularly with respect to key sources of carbon dioxide emissions. The use of specific fuels and technologies, such as gas boilers, coal-fired power plants, and cars with traditional internal combustion engines, is discouraged under some of these regulations. Governments must also prepare for and promote massive investments in infrastructure, including smart transmission and distribution networks.

2. REGULATIONS FOR CARBON EMISSIONS

Significant reductions in carbon emissions are necessary to keep global warming to 1.5°C over pre-industrial levels. A number of strategies to keep warming to 1.5°C were described in the Intergovernmental Panel on Climate Change (IPCC) special report on Global Warming of 1.5°C, each with varying carbon dioxide (CO_2) emission levels. The report places significant emphasis on the necessity of achieving net-zero global CO_2 emissions by approximately 2050. This means that the amount of CO_2 emitted into the atmosphere is balanced by the amount removed, for example through carbon capture and storage or by natural processes like reforestation. To achieve this, the report suggests that global CO_2 emissions need to decline by about 45% from 2010 levels by 2030 and reach net-zero by around 2050. Methane and nitrous oxide emissions are other greenhouse gases that must be drastically decreased. The study emphasizes how critical it is to reduce emissions quickly and drastically in order to mitigate the effects of climate change, especially in areas that are already vulnerable. In order to accomplish these carbon reductions, it also emphasizes the necessity of quickly and widely adopting energy-efficient measures, renewable energy sources, modifications to land use practices, and technical advancements. Overall, the IPCC's 1.5°C policy emphasizes how urgently strong action is needed to cut carbon emissions and slow down climate change in order to protect the earth and its people from the most severe consequences of global warming (Masson-Delmotte, et al., 2019).

The COP21, or the 21st Conference of the Parties, refers to the 2015 United Nations Climate Change Conference held in Paris, France. The goal of the conference was to achieve a universal agreement among nations to limit global warming to well below 2 degrees Celsius above pre-industrial levels, with efforts to limit the temperature increase to 1.5 degrees Celsius. To achieve this goal, countries recognized the imperative to reduce greenhouse gas emissions, particularly CO_2 emissions, which are the primary driver of climate change. While the specifics of CO_2 emission reduction targets varied among countries, the overall aim was to achieve a significant decrease in global CO_2 emissions over time. Many countries committed to transitioning to low-carbon energy sources, increasing energy efficiency, enhancing carbon sinks through afforestation and reforestation, and implementing policies to promote sustainable development and reduce reliance on fossil fuels. Overall, COP21 and the Paris Agreement underscored the urgency of addressing CO_2 emissions to mitigate climate change and protect the planet and its inhabitants from its most severe impacts. The agreement represents a historic milestone in international efforts to combat climate change and transition to a low-carbon, sustainable future (What is Paris Agreement?, n.d.).

3. WHAT ARE CARBON DIOXIDE REMOVAL AND NEGATIVE EMISSIONS?

According to IPCC while the process of removing CO_2 from the atmosphere refers to Carbon dioxide removal (CDR), practices or technologies that remove CO_2 with opposite emissions described as achieving ‘negative emissions’. If it involves removing gases other than CO_2, the process can be referred as greenhouse gas removal. CDR and negative emissions constitute strategies in mitigating climate change, employing a suite of methods and technologies to actively extract carbon dioxide from the atmosphere. These endeavors are instrumental in achieving net-zero or even net-negative carbon emissions, critical milestones for curbing global warming and its associated impacts.

Negative CO_2 emissions are essential to the wider range of climate mitigation initiatives because they are achieved through an integrated strategy that includes afforestation and reforestation initiatives, carbon capture and storage (CCS) technologies, bioenergy with carbon capture and storage (BECCS) systems, direct air capture (DAC) technologies, and improvements to natural carbon sinks. In order to maximize forests' natural capacity to store carbon, planned tree planting and ecosystem restoration are known as afforestation and reforestation. Through photosynthesis, trees are able to take CO_2 from the atmosphere, which is stored in their biomass and soil via these actions. Furthermore, by storing CO_2 emissions underground, CCS systems absorb emissions from power plants and industrial operations and prevent them from being released into the environment. BECCS combines the production of bioenergy with CCS by using biomass as a renewable energy source and capturing and storing the associated CO_2 emissions. To attain zero emissions, these methods make use of geological storage and biological processes. Innovative technologies such as DAC offer a direct means of extracting CO_2 from ambient air using chemical processes or sorbents. DAC technologies, which absorb carbon dioxide from diffuse sources including transportation and agriculture, are a complement to other negative emissions methods. Moreover, increasing soil carbon sequestration and ecosystem restoration as examples of natural carbon sink enhancements can increase the planet's ability to absorb and store carbon. These natural solutions take advantage of the ecosystems' inherent capacity to sequester carbon, such as wetlands, forests, and oceans.

Beyond immediate emissions reduction, negative CO_2 emissions and the idea of carbon dioxide removal are crucial for climate stabilization and resilience. These innovations and actions help for keeping global warming at safe levels, protect ecosystems, and protect vulnerable communities from the effects of climate change by actively removing CO_2 from the atmosphere. However, overcoming a number of obstacles, such as those related to technological maturity, scalability, environmental effects, and energy requirements, is necessary to fully realize the potential of negative emissions systems. To overcome these obstacles, politicians, scientists, businesses, and civil society will need to work together to fully utilize the potential of carbon dioxide removal and negative CO_2 emissions in the battle against climate change.

4. BIOENERGY WITH CARBON CAPTURE AND STORAGE (BECCS)

The order of the structure of the bioenergy with carbon capture and storage part is shown in Figure 3 and this part of the thesis discusses the topics in this order as shown.

Figure 3. BECCS Outline

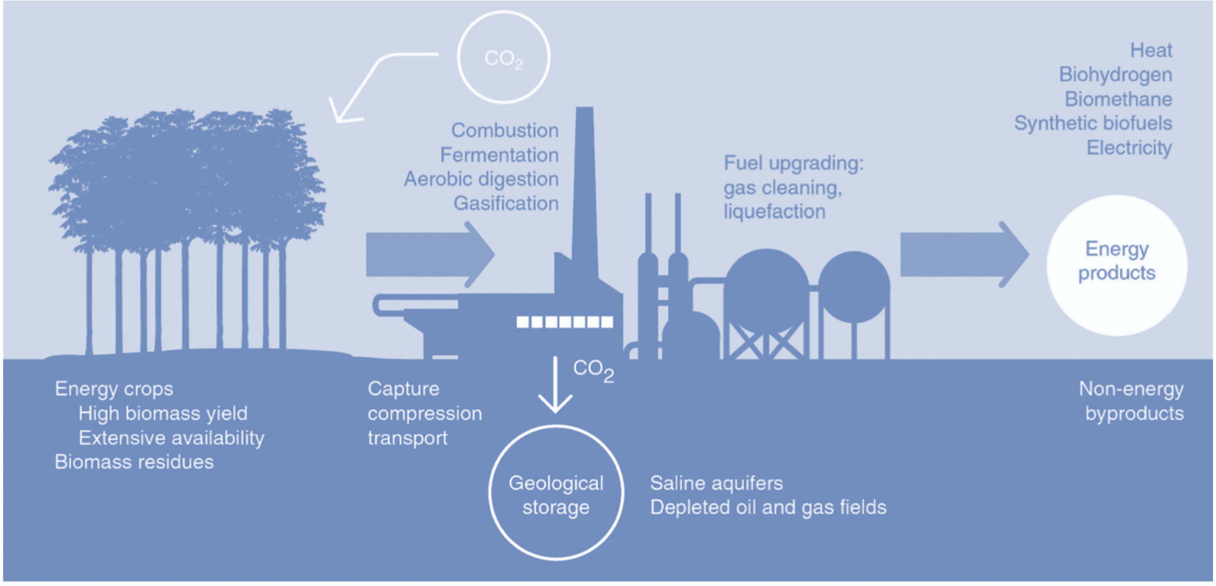

Figure 4. Concepts of BECCS (Bui, 2018)

CCS and negative emissions technologies play an essential role in reductions in atmospheric CO_2 concentration. Bioenergy with carbon capture and storage is one of the negative emissions technologies and it combines bioenergy applications with CCS. BECCS is an interdisciplinary grouping of technology spanning many industries and frequently multiple geographies. First, the idea of producing hydrogen using BECCS technology was presented. Later, the concept was modified to produce electricity with "negative emissions." The graphical representation of the BECCS concept is shown in Figure 4. There is a net transfer of atmospheric CO_2 into biomass during the period of biomass growth. Via photosynthesis, CO_2 from the environment is absorbed into the biomass of plant materials in a BECCS chain. After that, it is burned or converted (e.g. via gasification) in power plants, biorefineries, or industrial facilities that have CO_2 capture devices installed to stop the gas from flowing back into space. The CO_2 arising from the combustion of this biomass is captured then injected in deep geological formations. If emissions from feeding the biomass and capturing the CO_2 are not greater than the quantity of CO_2 taken from the air by photosynthesis, this process leads to a net transfer of CO_2 from the atmosphere to the ground. Various carbon capture technologies can be employed like post-combustion capture, Pre-combustion capture and Oxy-fuel combustion (A. BASILE, 2011). Biomass is generally considered a CO_2 neutral substitute for fossil fuels, where co-combustion has also been shown to reduce the emissions of pollutants SO_X, NO_X and particulates. This concept can include different industrial and energy technologies with a wide range of CO_2 emissions amounts, such as biomass conversion to liquid and gaseous fuels, biomass combustion (dedicated or co-firing) for power production, pulp and paper production, biorefineries. In theory, BECCS offsets short-term greenhouse gas emissions increases resulting from delays in implementing climate policy, providing net negative emissions in the long term.

In comparison, carbon capture and sequestration on fossil fuels (Fossil-CCS) takes carbon from the geosphere and returns it there, while BECCS takes carbon from the atmosphere, puts it temporarily into the biosphere, and then permanently into the geosphere. Thus, BECCS can permit the offsetting of emissions from industries (such as aviation, shipping, iron and steel) where achieving CO_2 reductions is difficult because of technical, financial, or political limitations. Many Fossil-CCS plants have the potential to become BECCS plants by switching their fuel feedstock, for example, a coal-fired power plant with CCS converted to co-fire biomass (Bui, 2018).

4.1. System Considerations

In this section the availability of biomass feedstocks and land for their cultivation will be the focus because these are key requirements for the feasibility of large-scale BECCS. In general, biomass refers to material of biological origin that is produced quickly by photosynthesis. Therefore, it does not include material that has become peat or fossilized or embedded in geological formations. Biomass feedstocks come in a wide variety and can be categorized in a number of ways, such as marine vs terrestrial, wastes vs residues, agricultural vs forest. Even though there seem to be a lot of potential feedstocks, competition for feedstock among other industries and with other ecosystem services, such as food production, may severely restrict their availability for BECCS. Figure 5. shows a tree diagram of different biomass conversion technologies and the variety of end products for each conversion pathway.

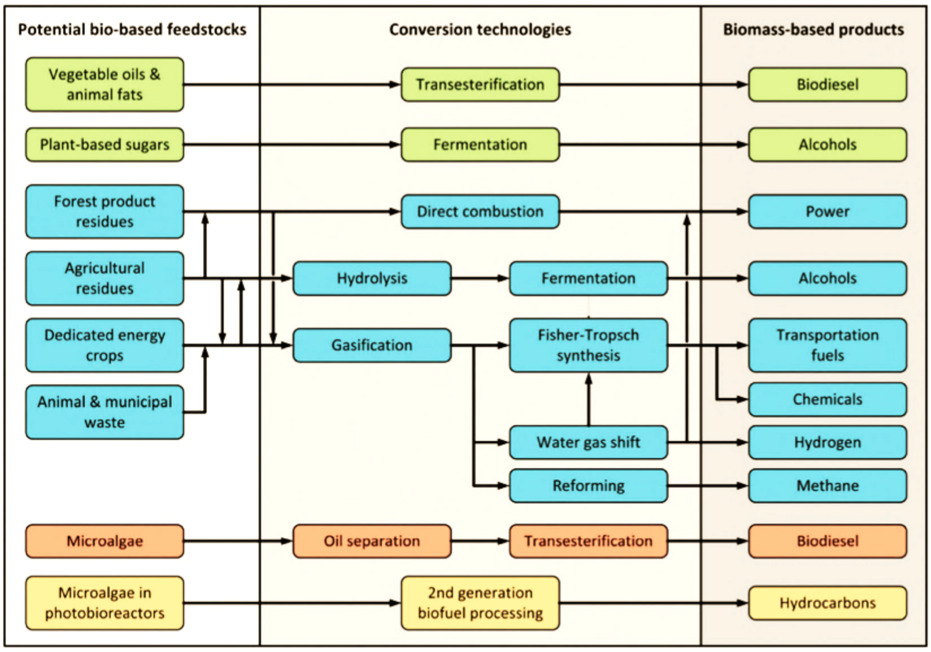

Figure 5. Biomass feedstock conversion pathways and product tree (Bui, 2018)

There is a high amount of food waste accessible right now. However, this amount could change over time through the changes in consumer behavior, distribution, processing, storage and agricultural productivity. The seasonal availability of feedstocks for large-scale BECCS is another problem, as harvesting schedules requires pre-treatment and storage. The availability in the future will also be influenced by advancements in cultivation techniques, yields and demand.

The availability of land for the production of biomass feedstock is a major factor for large-scale BECCS. Land demand for BECCS is relatively high and largely depends on the selected feedstock. Two key concerns need to be answered in order to meet BECCS's land requirements, which are estimated to be between 380 and 990 Mha: (i) how this land can be provided, and (ii) how much can be freed up by other means. One way to partially meet land requirements is to use marginal lands. Dietary changes are another way to release large amounts of land. The average diet with a high amount of animal products (meat, dairy, eggs, and fish) has a land intensity of 1.08 hectares annually per person (cropland accounts for 0.34 hectare and pasture for 0.74 hectare annually). With a 7.5-billion-person world population, a complete switch to a plant-based diet could free about 605–685 Mha of cropland and 3165–3315 Mha of pasture. However, it is unlikely that human society will undergo such a radical shift in behavior. Moreover, free allocations between pastures and cropland are generally not possible, meaning that only a certain percentage of pastures will be suitable as cropland. According to less radical estimates, 2.2 billion people might free up 140 million hectares of farmland and 500 million hectares of pasture if they reduced their use of animal products by 40%. Improvements in agricultural production and livestock productivity or a decrease in food waste are further options for freeing up land since the land area linked to food waste for both crop and animal commodities combined is close to 1400 Mha. In conclusion, if we made significant dietary and agricultural system reforms, we could make available enough space for large-scale BECCS deployment, or bioenergy deployment (Bui, 2018).

4.2. BECCS Cost

Various studies have attempted to quantify the emissions reductions and costs associated with different BECCS options. One of these studies is Biomass CCS Study which is held in International Energy Agency (IEA) greenhouse gas emissions (GHG) Programme. In this section two different technologies of this programme are discussed. The first technology is based on a Super Critical circulating fluidized bed technology (CFB) boiler co-fired with coal and biomass. The boiler is equipped with fuel gas desulphurization (FGD) based on wet limestone. CO_2 capture and compression are considered. The biomass fired corresponds to 10% of total fired duty (based on LHV). The second technology is based on a SubCritical CFB boiler fired with biomass. CO_2 capture and compression are considered. The configuration of the complex is based on a steam generator with superheating and single steam reheating.

Depending on the case studies and IEA GHG Programme summary and comparison of these two technologies are shown in Table 2. According to the IEA analysis, a supercritical circulating fluidized bed boiler with only 10% biomass co-firing would have negative emissions of -32g/kWh, whereas a freestanding biomass plant with CO_2 collection of up to -1573gCO_2/kWh would have negative emissions.

Table 2. Production of electricity cost from BECCS (Cavezzali, Cotone, Gaspanini, & Domenichini, 2009)

Study	*Technology*	*Production of Electricity Cost*
IEAGHG 2009	CFB boiler, biomass only	0.1 euro/KWh
	CFB, 10% biomass cofired	0.25 euro/KWh

Since there is a lack of commercial experience with a full-scale CCS plant, estimations of BECCS costs are inherently quite uncertain and depend on a variety of factors and assumptions. Although these estimates are not directly comparable, they give an idea of possible costs because they are based on widely diverse assumptions and technologies. With reference to the EU ETS (Emissions Trading Scheme), the IEA GHG study estimates an ETS certificate price of €48-55/tCO_2 (€176-202/tC) would be necessary for a biomass co-fired plant with capture to be competitive with an equivalent plant without capture and €65-76/tCO_2 (€238-278/tC) for dedicated biomass plant with capture (Cavezzali, Cotone, Gaspanini, & Domenichini , 2009).

5. DIRECT AIR CAPTURE (DAC)

The order of the structure of the direct air capture part is shown in Figure 6 and this part of the thesis discusses the topics in this order as shown.

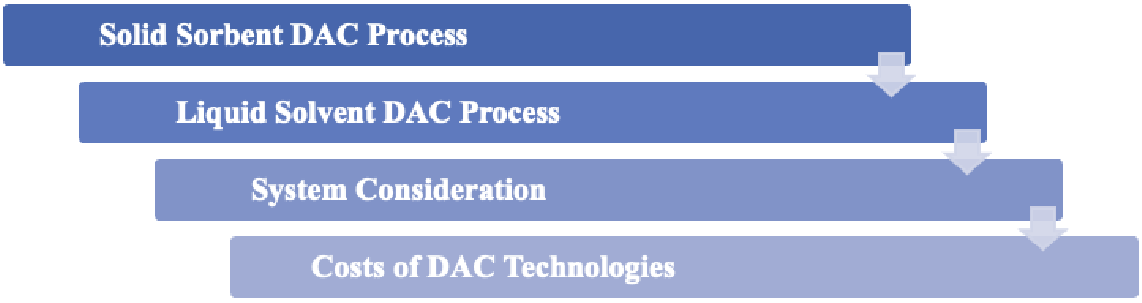

Figure 6. Direct Air Capture (DAC) outline

An increasing amount of carbon dioxide and other harmful gases are in the atmosphere, which has led to a number of problems about these gases' effects on human and animal health. Entire human health and safety will be greatly enhanced by a method for directly extracting carbon dioxide from the environment. Researchers have proposed and recommended a variety of strategies and approaches to reduce the impact of climate change by lowering the atmospheric concentration of carbon dioxide. DAC has received great amount of attention as a negative carbon emission technology that could ease the addressing of global climate change. Currently, 19 DAC units are in operation around the world, catching 10,000 tCO_2/year on average (Direct Air Capture, 2021). This section aims to consider a process to capture the carbon dioxide directly (Direct Air Capture) from the atmosphere. DAC is a typical negative emission technology that can take CO_2 directly from the air in contrast to traditional CO_2 capture techniques, is currently being considered widely as a possible way of achieving negative carbon emission (Okesola, 2018).

The DAC concept is introduced for the first time in 1999. Over the next two decades, DAC has shown itself to be a promising technology for mitigating climate change, and a considerable amount of research has been done from the perspective of CO_2 capture from ambient air. As the definition of DAC is so broad, there are a variety of promising and developing DAC methods. The two processes most advanced in development are solid sorbent DAC and liquid solvents. Between the contactors used in liquid solvent-based and solid sorbent-based separation procedures, there are inherent material differences. The amount of CO_2 extracted from the atmosphere per unit of time and contact area of the separation device is used to measure the CO_2 flux. Therefore, the rate of CO_2 removal per unit of contactor cross sectional area may be estimated by using this parameter. Through a chemical reaction with a base, CO_2 is successfully removed through the air. The key is to increase the quantity of interactions that occur between the base chemistry in the contactor and the CO_2 that is drawn in from the air (McQueen, A review of direct air capture (DAC): scaling up commercial technologies and innovating for the future, 2021).

5.1. Solid Sorbent DAC Process

CO_2 molecules interact with materials that are hierarchically porous in the solid sorbent technique, allowing CO_2 to be extracted from the incoming gas mixture. Materials that have different pore sizes and targeted connectivity to reduce mass transfer resistance through the material while preserving sufficient pore volume for high surface area and chemistry are referred to as hierarchically porous materials. Effectiveness in separating diluted gas mixtures is well known for adsorption. Through strong covalent bonds known as chemisorption or weak intramolecular forces known as physisorption, solid sorbents can extract CO_2 from gas mixtures. This heuristic has certain exceptions when it comes to zeolite-based chemisorption processes. An amine surface functionalization can be applied to solid sorbents to improve their interactions with CO_2 molecules and increase their selectivity for CO_2. Many support structures are being investigated currently for use as solid sorbents for DAC such as metal-organic frameworks (MOFs), activated carbon, silica materials, zeolites, porous organic polymers, carbon molecular sieves and carbon nanotubes.

A representative process flow diagram for the stationary bed solid sorbent DAC process is shown in Figure 7. The adsorption and desorption processes for the solid sorbent process are performed in batch, with each composed of multiple process steps. In this case, liquid flows are shown by blue lines and gaseous flows by green lines. The initial phase of desorption where residual air is removed from the contactor to prevent dilution of the produced CO_2 after evolution from the sorbent, represented by the orange line from the contactor to the vacuum pump.

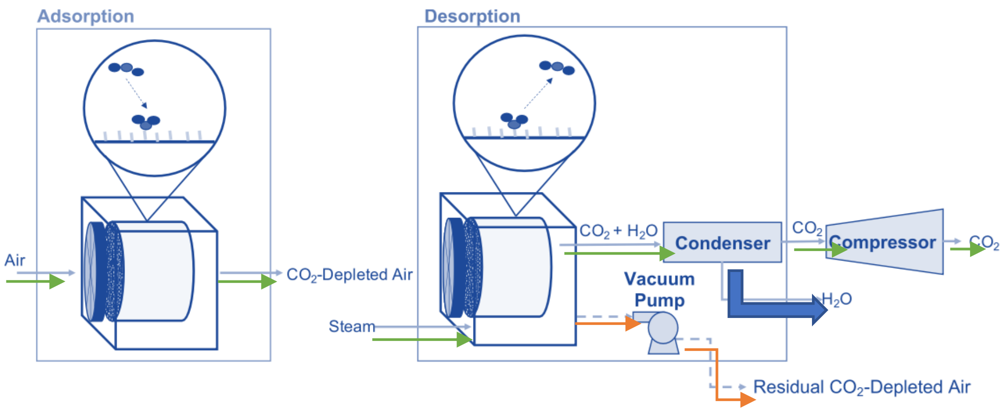

Figure 7. Representative process flow diagram for solid sorbent DAC (McQueen, A review of direct air capture (DAC): scaling up commercial technologies and innovating for the future, 2021)

In this process, fans push air through the contactor unit, where CO_2 adsorbs onto the solid sorbent at ambient conditions. CO_2 is selectively removed by the sorbent, and CO_2-depleted air leaves the system. The device is changed from adsorption to desorption mode after the solid sorbent has reached the desired level of CO_2 uptake or is saturated with CO_2. At this stage, the contactor is closed off from the surrounding environment. In addition to reducing amine degradation from air, a vacuum pump removes residual air from the contactor to avoid diluting the CO_2 generated by remaining oxygen and nitrogen in the contactor. According to earlier research, this vacuum pressure is approximately 30 mbar, and the vacuum stage can lower the temperature needed for regeneration. After the vacuum stage, the material is heated to the regeneration temperature (around 80–120 °C) by sending steam into the contactor. The released CO_2 is also flushed from the contactors by the steam. After that, it is separated from the water in the condenser and transported to compression for further use, storage, or shipment. Each of the DAC approaches utilizes distinct kinetics to effectively separate CO_2. The sorbent substrate's properties and functionality, along with the CO_2 content in the gas phase, have a significant impact on the kinetics for the solid sorbent scenario. Diffusion resistance, both internal and external, is what essentially controls adsorption. The system's mass transfer is facilitated by the diffusion of a thin layer of fluid, which is the characteristic of the external resistance. Here, the sorbent's mass transfer restrictions are largely dependent on the thickness of this fluid boundary. Internal resistance plays a significant role in the overall system's dynamics and includes internal diffusion at the micro, meso, and macropore levels. CO_2 molecules are subject to surface and capillary forces in the micropores and mesopores, respectively. Intermolecular forces are typically not experienced by the macropores; instead, they help the system's bulk fluid flow (McQueen, A review of direct air capture (DAC): scaling up commercial technologies and innovating for the future, 2021).

5.1.1. Adsorption Materials

Physical adsorption materials, such as zeolites and metal-organic frameworks (MOF), offer a wide range of adsorbents with stable structures and simplicity of preparation.

Zeolites in particular are frequently cited as benchmark materials for physisorption. Numerous zeolite architectures have shown to be highly useful in the adsorption industry. Medium-sized zeolites exhibit superior CO_2 adsorption ability under low pressure conditions compared to smaller-sized zeolites. Figure 8. illustrates the structure of Zeolites. Zeolites function better at low CO_2 partial pressure than carbon-based adsorbents and may interact with CO_2 depending on the alkali cation present on the surface. However, the most difficult barrier for zeolites to overcome is their low CO_2 selectivity. There have been several reported modification techniques that help zeolites become more CO_2 selective.

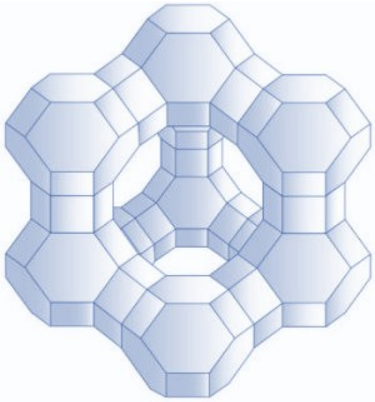

Figure 8. Structure of Zeolite (Woodford, 2023)

Because of their lower adsorption, heat and greater CO_2 adsorption capacity, MOFs are more acceptable DAC candidates than traditional amine-grafted porous materials. MOFs show decreased CO_2 uptake under low CO_2 concentrations or in the presence of moisture, while having outstanding qualities like well-developed porosity, adjustable pore size, flexible topology, artificially directional production, and variable surface chemistry. Some of the MOF structures are shown in Figure 9. The key for selecting the right MOFs for CO_2 capture is the pore apertures of the MOFs should be approximately the same size as the kinetic diameter of the CO_2 molecule (~3 Å). Additionally, by varying the kind of ligands or metal nodes, the pore size can be changed.

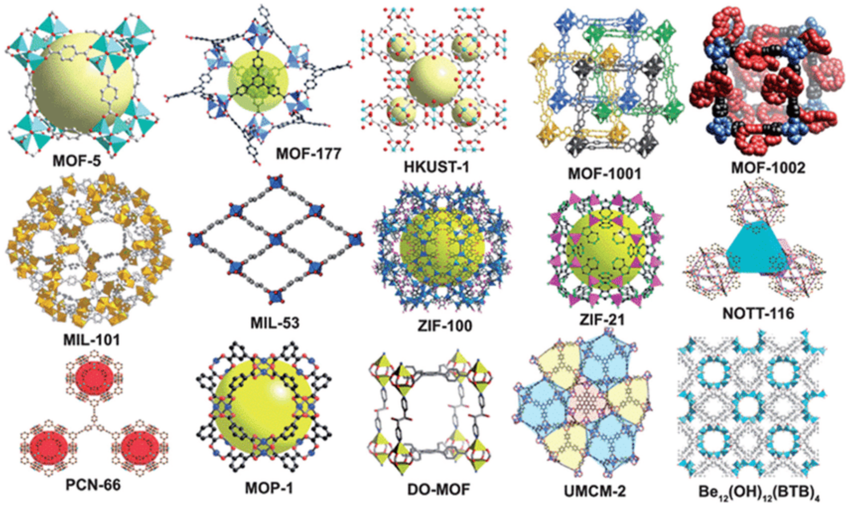

Figure 9. Metal-organic framework (MOF) structures (Kampouraki, 2019)

Due to their diverse framework topologies, pore systems, and large surface areas, zeolitic imidazolate frameworks (ZIFs), a new subclass of MOFs, have gained a lot of attention in the field of CO_2 capture. ZIFs include both bulk ZIF materials and supported ZIF membranes. Three thermally and chemically stable ZIFs (ZIF-68, ZIF-69, and ZIF-70) were created by BANERJEE and these ZIFs had an exceptionally high affinity and capacity for CO_2. The ZIFs have permanent pores with heterogeneous link functioning in the pore walls. Specifically, when ZIF-69, ZIF-68, and ZIF-70 were exposed to streams containing a binary mixture of CO_2/CO (50:50 v/v) at 25 °C, they completely retained CO_2 and allowed CO to pass through. These large pores have diameters of 7.2, 10.2, and 15.9 Å and are connected through tunable apertures (4.4, 7.5, and 13.1 Å). (Shi, Zhao, & Ni, 2023)

To release the adsorbed CO_2, the sorbent material is usually heated or subjected to reduced pressure. The desorbed CO_2 is collected and typically concentrated to a high purity level. This step may involve compressing the CO_2 gas to make it easier to handle and transport. Captured CO_2 can be used in various industrial processes, such as enhanced oil recovery, production of synthetic fuels, chemical manufacturing (e.g., urea production). Alternatively, CO_2 can be stored in geological formations, such as depleted oil and gas fields or deep saline aquifers, as part of a process known as CCS. This helps in sequestering CO_2 away from the atmosphere for long-term storage, mitigating its contribution to climate change.

5.2. Liquid Solvent DAC Process

The liquid solvent-based method involves the absorption of gaseous CO_2 into a liquid solvent, which produces two leaving streams: one liquid that is rich in CO_2 and the other that is gaseous and depleted of CO_2. Structured packing is commonly used in solvent-based methods to enhance the surface area of contact between the liquid and gas phases. When using solvent-based DAC with structured packing, the gas-side pressure drop typically declines while the surface area is increased. To absorb CO_2, the solvent-based method needs a strong basic hydroxide solution. After then, there is an anionic exchange, which leads to the precipitation of calcium carbonate pellets. Recovering CO_2 from precipitated calcium carbonate using the solvent technique to DAC demands high temperatures. Liquid solvent DAC is not the only application where a trade-off must be made between the need for regeneration energy and the strength of the capture agent. The high energy required of this separation is further driven by the fact that the severe dilution of CO_2 in air necessitates the use of a strong base for adequate separation.

Different kinetics are used by each of the DAC methods to efficiently separate CO_2. Fast pseudo first order kinetics and the gas phase CO_2 concentration are the limitations of current solvent DAC technology. To properly define this system, four steps need to be taken into account: gas phase diffusion, diffusion across the gas–liquid interface, liquid-phase diffusion, and chemical reaction. The term "gas phase diffusion" describes how CO_2 diffuses through air and eventually meets the gas–liquid contact. Once at the interface, CO_2 will diffuse via the gas–liquid interface, where Henry's law can be used to calculate the CO_2 concentration. In general, the interfacial concentration of CO_2 increases with decreasing dimensionless Henry's law constant for a given solvent (McQueen, A review of direct air capture (DAC): scaling up commercial technologies and innovating for the future, 2021).

5.2.1. Alkali Scrubbing

Figure 10. shows the alkali-scrubbing process for the liquid solvent DAC system. It is comprised of two loops, the contactor loop and the calciner loop.

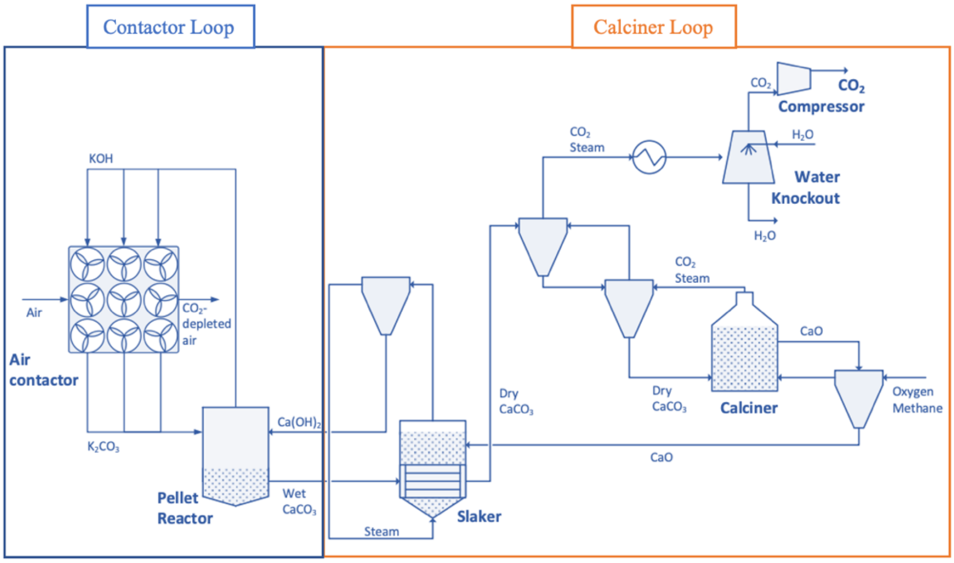

Figure 10. Schematic representation of the alkali-scrubbing DAC process (Sabatino, et al., 2021)

During the alkali scrubbing process, CO_2 is captured in a special air contactor unit and absorbed as potassium carbonates (K_2CO_3) in an aqueous potassium hydroxide (KOH) solution. The mechanism of absorbing carbon dioxide in alkaline solutions is well-known and involves two steps.

$CO_{2(aq)} + OH^- \Leftrightarrow HCO_3^-$ Equation 1

$HCO_3^- + OH^- \Leftrightarrow CO_3^- + H_2O$ Equation 2

Equation 1 is the rate limiting step of absorption mechanism. All alkali hydroxide sorbents share this mechanism; however, KOH is said to have the fastest kinetics.

The solution is pumped to a central regeneration facility after leaving the contactor. In order to make calcium carbonate ($CaCO_3$) and regenerate the KOH solution, which may be pumped back to the contactors, the K_2CO_3 here engages in an anionic exchange with calcium hydroxide ($Ca(OH)_2$) in the pellet reactors.

$K_2CO_{3(aq)} + Ca(OH)_{2(aq)} \Leftrightarrow 2KOH_{(aq)} + CaCO_{3(s)}$ Equation 3

$CaCO_3$ has an extremely low solubility in water and, therefore, precipitates and it is easily separated from the liquid phase. However, because $Ca(OH)_2$ is not very soluble in strongly alkaline solutions, the concentration of Ca^{2+} ions, which drives the rate of reaction in Equation 3, is low in these conditions. The produced $CaCO_3$ is then sent into a steam slaker unit, where the pellet reactors' $CaCO_3$ is dried using heat from the calciner products before being put into the calciner like shown in the Equation 4.

$CaCO_{3(s)} \rightarrow CaO_{(s)} + CO_{2(g)}$ Equation 4

Calcium oxide (CaO), water, and CO_2 are the products of a breakdown reaction that occurs when the $CaCO_3$ is heated to 900 °C in the calciner. Currently, natural gas and oxygen are delivered internally into the calciner to reach the necessary temperature. This produces a gaseous mixture that is mostly made up of CO_2 and water. The slaker performs the last stage of the regeneration cycle, where the hydration of CaO to $Ca(OH)_2$ occurs in accordance with Equation 5 (Sabatino, et al., 2021).

$CaO_{(s)} + H_2O_{(s)} \rightarrow Ca(OH)_{2(s)}$ Equation 5

After the regeneration of the sorbent in an alkali scrubbing DAC system, $Ca(OH)_2$ is recycled and reused in the CO_2 capture process. This continuous cycle of sorbent regeneration and reuse is critical for maintaining the efficiency and sustainability of the DAC system.

5.2.2. Amine Scrubbing

In the regeneration part where is considerably simpler, the amine-scrubbing method is different from the alkali scrubbing method. The process layout is shown in Figure 11.

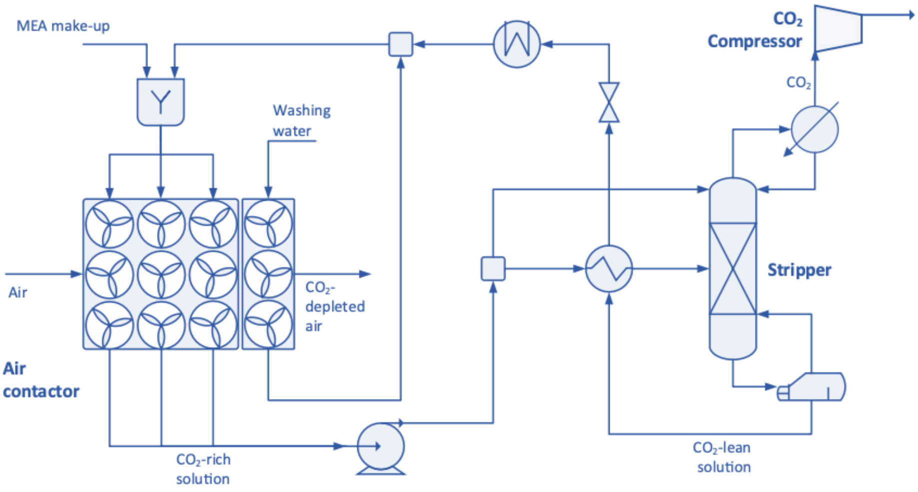

Figure 11. Schematic representation of the amine-scrubbing process (Sabatino, et al., 2021)

In the aqueous monoethanolamine (MEA) solution (C_2H_7NO), CO_2 is chemically absorbed through a reaction with the hydroxide ion, as demonstrated by Equations 1 and 2 and the following reactions (Equations 6 and 7).

$C_2H_7NO + CO_{2(aq)} + H_2O \Leftrightarrow C_2H_7NOCOO^- + H_3O^+$ Equation 6

$C_2H_7NO + H_3O^+ \Leftrightarrow C_2H_7NOH^+ + H_2O$ Equation 7

Compared to K_2CO_3, MEA has a comparatively high vapor pressure, which could lead to a significant solvent loss into the atmosphere. Furthermore, MEA is far more hazardous and may have negative effects on both people and the environment. This is why a water-wash section has been used to lower MEA emissions. After being pumped to the stripper pressure, the rich solvent stream is divided into two flows. While the largest flow is preheated by using a lean/rich heat exchanger, the other flow is kept cold and fed at the top of the stripper. This configuration uses the vapor from the hot, rich stream to heat the cold stream coming from the top, which is a common method of capturing CO_2 from flue gasses. The rich solvent stream is regenerated through stripping with steam (Sabatino, et al., 2021).

5.3. System Considerations

Direct air capture (DAC) technology, which involves removing carbon dioxide directly from the atmosphere, has garnered significant attention in the context of mitigating climate change. When considering the implementation of DAC systems, several key system considerations arise. These considerations are explained in the Table 3.

Table 3. System considerations of Direct Air Capture (DAC) (McQueen, A review of direct air capture (DAC): scaling up commercial technologies and innovating for the future, 2021)

System Considerations

Energy Requirements	Large quantities of energy are usually needed for DAC systems to function, mostly for the capture and regeneration operations. To make sure that the process has a net zero carbon footprint, it is essential to evaluate the energy source and system efficiency.
Cost	One of the important considerations in the application of DAC technology is cost. In addition to the expenses related to continuous maintenance and carbon capture, determining the economic feasibility of the technology requires evaluating the capital costs involved in constructing and managing DAC installations.
Scale	For DAC systems to be effective in dealing with climate change on a significant scale, they must be scalable. The land area needed for installation, the possibility of growing production to meet rising demand, and the difficulties of moving captured CO_2 for storage or use are all taken into account.

Carbon Capture Efficiency	An important consideration for assessing the effectiveness of DAC technology is the efficiency of carbon collection. Enhancing capture efficiency increases the process' overall viability and sustainability by lowering the energy and financial needs for each unit of CO_2 removed.
Carbon Storage or Utilization	To stop CO_2 from being released back into the atmosphere, it must either be kept underground (carbon storage) or used in other processes (carbon utilization). Determining the entire impact of DAC technology requires evaluating the viability and safety of storage solutions in addition to the potential value of carbon usage products.
Environmental Impact	It is crucial to assess how DAC systems affect the environment in addition to their capacity to capture carbon. This covers factors including water and land use, as well as possible emissions from building, running, and transportation.
Policy and Regulation	Regulations and policy frameworks have a big influence on how DAC technology is implemented. To fully understand the benefits and challenges of DAC implementation, it is essential to evaluate the legislative and regulatory context, which includes carbon pricing mechanisms, environmental permitting procedures, and incentives for carbon capture and storage.
Public Acceptance and Stakeholder Engagement	The successful application of DAC technology necessitates public acceptance and interaction with relevant stakeholders, including local communities, environmental organizations, and government. In order to increase support for DAC initiatives and make their implementation easier, it can be helpful to address issues with safety, environmental effect, and social equality.
Long-Term Viability	A number of variables, including market dynamics, climate change estimates, and technological improvements, must be taken into account while assessing the long-term viability of DAC technology. To make sure that DAC is a viable tool for addressing climate change in the years to come, ongoing innovation and adaptation will be required.

By carefully considering these system considerations, stakeholders can make informed decisions about the development, deployment, and management of direct air capture technology as part of broader efforts to mitigate climate change.

5.4. Costs of DAC Technologies

Briefly discussed above, the struggle areas for DAC are energy requirements, costs, environmental impacts, and political support etc. In order to better illustrate the current state of DAC, this section will review the status of these categories and present a few essential numerical and graphic data points. There are many factors that cause the fluctuations in costs. Some of these factors are capital cost, operating cost and the cost from energy sources.

5.4.1. Capital Cost

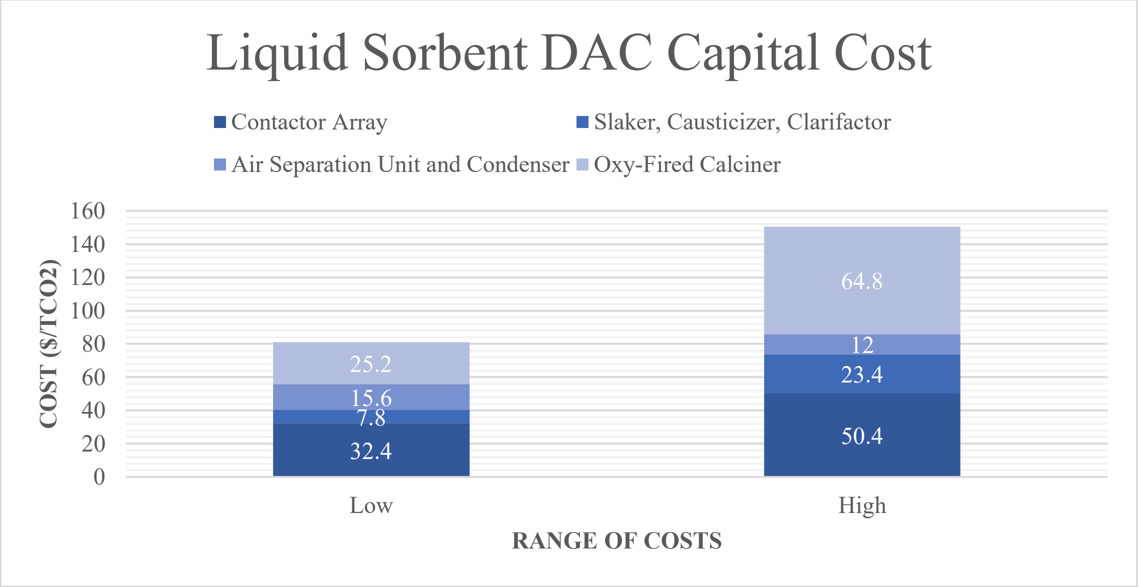

Figure 12. Liquid solvent DAC capital cost with low and high range (Ozkan, Priyadarshi Nayak, D. Ruiz, & Jiang, 2022)

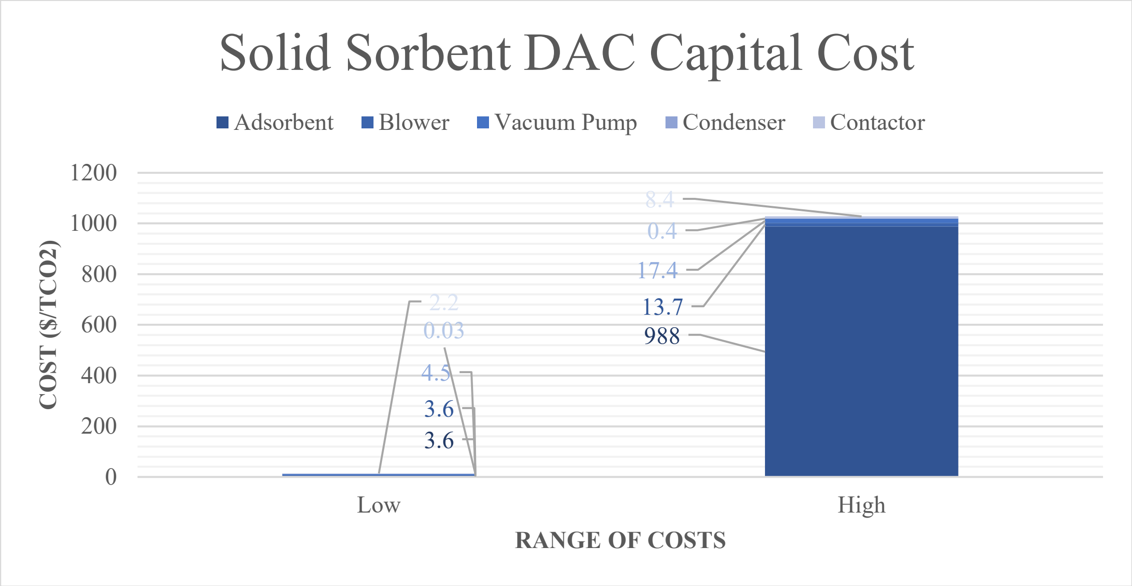

Figure 13. Solid sorbent DAC capital cost with low and high range (Ozkan, Priyadarshi Nayak, D. Ruiz, & Jiang, 2022)

Figure 12 and 13 illustrates how expensive liquid and solid DAC systems are, with capital expenses accounting for most of the total cost. According to records, the cost of this alone can exceed $1,000/tCO$_2$ for solid-based systems and $150/tCO$_2$ for liquid systems. On the other hand, the low range offers cost estimates of approximately $80/tCO$_2$ for liquid systems and approximately $200/t CO$_2$ for solid systems (Fuss, et al., 2018). The cost of the increased energy supply is not included in this charge. The expected cost range for a liquid-based system using natural gas as the energy source is $147–264/tCO$_2$. (Negative Emissions Technologies and Reliable Sequestration, 2019) A large additional expense is not seen with solid systems because of a smaller energy demanding process when compared to a liquid-based system (Negative Emissions Technologies and Reliable Sequestration, 2019).

5.4.2. Operating and Maintenance Cost

Operating and maintenance expenses are less than capital costs, but they are nevertheless crucial for maintaining the wellbeing of the facility and its equipment. Maintenance, labor, makeup, and waste removal are some of the costs that are covered in this area and relate to liquid operating and maintenance expenses. The costs for adsorption, steam, and the vacuum pump are in line with solid operating and maintenance.

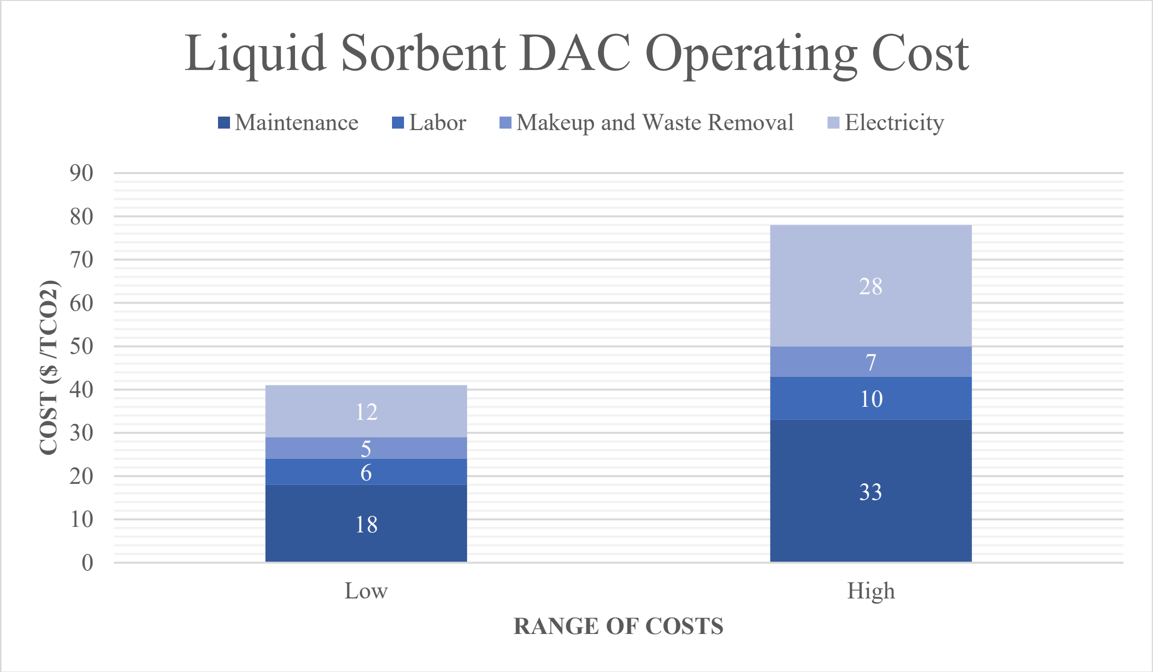

Figure 14. Liquid solvent DAC operating cost with low and high range (Ozkan, Priyadarshi Nayak, D. Ruiz, & Jiang, 2022)

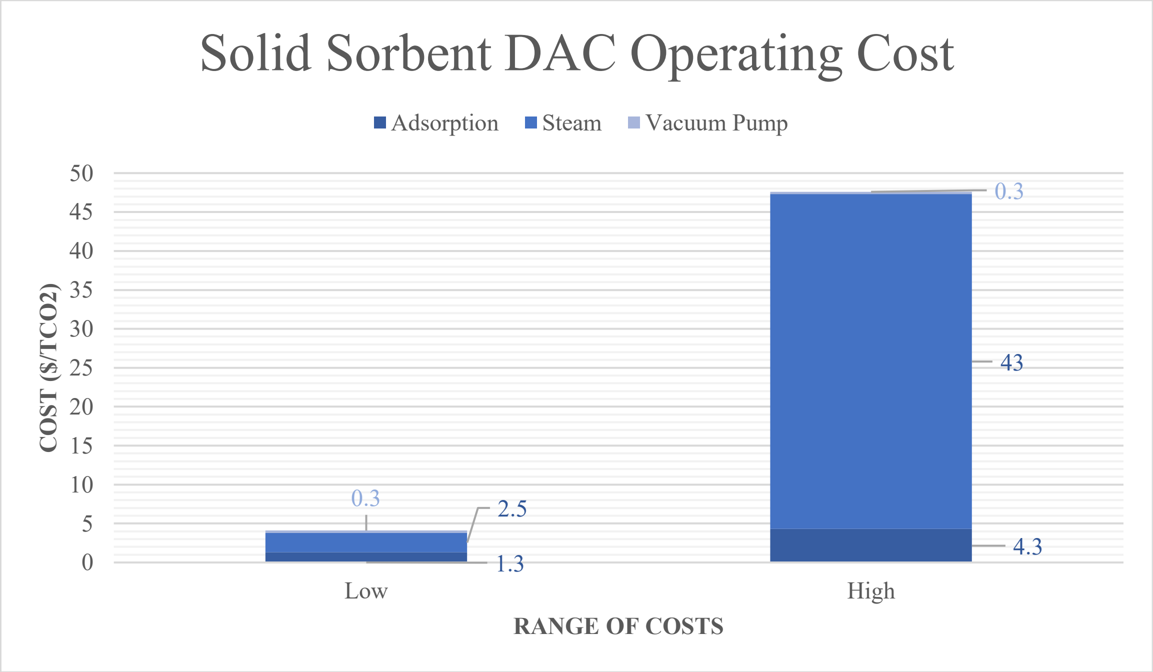

Figure 15. Solid sorbent DAC operating cost with low and high range (Ozkan, Priyadarshi Nayak, D. Ruiz, & Jiang, 2022)

Figure 14 and 15 illustrates that the pricing ranges for both technologies are less than $\$100/tCO_2$. For the liquid system, the low and high ranges are about $\$40/tCO_2$ and $\$80/tCO_2$, respectively. For the solid system, the low and high ranges are approximately $5/tCO2 and

\$50/tCO_2, respectively. When capital costs are combined with operation and maintenance charges, they might become extremely high costs, which could decrease the influence of DAC on mitigating climate change, if not reduced. Evidently, the quick adoption and implementation of DAC require cost reduction through study and accurate modeling (Negative Emissions Technologies and Reliable Sequestration, 2019).

5.4.3. Cost from Energy Sources

The technology is currently considered of struggle with capital and operating and maintenance costs, while the cost from possible energy sources has not been taken into account yet. This technology relies heavily on its energy supply, and the cost of that energy varies widely. This expense should be taken into account since it raises the cost of the technology significantly. To give heat and electricity to the proper components of the system, energy must be supplied in both electric and thermal forms. To do this, nuclear, solar, wind, coal, and natural gas are available as an energy sources. The price per ton of CO_2 produced by each of these sources will vary, impacting the total cost. The following sources produce different costs for capture: The cost of solar power is estimated to be \$430–690 tCO_2, the cost of wind power would be \$360–570/tCO_2, natural gas would cost \$88–228/tCO_2, the cost of coal is estimated to be \$88–228/tCO_2, and the cost of nuclear power would be \$370–620/tCO_2. It appears that the various energy sources on the list have a significant impact on the DAC systems' capture cost and, consequently, its appeal to the public. These prices highlight a significant cost differential between fossil fuels and renewable energy sources. Renewable energy sources like solar and wind have high costs at least \$430/tCO_2 and \$360/tCO_2, respectively. However, compared to the clean alternatives, the prices of coal and natural gas are much lower, ranging from \$88/tCO_2 to \$228/tCO_2, at their maximum. This is particularly significant when comparing the carbon footprints of fossil fuels and renewable energy sources. For DAC, this creates a challenging situation. In order to find a more efficient system while maintaining low costs, substantially more modeling is needed to address the energy and expense issues (McQueen, J. Desmond, H. Socolow, Psarras, & Wilcox, 2021).

To sum up, capital and operating costs ranges are shown in the Table 4 and the total cost would be changed depending on the cost from the energy sources as shown in Table 5. While the summation of capital and operating cost for Liquid solvent DAC varies between 122 – 228.6 \$, for the solid sorbent DAC cost varies between 18.03 – 1075.5 \$.

Table 4. Low and high-cost range of capital and operating costs for liquid sorbent DAC and solid sorbent DAC (Ozkan, Priyadarshi Nayak, D. Ruiz, & Jiang, 2022)

Liquid Sorbent DAC		***Low (€)***	***High (€)***
Capital cost	Contactor Array	30	28
	Slaker, Causticizer, Clarifactor	7.21	21.64
	Air Separation unit and Condenser	14.43	11.10
	Oxy-Fired Calciner	23.30	60
Operating Cost	Maintenance	16.64	31
	Labor	6	9
	Makeup and Waste Removal	5	7
	Electricity	11	26
	TOTAL:	***113***	***267***
Solid Sorbent DAC		Low (€)	High (€)
Capital Cost	Adsorbent	3.33	914
	Blower	3.33	13
	Vacuum Pump	4	16
	Condenser	0.03	0.40
	Contactor	2	7.77
Operating Cost	Adsorption	1.20	4
	Steam	2.30	40
	Vacuum Pump	0.30	0.30
	TOTAL:	***17***	***995***

Table 5. Low and high-cost range for different energy sources (Ozkan, Priyadarshi Nayak, D. Ruiz, & Jiang, 2022)

Energy Sources	***Low (€)***	***High (€)***
Solar	398	638
Wind	333	527
Natural Gas	81	211
Coal	81	211
Nuclear Power	342	573

6. NATURAL BASED SOLUTIONS

The order of the structure of the direct air capture part is shown in Figure 16 and this part of the thesis discusses the topics in this order as shown.

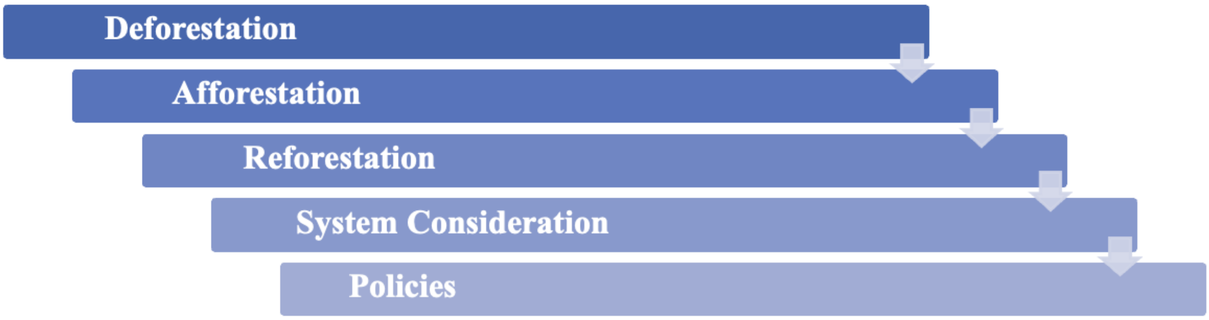

Figure 16. Natural Based Solutions Outline

Forests are invaluable ecosystems that play a crucial role in maintaining the balance of our planet's biosphere. They provide habitat for countless species, regulate climate, mitigate erosion, purify water, and offer numerous socio-economic benefits to human societies. However, during the past century, deforestation brought on by logging, urbanization, infrastructural development, and agricultural expansion has drastically decreased the amount of forest cover on Earth. In addition to increasing greenhouse gas emissions and degrading the soil, the loss of forest area has harmed ecosystem services and reduced biodiversity.

The function of trees in removing CO_2 from the atmosphere has drawn more attention in the context of climate change. During photosynthesis, trees absorb CO_2 and store it in their biomass and soil. Due to the release of stored carbon back into the atmosphere, deforestation and forest degradation are factors in carbon emissions. Because of this, forests are now both a victim and a solution for global warming, while forest restoration and conservation can lessen the effects of climate change, the loss of forest cover worsens it.

Beyond only planting trees, the goals of afforestation and reforestation also include improving biodiversity, reducing climate change, supporting sustainable development, and restoring the ecological services and functions of forests. The design, implementation, and monitoring of forest restoration projects are carried out by a variety of parties, including local communities, governments, non-governmental organizations, and the commercial sector. Research and practical afforestation and reforestation experiences throughout the years have yielded important insights into the ecological, social, and economic aspects of forest restoration. Technological developments in ecological modeling, remote sensing, and restoration have increased our comprehension of forest dynamics and the efficiency of restoration initiatives. Moreover, increased funding for afforestation and reforestation projects worldwide has resulted from the understanding of forests' importance in mitigating the effects of climate change and facilitating adaptation to them. Even with these improvements, there are still many obstacles to overcome before afforestation and reforestation programs can be put into action. Land tenure, financial limitations, regulatory frameworks, and social conflicts are some of the problems that may limit restoration projects' effectiveness and long-term viability. Planning and managing forest restoration projects must incorporate ecological, socioeconomic, and governance factors in an interdisciplinary manner to meet these problems.

6.1. Deforestation

Deforestation is the process of clearing or removing forests, typically for the purpose of converting the land to other uses, such as agriculture, urban development, or industrial activities. It involves the cutting down or burning of trees and vegetation, leading to the destruction or depletion of forested areas. Deforestation can have significant environmental impacts, including habitat loss, biodiversity decline, soil erosion, and disruption of local and global climate patterns. It's a major concern because of its adverse effects on ecosystems, wildlife, and the overall health of the planet. Since the turn of the century, the tropics have lost about 200 million hectares of forest, or less than tenth of the total forest area, and even larger amounts have been degraded. Deforestation is therefore the main cause of the decline in terrestrial biodiversity and the second-largest source of greenhouse gas emissions, after fossil fuels (Primary Forest Loss, 2024).

6.1.1. Causes of Deforestation

Understanding the primary drivers of deforestation requires being able to distinguish between the agents and causes of the phenomenon. Some of the main causes of deforestation is shown in Table 6.

Table 6. The causes of deforestation (Okia, 2013)

The Causes of Deforestation	
Expansion of Farming Land	The conversion of forests into agricultural land is one of the main causes of deforestation. The need for food crops rises in parallel with the world population, pushing agricultural frontiers into forested areas. Large-scale deforestation is mostly caused by cash crops like soybeans, palm oil, and cattle ranching in areas like Southeast Asia and the Amazon rainforest.
Logging and Timber Extraction	Another important factor contributing to deforestation is logging for timber and wood products. Both allowed and illegal commercial logging operations contribute to the global destruction and degradation of forests. The commercial use of timber for building materials, furniture, and paper goods results in the loss of priceless forest ecosystems.
Infrastructure Development	Destroying massive areas of forest is frequently necessary for the development of roads, highways, dams, and other infrastructure related projects. Infrastructure development, driven by urbanization and industrialization, fragments and disrupts forest ecosystems, leading to habitat loss and wildlife displacement.
Mining and Extraction	Large areas of forested land must frequently be cleared for mining operations, including surface mining and the extraction of minerals and resources including coal, gold, and oil. Increased mining activity results in deforestation, soil erosion, water pollution, and disturbance of nearby ecosystems.
Urbanization and Human Settlements	Forests have been cut down for homes, businesses, and infrastructure development as a result of the fast urbanization and population increase that propel cities and human settlements forward. Forest regions are being assaulted upon by urban sprawl, which is dividing habitats and decreasing biodiversity.
Fire and Agricultural Practices	Slash and burn agriculture, practiced in many tropical regions, involves the cutting and burning of vegetation to clear land for cultivation. Small-scale farmers frequently employ this method to prepare fields, but it can also lead to uncontrolled wildfires that spread to nearby forests, destroying habitat and resulting in extensive deforestation.

6.1.2. The Consequences of Deforestation

The consequences of deforestation extend far beyond the loss of trees. Table 7. explores the multifaceted implications of deforestation, ranging from ecological disruptions to socio-economic challenges.

Table 7. Consequences of deforestation (Okia, 2013)

Consequences of Deforestation	
Loss of Biodiversity	Deforestation causes ecosystems and habitats to be destroyed, which leads to the extinction of plant and animal species. A large amount of the biodiversity of the planet is found in forests, and the loss of these habitats puts many species in danger of going extinct.
Climate Change	Because forests absorb carbon dioxide from the atmosphere, they are essential for reducing the effects of climate change. Deforestation contributes to greenhouse gas emissions and global warming by releasing stored carbon into the atmosphere. Furthermore, the loss of trees worsens climate change by lowering the Earth's ability to absorb carbon dioxide.
Soil Erosion and Degradation	When trees are cut down, the soil becomes more vulnerable to wind and water erosion, which depletes nutrients, sediments rivers, and destroys productive land. Deforestation lowers soil quality and impacts agricultural output by raising the danger of floods, landslides, and soil degradation.
Disruption of Ecosystem Services	Important environmental services that forests offer include soil stabilization, pollination, and water regulation. Deforestation affects these functions, increasing crop yields, creating a shortage of water, and making people more vulnerable to natural disasters.
Social and Cultural Impacts	People living in rural areas and indigenous communities that depend on trees for their traditional ways of life are frequently uprooted by deforestation. Social conflict, poverty, and the extinction of traditional knowledge can result from losing access to forest resources.

Protecting the remaining forests is key to meeting several of the United Nations Sustainable Development Goals (SDGs) among other ecosystem services, water circulation, climate regulation, provide climate mitigation, livelihood support and biodiversity protection. A number of global accords have been made with the goal of reducing deforestation, including the Paris Agreement and the New York Declaration on Forests to the SDG objective to halt deforestation, restore degraded forests and substantially increase afforestation and reforestation globally (Bager, Persson, & N.P. dos Reis, 2021).

6.2. Afforestation – Reforestation

In response to the alarming rates of forest loss and degradation, afforestation and reforestation have gained prominence as key strategies for reversing the adverse impacts of deforestation and fostering sustainable land management practices. This section of thesis explores the significance of reforestation as a critical tool in combating deforestation, highlighting its ecological, social, and economic benefits, and examining the challenges.

6.2.1. Afforestation

Afforestation refers to the deliberate establishment of forests on land that has not been forested for a considerable period. Planting trees on land that was formerly utilized for mining, agriculture, urban development, or other non-forest uses is the method involved in this operation. The goal of afforestation is to bring more forest cover to regions where it has historically been absent or severely decreased as a result of human activity. The creation of new forest ecosystems is the aim of afforestation, which has several advantages for the environment, society, and economy. Benefits of afforestation are shown in Table 8.

Table 8. Benefits of afforestation (Terms and Definitions - FRA 2025, 2023)

BENEFITS OF AFFORESTATION	
Carbon Sequestration	By removing CO_2 from the atmosphere, afforestation contributes to the mitigation of climate change. By absorbing carbon dioxide during photosynthesis and storing it in their biomass and soil, trees help to mitigate global warming by lowering the atmospheric concentration of greenhouse gasses.
Biodiversity Conservation	A variety of plant and animal species find new habitats thanks to afforestation, which supports the preservation of biodiversity. A vast variety of plant and animal species, including rare and endangered ones, are supported by forest ecosystems, which also carry out vital ecological tasks like pollination, seed distribution, and habitat connectivity.

Soil Erosion Control	Trees lower the risk of landslides, erosion, sedimentation in water bodies, and soil stabilization. Tree roots anchor soil particles, increasing soil fertility and moisture retention while lowering runoff and soil loss.
Water Resource Management	Forests play a crucial role in regulating the water cycle, influencing precipitation patterns, and maintaining water quality. Enhancing groundwater recharge, controlling streamflow, lowering the possibility of floods and droughts, and improving watershed health are all benefits of afforestation.
Ecosystem Services	Numerous ecosystem services are offered by forests, such as the filtration of air and water, management of the climate, cycling of nutrients, and supply of raw materials including fuelwood, lumber, and non-timber forest products. These environmental services are improved by afforestation, which promotes sustainable development and human well-being.

6.2.2. Reforestation

Reforestation is the process of restoring forests on previously deforested or degraded land. By replanting trees or supporting natural regeneration, this approach seeks to restore the ecological services and biodiversity of degraded forest ecosystems. Planting tree seedlings, rebuilding degraded forest areas, shielding already-existing forests from additional degradation, and putting sustainable forest management techniques into practice are a few examples of reforestation operations. Projects to reforest may help in reducing the negative impacts of deforestation, including carbon emissions, habitat loss, soil erosion, and biodiversity loss. Reforestation helps mitigate climate change, protect watersheds, save soil, and provide ecosystem services by restoring forest ecosystems. Benefits of reforestation are shown in Table 9. To maintain the long-term sustainability of regenerated forests, successful regeneration necessitates careful site selection, the selection of suitable tree species, community involvement, monitoring, and adaptive management.

Table 9. Benefits of reforestation

BENEFITS OF REFORESTATION	
Ecological Restoration	Reforestation recovers the biological processes and biodiversity of forest ecosystems by restoring degraded or cleared landscape. Native plants and animals have a place to live in restored forests, which also help with ecological functions like soil formation and nutrient cycling and increase the resilience of ecosystems against environmental disturbances.
Carbon Sequestration and Climate Change Mitigation	By removing carbon dioxide from the atmosphere and storing it in soil and plants, reforestation contributes to slowing down climate change. Restored forests support attempts to mitigate climate change by acting as carbon sinks, absorbing CO_2 emissions and offsetting the carbon footprint of human activity.
Habitat Creation and Wildlife Conservation	Reforestation supports biodiversity conservation and wildlife habitat connectivity by generating new habitats for a range of plant and animal species. Restored forests provide food, shelter, and breeding sites for a variety of wildlife species, including endemic and endangered ones. They also support various ecosystems.
Soil and Water Conservation	Through stabilizing soil, lowering runoff, and controlling streamflow, reforestation contributes to improved soil fertility, improved water quality, and prevention of soil erosion. Sustainable management of water resources is supported by restored forests because they also help flood control, groundwater recharge, and the health of watersheds.
Socio-economic Benefits	Reforestation benefits local economies and communities in a number of ways, including by creating jobs in the forestry and related sectors, generating income from sustainable forest management techniques, and supplying ecosystem services like ecotourism, recreation, and the preservation of cultural heritage.

Both afforestation and reforestation play crucial roles in addressing global environmental challenges, such as climate change, biodiversity loss, and ecosystem degradation. By increasing forest cover and restoring degraded forest ecosystems, these practices contribute to the conservation of natural resources, enhancement of ecosystem services, and promotion of sustainable development (Sacco & A. Hardwick, 2021).

6.3. System Considerations of ARPs

Reforestation and afforestation, while crucial for environmental sustainability and ecosystem restoration, involve various system considerations to ensure their effectiveness and success. Some key considerations are explained in Table 10.

Table 10. System considerations of ARPs (Environmental Requirements for Afforestation, 2023)

System Considerations	
Ecological Suitability	It is important to choose tree species that are suitable with the soil, climate, and ecosystem dynamics of the area. Selecting native plants protects the region's ecological integrity and helps in the preservation of biodiversity.
Site Preparation	For tree planting initiatives to be successful, the site must be properly prepared. To provide the ideal environment for tree growth, this may entail removing invasive species, managing erosion, and treating soil compaction.
Water Availability	Enough water is essential for the development and growth of trees. Water supply should be taken into account, particularly in dry or semi-arid areas, where the implementation of suitable irrigation systems may be necessary.
Monitoring and Maintenance	Newly planted trees require constant care and attention to ensure their survival and healthy growth. This covers tasks like pruning, insect control, weed control, and necessary watering.
Community Engagement	Reforestation and afforestation initiatives cannot succeed in the long run unless local people and stakeholders are involved. Building support and ensuring project sustainability can be achieved by including communities in decision-making processes, offering education and training, and encouraging a sense of ownership.

Biodiversity Conservation	By encouraging the planting of a variety of native species and constructing wildlife habitat corridors, afforestation and reforestation initiatives should place a high priority on biodiversity protection. This improves overall ecological function and supports the resilience of ecosystems.
Carbon Sequestration	A vital part of carbon sequestration and mitigating climate change is afforestation and reforestation. The climate advantages of these initiatives can be maximized by selecting tree species with high potential for sequestering carbon and by putting sustainable management practices into place.
Land Tenure and Rights	In order to prevent conflicts and guarantee the long-term preservation of afforested or reforested lands, it is necessary to make land tenure and rights clear. Clear land tenure agreements promote sustainable land management techniques and help in the prevention of land grabbing.
Economic Viability	For afforestation and reforestation operations to be sustainable over the long term, economic viability is a critical factor. Investigating prospects for agroforestry, ecotourism, carbon offset markets, and other sustainable land use models that produce revenue and advance conservation goals are a few examples of how to do this.
Policy and Legal Frameworks	For afforestation and reforestation projects to be supported and regulated, appropriate legislative and policy frameworks are required. This includes tools for tracking and enforcing compliance, laws to stop deforestation and encourage sustainable land management, and incentives for landowners.

6.4. Policies for Afforestation and Reforestation

Policies such as the National Forest Policy, Afforestation and Reforestation Programs, Forest Conservation Laws and Regulations, Land Use Planning and Zoning Regulations, Carbon Offset Mechanisms, Community Forestry Regulations, Ecosystem Restoration Policies, and International Agreements and Initiatives are critical for addressing global environmental challenges and fostering sustainable development through reforestation and afforestation efforts. These regulations are essential for reducing the effects of climate change, preserving biodiversity, safeguarding ecosystems, and advancing socioeconomic development. Reforestation strategies aim to improve air quality, enhance carbon sequestration, and mitigate greenhouse gas emissions by restoring damaged forests and fields, with the support of initiatives such as the Bonn Challenge. The goals of reforestation initiatives, such as those in line with the United Nations Framework Convention on Climate Change (UNFCCC) obligations, are to increase green cover, strengthen ecosystem resilience, and develop new forests on formerly unforested areas. By providing habitats for a variety of plant and animal species, maintaining genetic diversity, and promoting ecosystem services like pollination, water control, and soil fertility, both forms of policy aid in the conservation of biodiversity. Furthermore, by fostering ecotourism and recreational activities, producing revenue from sustainable forest management methods, and opening up job opportunities, these policies also contribute to economic growth. Policies for reforestation and afforestation, as indicated in the efforts above, are crucial instruments for creating more resilient, equitable, and sustainable societies in the face of environmental difficulties on a global scale. These policies address these interconnected environmental, social, and economic objectives.

7. CALCULATION METHODOLOGY OF CO_2 EMISSIONS BY TREE

The order of the structure of the calculation methodology part is shown in Figure 17 and this part of the thesis discusses the topics in this order as shown after.

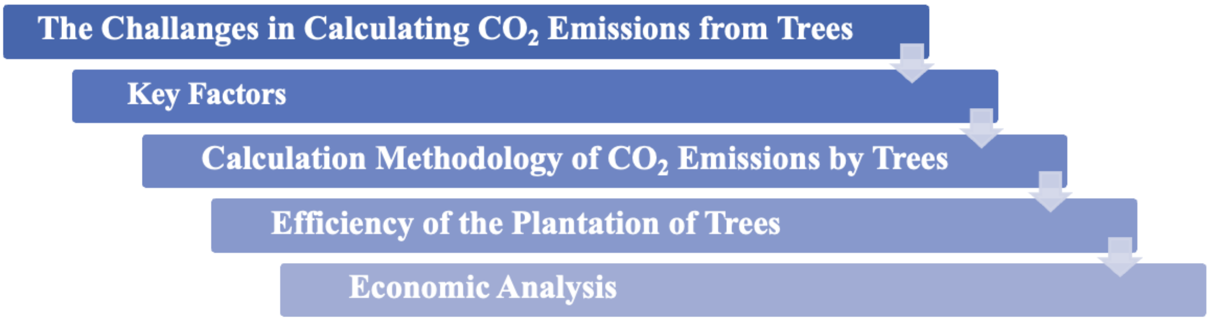

Figure 17. Calculation Methodology of CO_2 Emissions by Tree

The creation and improvement of reliable mathematical techniques for calculating CO_2 emissions from trees is essential for this understanding. There have been several challenges in estimating the carbon balance of forests, from the variety of tree species and ecosystems to the unpredictability of environmental factors and management techniques. Significant uncertainties in carbon accounting resulted from the frequent use of broad assumptions or rudimentary models in traditional methodologies. Standardized procedures and criteria for estimating CO_2 emissions from trees have been developed in response to the pressing necessity of addressing climate change. This has made comparisons and consistency between studies and geographical areas easier. These protocols offer a framework for carrying out thorough carbon accounting that takes into account important variables such as land-use change, biomass increase, mortality, and degradation. Despite these advancements, challenges persist in accurately quantifying CO_2 emissions from trees, particularly in the context of dynamic environmental changes and anthropogenic disturbances. Climate variability, land-use practices, pests, diseases, and natural disasters can all influence carbon fluxes in forest ecosystems, necessitating adaptive and resilient calculation methods capable of accounting for these uncertainties (Penman, et al., 2004). Considering these challenges and opportunities, this part of the thesis seeks to create an analytic CO_2 emission method from trees with a focus on their strengths, limitations, and applicability in different contexts. By synthesizing insights from the latest scientific research and practical experiences, this study aims to provide evidence-based guidance for sustainable forest management and climate change mitigation initiatives, as well as to contribute to the current conversation on forest carbon accounting.

For a number of reasons, guidelines for calculating CO_2 emissions from trees are crucial. In the first place, it guarantees uniformity and standardization in measurement techniques, enabling precise and equivalent data across various locations and periods. Maintaining this consistency is essential for tracking changes in carbon fluxes and stocks over time, as well as evaluating how well conservation and forest management initiatives are working. Secondly, guidance makes it possible for stakeholders and policymakers to make better-informed decisions by lowering uncertainty in greenhouse gas inventories and increasing the accuracy of emissions estimates. Guidance can also help nations with limited resources develop their ability and knowledge of technology so they can engage more successfully in global efforts to tackle climate change. One of the useful guidelines is the UNFCC (United Nations Framework Convention on Climate Change) framework on REDD+ (Reducing Emissions from Deforestation and Forest Degradation, and the role of conservation, sustainable management of forests, and enhancement of forest carbon stocks). It is a comprehensive system created to handle the major causes of global greenhouse gas emissions, deforestation and forest degradation. REDD+ aims to incentivize developing countries to reduce emissions from forested lands through financial incentives, capacity-building support, and technology transfer from developed nations. It is a comprehensive system created to handle the major causes of global greenhouse gas emissions, deforestation and forest degradation. Under REDD+, developed countries will transfer technology to developing countries and provide financial incentives to encourage them to cut emissions from forested areas. The framework prioritizes increasing forest carbon storage in addition to forest conservation and sustainable management. Furthermore, REDD+ recognizes the need of protecting biodiversity as well as the rights of local communities and indigenous peoples. REDD+ plays an important role in global climate change mitigation efforts by giving countries a framework to engage in emissions reduction efforts while supporting sustainable development (Fact Sheet: About REDD+ , 2016). Another good practice guidance is the IPCC (Intergovernmental Panel on Climate Change) for LULUCF (Land Use, Land-Use Change, and Forestry) provides comprehensive guidelines for measuring, reporting, and verifying greenhouse gas emissions and removals associated with activities in the land use sector. It provides best practices and standardized approaches for evaluating carbon fluxes and stocks, accounting for changes in land use, and calculating emissions and removals from operations including afforestation, deforestation, and forest management. The guidance intends to improve the accuracy and dependability of reporting on land-use related emissions and removals by encouraging consistency and transparency in accounting methods. This will enable successful efforts to mitigate and adapt to climate change at both the national and international levels (Penman, et al., 2004). Additionally, the global tree C-Sink guidelines provide a framework for estimating and accounting for carbon sequestration by trees on a global scale.

For the purpose of measuring the quantity of carbon stored in trees and forests, as well as the carbon fluxes connected to different land use and management methods, these recommendations provide standardized methodologies and best practices. The guidelines seek to increase the accuracy and comparability of carbon sequestration estimates across various locations and projects by fostering consistency and transparency in carbon accounting (Ithaka Institute, 2024). Overall, by offering the required instruments and procedures for tracking, reporting, and validating emissions from forested areas, guidelines for the computation of CO_2 emissions from trees significantly contribute to the global climate action effort. Although there are many tools and guidelines for calculating CO_2 emissions, accurately calculating these emissions presents numerous challenges and complexities that must be addressed to ensure robust and reliable results. The dynamic and varied structure of forest ecosystems makes it difficult to calculate CO_2 emissions from trees. A major challenge is the great variety of tree species found in forests across the globe, each with its own development habits, physiological traits, and reactions to external factors. Because tree species vary so much, it is difficult to build general models or equations for estimating carbon stocks and fluxes. Instead, species-specific techniques that take into account the unique characteristics of individual taxa are required. Other difficulties to calculate CO_2 emissions are shown in table 11.

Table 11. The challenges in calculating CO_2 emissions from trees

Variability in Tree Species and Ecosystems	*There are many kinds of trees in forests, and each has its own growth patterns and physiological traits. The structure, composition, and environmental circumstances of ecosystems differ, which makes it difficult to create general models or equations for carbon accounting (Nowak, et al., 2008).*
Uncertainty in Biomass Estimation	There are difficulties in precisely measuring tree biomass, which is an essential quantity for carbon accounting because trees vary widely in size, shape, and density. Certainties can be introduced by estimation techniques like remote sensing or allometric equations, particularly in thick or heterogeneous forests (Qin, Meng, Zhou, Liu, & Xu, 2020).
Temporal Dynamics	In forest ecosystems, seasonal variations, tree growth cycles, disturbances (such as storms and wildfires), and long-term successional processes all have an impact on the temporal variability of carbon fluxes. Long-term modeling and ongoing monitoring are necessary to capture these patterns (Seidl, 2011).
Spatial Heterogeneity	Because of several factors like topography, soil characteristics, and land-use history, forests display regional variation in their carbon stocks and fluxes. Robust spatial modeling methodologies are necessary because scaling up localized measurements to regional or global levels generates errors.

Mortality and Decay Processes	Decomposition and tree death are important aspects of the forest's carbon cycle. However, due to the influence of several factors, including climate, species composition, and disturbance regimes, it is difficult to forecast mortality rates, decomposition rates, and subsequent CO_2 emissions with any degree of accuracy (Qin, Meng, Zhou, Liu, & Xu, 2020).
Interactions with Climate Change	Growth rates, phenology, and disturbance regimes are all impacted by climate change in forest ecosystems, and these changes have an impact on carbon dynamics. Calculating CO_2 emissions becomes more difficult and uncertain when climate change estimates are incorporated into carbon models.
Anthropogenic Disturbances	Deforestation, logging, and land conversion are examples of human activities that have a major impact on the carbon stocks and fluxes in forests. Robust monitoring systems and precise accounting techniques are needed to quantify the effect of these disturbances on CO_2 emissions (Seidl, 2011).
Data Limitations	Sufficient availability and quality of data are essential for precise carbon accounting. Nevertheless, the accuracy of CO_2 emission estimates may be limited by biases, inconsistencies, and gaps in field observations, remote sensing databases, and climate projections.

7.1. Key Factors that Affect the Calculation of CO_2 Emissions Absorbed by Trees

Trees use a process known as photosynthesis to take up CO_2 from the atmosphere. Through their leaves, plants absorb CO_2 and use it to create the sugars they need to thrive. This process is known as photosynthesis. After being absorbed, the carbon is subsequently sequestered and the amount of CO_2 in the atmosphere is decreased by being stored in the branches, roots, and trunk of the tree (Schulz, 2023). A tree's capacity to absorb CO_2 varies according to several factors, each contributing to the complexity and variability of carbon accounting in forests. These factors are:

- Tree species
- Tree age and size
- Plantation density

- Land use history
- Climate and environmental conditions
- Disturbances and events
- Management practices
- Soil organic carbon storage

In this part, key factors that affect the calculation of CO_2 emissions absorbed by the trees are explained with several researches and case studies.

1. Tree Species

Because different tree species have different growth characteristics and functional properties, they sequester carbon at different rates and accumulate biomass at different rates. The distribution of biomass is influenced by the distinctive growth patterns of various tree species. While some species invest more of their energy to below-ground structures like roots, others invest their efforts on above-ground biomass like stems, branches, and leaves (Scalon, et al., 2023). Fast-growing pioneer species, for instance, frequently give priority to growing above ground in order to optimize light absorption and gain a competitive edge, which results in a relatively low biomass allocation below ground. On the other hand, slow-growing, long-lived species might devote more resources to underground features, including massive root systems, in order to improve stability and nutrient uptake. For example, while slower-growing tree species like oak and beech store more carbon during their longer lifespans, faster-growing tree species like eucalyptus absorb CO_2 more quickly. When fully grown, broad-leaved trees typically retain more CO_2 than conifers, although conifers grow considerably more quickly.

2. Tree Age and Size

Tree absorption and CO_2 emissions can be significantly impacted by both age and size. Compared to adult trees, young trees usually absorb less CO_2 because of their smaller biomass. Trees often get bigger as they get older, which increases their ability to absorb CO_2 until they achieve maturity. When a mature tree reaches a certain point, it may stop growing and go through a process known as "carbon saturation," in which it absorbs CO_2 at a rate similar to its respiration and achieves a net carbon balance. Contrary to expectations made by vegetation models, research that used data from the European Space Agency's SMOS satellite mission discovered that forests 140 years of age and older were approximately carbon neutral. In addition, older trees also face the risk of declining health or mortality, which can result in the release of stored carbon back into the atmosphere as the tree decomposes or burns (Younger trees champion carbon capture, 2023). According to a Nature study, at the individual tree level, tree growth and carbon capture rates rise with tree size. The growth rate of larger trees within a species is almost three times quicker than that of smaller trees, indicating the significance of tree size in sequestering carbon. (Stephenson, 2014) Although a tree's ability to absorb carbon can vary, it is widely thought that a tree can store 167 kg of CO_2 annually. Thus, increasing the number of trees planted, especially larger ones, can help offset carbon emissions to a considerable extent. Certain species, like eucalyptus, develop more quickly and absorb CO_2, whilst other species, like oak or beech, grow more slowly but accumulate more carbon over time (Collins, 2022). Bigger trees can absorb more CO_2 because they have larger canopies, which provide greater surface area available for photosynthesis. Nevertheless, when they break down carbohydrates and other organic materials, larger trees may also breathe more deeply and release more CO_2. This respiration rate can vary depending on species, health, and environmental conditions, but it usually increases with size (Isaifan & Baldauf, 2018).

3. Plantation Density

The quantity of CO_2 that can be sequestered is directly impacted by the plantation density. Trees that are thickly planted are usually found near to one another, which creates competition for resources like light, water, and nutrients. Although individual tree development may be slowed as a result of this competition, total biomass accumulation per unit area may increase. Increased photosynthesis and consequent CO_2 absorption from biomass could result in increased carbon sequestration. However, individual trees might not grow to their full potential due to competition for resources, which could reduce the plantation's overall capacity to sequester carbon. Trees are planted far apart in low-density plantations, giving each one greater access to resources. Due to less competition, trees in low-density plantations may grow at a faster rate on an individual basis than those in high-density plantations. In comparison to high-density plantations, the overall biomass per unit area may be lower even though individual tree growth may be faster. Less carbon sequestration and CO_2 absorption capacity per unit area could be the result of lower biomass. There is often an optimal plantation density that balances maintaining healthy tree growth with maximizing carbon sequestration. The best density will depend on a number of variables, including the type of tree, the site's characteristics, the management goals, and the climate in the area. Achieving a balance between optimizing carbon sequestration and maintaining healthy tree growth and ecosystem functioning is essential (Coomes & GRUBB, 2000).

4. Land Use History

The soil and tree carbon stores are released into the atmosphere when forests are removed for plantations, agriculture, or other land uses, which increases CO_2 emissions. The carbon held in a tree's biomass is released into the atmosphere as CO_2 when the tree is cut down, either by logging or clearing. This can happen through burning or decomposition. For example, depending on the prior land usage, the construction of plantations, such as oil palm or acacia, might have different effects on CO_2 emissions. Compared to plantations established on farmland or agroforest, those established on forest landscapes emit more CO_2 (Agus, et al., 2013). A carbon sink can be formed from land that was removed or deforested in the past but has since experienced afforestation or forest regrowth. Through photosynthesis, trees that are growing or replanted start to take in CO_2 from the environment, storing it in their biomass and soils. A number of variables, including tree species, site characteristics, and management techniques, can affect how quickly carbon is sequestered during forest regeneration. CO_2 emissions may be impacted by the vegetation structure of the land both before and after conversion. The vegetation structure of forests and shrublands is more complicated than that of plantations, which are distinguished by a consistent planting density. Variations in plant structure can have an impact on the rates of CO_2 emissions during land use change as well as the amount of carbon retained in biomass (Pan, Birdsey, Phillips, & Jackson, 2013).

5. Climate and Environmental Conditions

Through the process of photosynthesis, trees absorb carbon dioxide from the atmosphere, which helps to mitigate the effects of climate change. However, a variety of climatic and environmental factors affect trees' capacity to absorb CO_2. The rate of photosynthesis and respiration in trees is influenced by temperature. Warmer temperatures generally result in higher rates of photosynthesis and higher CO_2 absorption. But excessive heat can also cause stress to trees, which can have an impact on their metabolism and growth. Furthermore, water supply must be sufficient for photosynthesis to occur. Trees can sustain higher rates of carbon uptake and photosynthesis in areas with enough rainfall. On the other hand, a drought may prevent development and photosynthesis, which lowers a tree's capacity to absorb CO_2. Increased carbon uptake in trees can result from photosynthesis being stimulated by elevated atmospheric CO_2 concentrations. Under specific circumstances, this phenomenon—known as the CO_2 fertilization effect—can promote the growth of particular tree species and forests. Tree development and carbon sequestration are influenced by the fertility, moisture content, and structure of the soil. Healthy tree growth and improved carbon storage can be achieved with healthy soils that contain enough organic matter and nutrients. Storms, hurricanes, and wildfires are examples of extreme weather events that can harm or completely destroy trees, releasing stored carbon back into the atmosphere. The ability of forests to sequester carbon may be impacted by changes in the frequency and intensity of these events brought on by climate change. The way that different tree species and ecosystems react to changing climate conditions varies. For instance, trees in temperate or boreal forests may absorb CO_2 at a different rate than trees in tropical rainforests. The distribution and composition of forest ecosystems can change due to climate change, which can impact the ecosystems' overall ability to sequester carbon. In summary, the ability of trees to absorb CO_2 is intricately linked to climate conditions. Changes in temperature, precipitation, atmospheric CO_2 concentration, and extreme weather events can influence tree growth, productivity, and carbon sequestration rates.

6. Disturbances and Events

Strategies for managing forests and mitigating climate change must take into account how events and disturbances affect these emissions. It has been demonstrated that disturbances like pest outbreaks, logging, and wildfires significantly affect the amount of CO_2 that trees emit. The carbon balance in forests may be greatly impacted by these occurrences because they may cause a sudden release of carbon that has been stored in soil and vegetation. The direct outcome of logging and deforestation is the release of CO_2 into the atmosphere from harvested and decomposing trees. The area that can be used to sequester carbon in the future is also decreased by the loss of forest cover. For instance, research in a tropical forest discovered that, in comparison to unlogged regions, selective logging increased CO_2 emissions by 37%. Similar to this, it has been demonstrated that when trees burn and soil-stored carbon is destroyed, wildfires cause a significant release of CO_2. The quick release of carbon stored in trees as CO_2, CO, and other gasses is caused by wildfires. Changes in species composition and forest structure following a fire can have an impact on long-term carbon dynamics. The dominance of fire-adapted species may affect the capability of future carbon storage. Diseases and pests can seriously harm or even kill trees, which increases CO_2 emissions from organic waste that decomposes. Trees that are infested may develop more slowly, which will limit their capacity to sequester carbon. The composition and structure of a forest can change due to widespread tree death (Poland, et al., 2021).

7. Management Practices

Trees can absorb more carbon when they are included in animal agriculture systems (silvopasture) or row crop agriculture systems (agroforestry), which helps remove and store CO_2. Trees' CO_2 emissions can be greatly impacted by field management techniques. Reforestation and the restoration of forest ecosystems following natural disturbances such as wildfires or deforestation can boost the amount of carbon that trees and forests remove from the atmosphere, improving their capacity to store CO_2. Because of their increased exposure to light, trees on forest edges grow more quickly and absorb more carbon, hence managing these edges is essential. CO_2 emissions are influenced by soil respiration, which is influenced by temperature and moisture. Controlling soil properties, particularly along forest boundaries, can influence soil carbon release and the global carbon balance. Achieving a balance between minimizing disturbances and emissions and maximizing production, resilience, and health of the forest is essential to effective management. Achieving the greatest possible contribution of forests to climate change mitigation requires the application of sustainable and adaptive management strategies (Colarossi, 2022).

8. Soil Organic Carbon Storage

The entire quantity of organic carbon present in a given volume or mass of soil over a predetermined region and depth is referred as soil organic carbon storage, or SOC storage. It is the total quantity of carbon stored in organic matter found in soil, such as humus, microbial biomass, and digested plant and animal waste. In addition to being an essential part of the global carbon cycle, SOC storage is also important for soil fertility, ecosystem sustainability, and climate control. Higher SOC levels are frequently associated with increased soil fertility, which supplies vital nutrients for the development of trees. More photosynthesis from larger trees takes in more CO_2 from the atmosphere and stores it as biomass. Trees that thrive in nutrient-rich soils store more CO_2 in their biomass, which includes their roots, branches, trunks, and leaves. This process lowers the atmospheric concentration of CO_2. A higher SOC helps improve the structure of the soil, which increases water absorption and retention. Tree roots benefit from this by having a steadier and encouraging environment. In addition to enhancing general tree health and lowering stress-related CO_2 emissions from root respiration and decay, healthy root systems also increase tree stability and access to water and nutrients.

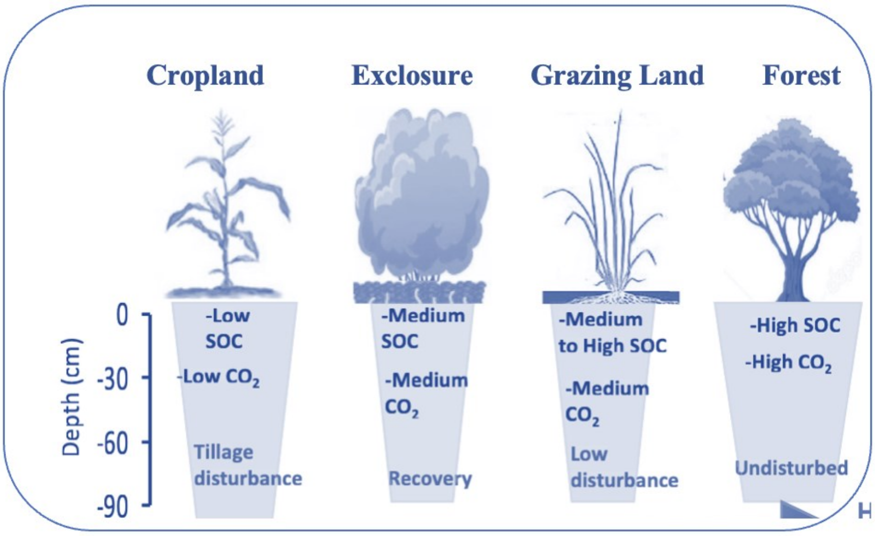

Figure 18. Conceptual diagram of SOC and CO_2 emission rate distribution

Figure 18. summarizing factors and mechanisms driving SOC and CO_2 emission rate distribution under different land use types. As can be seen from the figure, while the SOC amount increases, the emission rate of CO_2 also increases. In addition, long-term carbon storage is superior in soils with high organic carbon content. By continuously adding organic matter to the soil through root exudates and leaf litter, trees growing in these types of soils add to this carbon pool. A strong carbon sink is produced by the interaction of increasing biomass carbon (from tree growth) and soil carbon (from SOC storage), which lowers total CO_2 emissions to the atmosphere (Okolo, et al., 2023).

SOC storage changes over time due to various natural and anthropogenic factors. These factors influence both the input (addition) and output (loss) of organic carbon in the soil, and explained in the Table 12.

Table 12. Factors influencing changes in SOC storage (Sun, Zuoxin Tang, Michael G. Ryan, Yeming You, & Osbert Jianxin Sun, 2019)

Factors Influencing Changes in SOC Storage

Climate	In general, warmer temperatures stimulate more microbial activity, which speeds up the breakdown of organic matter and decreases the amount of SOC stored. Sufficient moisture affects the rates of decomposition as well as plant development and the addition of organic matter to the soil.

Vegetation and Land Use	Different plants contribute varying amounts of organic matter. When compared to annual crops, forests and perennial grasses typically improve SOC storage. Converting forests to agricultural land generally leads in SOC loss due to reduced organic inputs and increased decomposition rates.
Soil Properties	Higher SOC levels are maintained in clay-rich soils because they protect organic matter from degradation more effectively than sandy soils. Organic matter decomposition rates and microbial activity are influenced by the pH and nutrient levels of the soil.
Land Management Practices	Disturbance from tillage can increase oxidation and decomposition of organic matter, leading to SOC loss. However, Properly managed grazing can maintain or enhance SOC levels, while overgrazing can lead to soil degradation and SOC loss.
Disturbances	Fires, storms, pest outbreaks, urbanization, mining and other land-use changes can reduce SOC through direct loss of organic matter and increased decomposition.

Following these factors can be held not only by calculation method which is going to be explained in the next part but also by satellite imagery and sensors. In comparison to conventional field-based techniques, the use of satellite imagery and sensors in remote sensing provides numerous advantages when evaluating plant cover, changes in land use, and other factors impacting Soil Organic Carbon Stocks (SOCS). Researchers may track changes in the environment, land use, and vegetation cover over time by using remote sensing data, which can provide important insights into the dynamics of SOCS. Accurate representation of SOCS variations is made possible by the ability of satellite sensors, such as Sentinel-1, Sentinel-2, and other remote sensing platforms, to record changes in spectral reflectance in various electromagnetic spectrum regions (Lei, et al., 2024). With the use of these technologies, changes in the forest vegetation cover, deforestation, and carbon emissions may be mapped spatially and temporally, leading to a thorough understanding of the variables affecting the dynamics of SOCS. In general, satellite data and sensors are vital resources for researching and tracking the variables influencing soil organic carbon sequestration (SOCS), enabling well-informed choices on land use and carbon sequestration tactics. How remote sensing works for SOCS assessment is shown in Table 13.

Table 13. How remote sensing works for SOCS assessment

How remote sensing works for SOCS assessment?	
Satellite Imagery	
Types of Satellites: Satellites such as Landsat, Sentinel, MODIS, and commercial satellites like WorldView provide high-resolution images of the Earth's surface **(Lei, et al., 2024).**	**Spectral Bands:** These satellites capture data in multiple spectral bands (visible, near-infrared, thermal, etc.), which are useful for identifying different types of vegetation and land cover (Xie, Yu, & Sha, 2008).
Sensors and Indices	
Multispectral and Hyperspectral Sensors: These sensors capture data across multiple wavelengths, allowing for detailed analysis of surface features.	**Vegetation Indices:** Indices such as the Normalized Difference Vegetation Index (NDVI), Enhanced Vegetation Index (EVI), and Soil Adjusted Vegetation Index (SAVI) are calculated from satellite data to assess vegetation health, biomass, and productivity (Silva, et al., 2019).
Land Use and Land Cover (LULC) Classification	
Classification Algorithms: Machine learning algorithms and classification techniques (e.g., supervised and unsupervised classification, random forests, support vector machines) are used to classify land cover types from satellite imagery **(Talukdar, et al., 2020).**	**Change Detection:** Techniques such as change detection analysis help identify changes in land use over time, providing insights into deforestation, urbanization, agricultural expansion, and other land use changes (Liu, Song, Meng, & Liu, 2023).

To sum up, because biological, environmental, and human factors are complex and dynamic, it is challenging to take into consideration every element that influences a tree's CO_2 emissions. It is difficult to distinguish distinct impacts and create an accurate model of the overall carbon dynamics since each factor interacts and influences the others in intricate ways. Comprehensive understanding and effective management require interdisciplinary approaches, advanced technologies, and long-term monitoring to capture the full range of influencing parameters.

7.2. Calculation Methodology of CO₂ Emissions by Trees

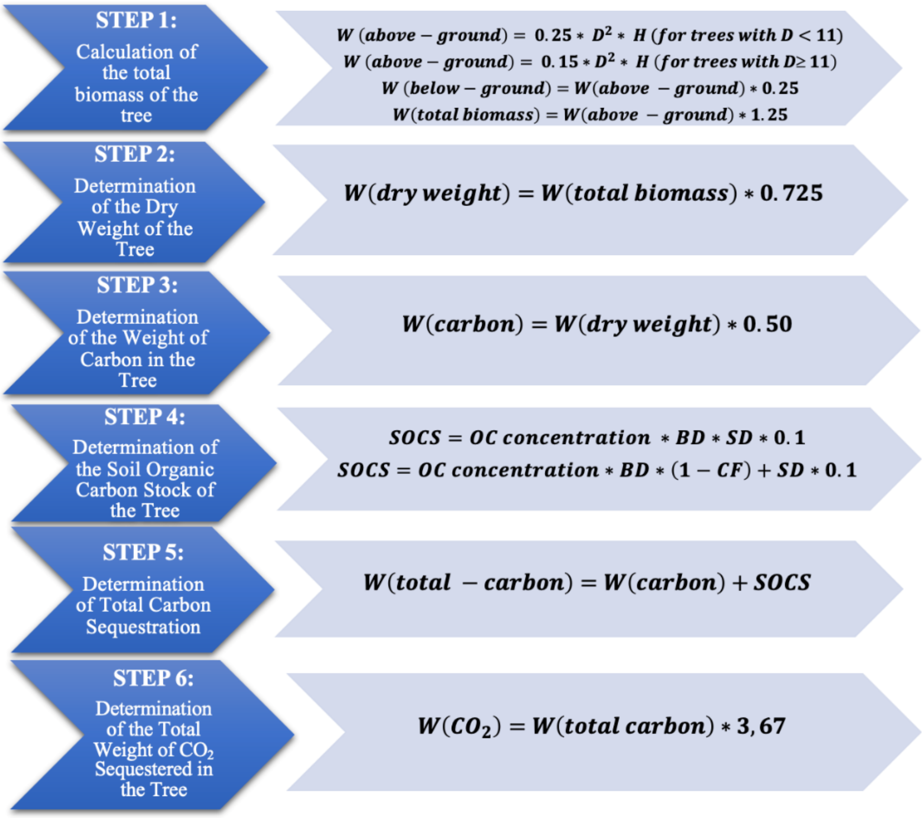

Figure 19. Summary of calculation methodology

Creating a calculation method for CO_2 emissions by trees can be challenging due to various factors and complexities involved in accurately quantifying carbon sequestration as explained in the above part. This part of the thesis aims to create an effective and useful calculation method of CO_2 emissions as shown in Figure 19 by different type of trees which are located in the different type of lands. This calculation method involves different case studies and researches with necessary assumptions.

7.2.1. STEP 1: Calculation of the total biomass of the tree

A tree's overall biomass can be computed by taking into account different components such as stems, branches, leaves, and roots. A tree's biomass is usually calculated by measuring various tree sections and using particular formulas to get an idea of the total biomass. Total biomass is one of the most important metrics for determining a tree's capacity to sequester carbon dioxide and its overall impact on the carbon cycle. Total biomass includes above and below ground biomass, and their calculations are shown in below.

- Calculation of above ground biomass

The total mass of biomass found in live trees (including stems, branches, and leaves), brush, and woody live plants above ground is referred to as above ground biomass. The majority of the carbon is stored in this large pool. Approximately 80% of carbon (C) in all above-ground plants is found in forest biomass (Peichl & M. Altaf Arain , 2007).

Georgia Forestry Commission members who realized that aboveground biomass depends on many different components conducted research to develop reliable weight equations for the trees. The tree data used to develop the equations were collected in a number of individual studies over a period of several years. In some studies, sample trees were selected by random sampling technique to ensure uniform sample number across all diameter classes. Cross sectional disks of wood and bark were removed from along the stem and branches of sample trees for laboratory determination of moisture content, specific gravity and percentage of bark. These determinations provide the necessary data for computing green and dry weight per cubic foot of branch wood and bark.

Data analysis

In this research, regression equations to estimate weight were calculated by using the models:

$$\log Y = a + b * logX + \varepsilon \qquad \text{Equation 8}$$

$$\log Y = a + b * logX_1 + c * logX_2 + \varepsilon \qquad \text{Equation 9}$$

Where Y=predicted component weight; X=D^2, D^2Th, D^2H4 or D^2Mh; Th=total height; D=diameter at breast height (DBH); H4=height to 4 inch diameter outside bark(d.o.b.); Mh=merchantable height; X_1= D^2; X_2=Th, H4 or Mh; ε=experimental error; a,b,c= regression coefficients

When Equation 9 was used with D^2+Mh for sawtimber trees > 11 inches, the residuals indicated good predictability, so Equation 9 was the equation selected.

$$\log Yp = a + b * logX + \varepsilon \qquad \text{Equation 10}$$

$$\log Ys = a + b * \log{(11^2 H)} + c * \log{(D^2/11^2)} + \varepsilon \qquad \text{Equation 11}$$

Where Y_p = predicted component weight for trees < 11.0 inches DBH; Y_s = predicted component weight for trees ≥ 11.0 inches DBH;. X = D^2, D^2Th or D^2H4; H = Th or H4; D = DBH; ε=experimental error; a,b,c= regression coefficients.

Equation 10 for trees < 11.0 inches DBH and Equation 11 for trees ≥ 11.0 DBH. The 11 – inch point was not the optimum point to shift from one equation to the other for all species or tree components but it was the more desirable from a practical standpoint. To adjust for this bias, a correction factor was computed and applied to each model, and the final equations to calculate above ground biomass are: (III, Joseph R. Saucier, & W. Henry McNab, 1988)

$$\boldsymbol{W\ (above - ground) = 0.25 * D^2 * H\ (for\ trees\ with\ D < 11)} \qquad \text{Equation 12}$$

$$\boldsymbol{W\ (above - ground) = 0.15 * D^2 * H\ (for\ trees\ with\ D \geq 11)} \qquad \text{Equation 13}$$

Where W above-ground = Above ground weight (pounds); D = the diameter at breast height (inches); H = Height of the tree (feet)

As standard procedure, DBH is measured from 1.3 m above ground height. This is a simple procedure for a relatively straight tree with one trunk, but with trees of different sizes, growing at varying angles, on slopes or with exposed roots (such as mangroves), DBH measuring techniques are adapted accordingly, this can be seen in the Figure 20 (The Power of Trees: How do trees store carbon and how do we measure it? , 2024).

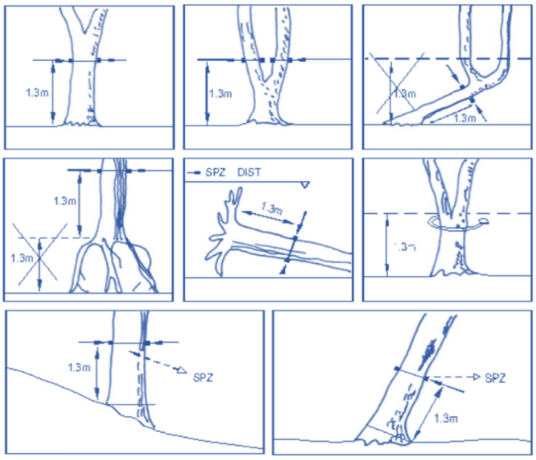

Figure 20. Determination of DBH in special cases (The Power of Trees: How do trees store carbon and how do we measure it?, 2024)

- Calculation of below ground biomass

Belowground biomass (BGB) is a crucial C pool for a variety of vegetation types and land-use systems, with estimates indicating that it makes up 20% of total biomass. However, below ground stocks are poorly estimated and hence the potential of forests to mitigate climate change remains a major source of uncertainty. Thus, a crucial element of many applications is the precise calculation of below ground biomass (Handavu, Stephen Syampungani, Gudeta W. Sileshi, & Paxie W. C. Chirwa, 2021). As mentioned in the above, below ground biomass is around 20% of total biomass, which makes the below ground biomass as 25% of above ground biomass. Thus, the following Equation 14 should be followed during the calculations.

$$\boldsymbol{W\ (below-\ ground)\ = W\ (above-\ ground)\ *\ 0.25} \qquad \text{Equation 14}$$

$W_{\text{below-ground}}$ = Below ground biomass of tree (pounds/tree)

- Calculation of Total Biomass of Tree

Since the total biomass of tree is summation of above ground and below ground biomass, equation to calculate total biomass of tree is shown in the Equation 15 and 16.

$$\boldsymbol{W\ (total\ biomass) = W\ (above-\ ground) +\ W\ (below-\ ground)} \qquad \text{Equation 15}$$

$$\boldsymbol{W\ (total\ biomass)\ =\ W\ (above-\ ground)\ *\ 1.25} \qquad \text{Equation 16}$$

$W_{\text{total biomass}}$ = Total biomass of tree (pounds/tree)

7.2.2. STEP 2: Determination of the Dry Weight of the Tree

Determining the dry weight of trees is an important aspect of forestry and ecological research, particularly for estimating biomass and carbon sequestration. The proportion of dry weight in a tree's overall biomass varies based on a number of variables, such as the species of the tree, the portion of the tree being measured (leaves, branches, stem, roots, etc.), and the growing environment. Due to the considerable water content of live trees, the dry weight of a tree's biomass often makes up a large percentage of its overall biomass (Santos-Martin, Rafael M Navarro Cerrillo, Rachmat Mulia, & Meine Van Noordwijk, 2010). A typical procedure is to weigh a sample of the tree, dry it completely in an oven, and then weigh it once more to find the dry weight. A tree's dry weight is commonly determined by multiplying its weight by its dry matter percentage. The average tree generally includes 72.5% dry matter and 27.5% moisture (Gebremeskel, Tesfay, Birhane, Mekonen Rannestad, & Gebre, 2021). By doing this, the variations brought on by the water content are eliminated to make the biomass measurement more accurate. Thus, the calculation of dry weight of the tree can be determined with the Equation 17.

$$\boldsymbol{W(dry\ weight)\ =\ 0.725\ *\ W(total\ biomass)} \qquad \text{Equation 17}$$

$W_{\text{dry weight}}$ = Dry weight of the tree (pounds/tree)

7.2.3. STEP 3: Determination of the Weight of Carbon in the Tree

Determining the carbon weight in a tree is crucial for understanding its role in carbon sequestration. Calculating the carbon content based on the dry weight of the biomass. A conversion factor of 0.50 is used to convert biomass (dry weight) to carbon equivalents (C), since the carbon content is generally about 50% of the dry weight biomass (Petersson, et al., 2012). This systematic approach helps quantify the amount of carbon stored in trees, aiding in carbon accounting and informing forest management practices. With the general assumption of 50% of dry weight, carbon in the tree is:

$$\boldsymbol{W(carbon) = W(dry\ weight) * 0.50} \qquad \text{Equation 18}$$

W_{carbon} = Weight of carbon in the tree (pound/tree)

The important consideration about the units is since the studies held in USA, the first step calculated by USA units such as inch, feet and pound and conversion factors decided with them. After this step, by using the conversions which are shown in Table 14. all the units will be held as European units which are centimeter, meter and kilogram.

Table 14. Unit Conversions

Unit Conversions	
1 pound	0.45359237 kilograms (kg)
1 inch	2.54 centimeters (cm)
1 feet	0.3048ers (m)

7.2.4. STEP 4: Determination of the Soil Organic Carbon Stock of Tree

Determining the Soil Organic Carbon Stocks (SOCS) is essential for precisely calculating the amount of CO_2 that trees absorb because it offers a thorough understanding of the carbon that is stored in both the soil beneath the trees and the trees themselves. Through photosynthesis, trees take in CO_2 from the atmosphere and store it as carbon in their biomass. But eventually, a large amount of this carbon contributes to soil organic carbon by returning to the soil through leaf litter, root exudates, and decomposing organic matter. In addition to the carbon sequestration measured in the trees, SOCS acts as an indicator of the soil's ability to retain carbon. Calculating SOCS involves several steps and methodologies, in this part of the thesis focuses on direct field measurement and calculation of SOCS by equations.

The location where the plantation is going to be held is one of the most important steps as explained in the key factors that affect the calculation of CO_2 emissions absorbed by trees part. Therefore, identifying the study area and selecting sampling sites are the first step of direct field measurement. After the first step, this is the point at which SOC stock measurement should be started. SOC concentration is a dry combustion measurement of the total carbon content of the soil. To calculate SOC, a measurement of the inorganic carbon concentration is deducted from the total carbon if the soil is calcareous (containing free carbonates). A SOC concentration of 0 to 15 cm is sufficient for monitoring soil health; however, voluntary carbon markets are changing to demand estimations of SOC stock from 0 to 30 cm soil depths (Morgan & P. Ackerson, 2022). To be secure, manual soil sample collection will take place at random places utilizing samplers such as the 4-cm-diameter Eijkel-Kamp core sampler, which will be used to collect soil samples at depths of 0 to 30 cm (Lopez-Bellido, Lopez-Bellido, Fernandez-Garcia, Muñoz-Romero, & Lopez-Bellido, 2016). After the collection, soil samples should be dried, shredded, homogenized and sieved in the laboratory analysis. By employing dry combustion and an elemental analyzer like the EA 3000 Eurovector SpA Milan, Italy, it is possible to ascertain the C content of the wood samples and the organic C content of the soil samples. Therefore, the mass of carbon per unit area in a field needs to be determined in order to calculate the amount of carbon present in each field. This mass of carbon per unit area as called the SOC stock. It is possible to compare soil carbon stocks to atmospheric carbon emissions and carbon mass (as the greenhouse gas of CO_2). Measuring the bulk density and C stock of the tree is necessary to calculate the soil carbon stock. The following Equation 19 created by the measurements of randomly selected trees to find the carbon stock of a tree.

$$CS = C\ concentration * WD * WV \qquad \text{Equation 19}$$

Where CS= tree carbon stock; C= tree carbon (g/kg); WD= wood density (Mg/m^3); WV= wood volume (m^3) (Lopez-Bellido, Lopez-Bellido, Fernandez-Garcia, Muñoz-Romero, & Lopez-Bellido, 2016).

The wood volume of each selected tree is calculated according to the biometric measurements (length and diameter of the trunk and different branching categories). The measurements from the selected trees in each plantation were averaged. Thus, the tree C stock is obtained by Equation 19.

The soil organic carbon (SOC) stock at the sampled depth (0 – 30 cm) is calculated using the Equation 20:

$$\boldsymbol{SOCS = OC\ concentration * BD * SD * 0.1} \qquad \text{Equation 20}$$

Where SOCS= soil organic carbon stock (Mg C/ha); OC= organic carbon (mg C/g soil); BD= bulk density (g/cm^3); SD= soil depth (cm) (Lopez-Bellido, Lopez-Bellido, Fernandez-Garcia, Muñoz-Romero, & Lopez-Bellido, 2016).

If the sampling soils with coarse fragment volumes greater than 2%, it also needs an estimate of coarse fragment volume in the soil. This idea is explained by the Soil Science Society of America in the webinar series produced in partnership with The Soil Health Institute and sponsored by The Walton Family Foundation. Coarse fragments are the mineral components of soil that are larger than sand particles, or >2mm diameter. In short, SOC stock at a given depth is a function of carbon concentration (OC), bulk density, and coarse fragment (CF) measurement across a soil thickness or depth increment, as follows (Morgan & P. Ackerson, 2022):

$$\boldsymbol{SOCS = OC * BD * (1 - CF) + SD * 0.1} \qquad \text{Equation 21}$$

Where SOCS= soil organic carbon stock (Mg C/ha); OC= organic carbon (mg C/g soil); BD= bulk density (g/cm^3); CF= coarse fragment; SD= soil depth (cm).

In the Equations 20 and 21, 0.1 is a conversion factor to get the units from those they are reported in by laboratories mg C/cm^2 to Mg C/ha.

Coarse Fragments of the soil can be decided with analysis. However, it is one of the hardest things to quantify in soil landscape. Therefore, instead analyzing the coarse fragments for each land, it is more convenient to use the coarse fragments map published by European Soil Data Center (ESDAC). The coarse fragments map (Figure 21.) shows how the main mountain ranges in Europe's spatial distribution correspond with the coarse fragments' distribution (Topsoil physical properties for Europe, 2016).

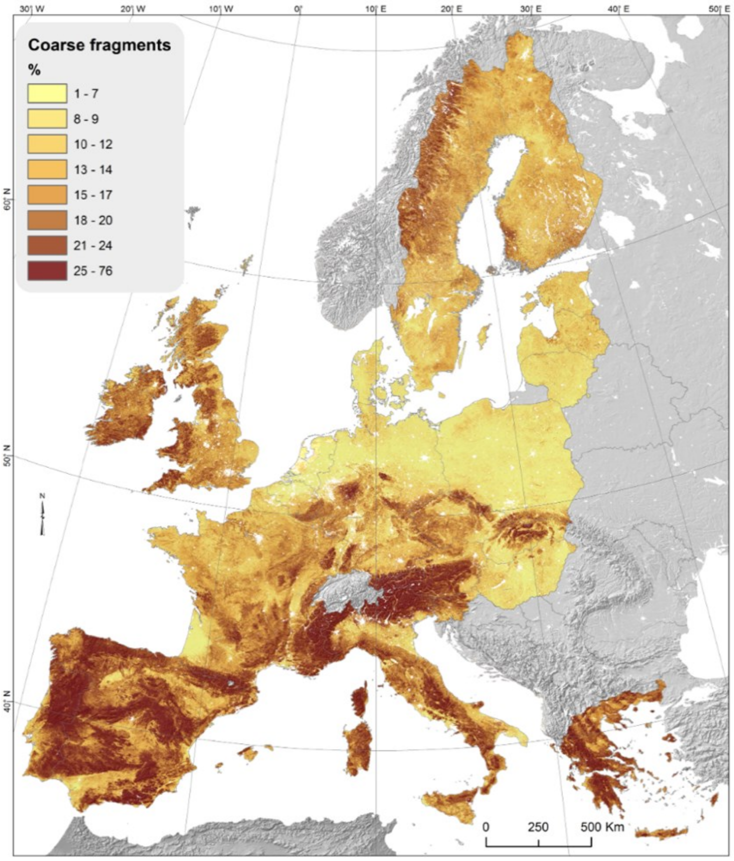

Figure 21. Topsoil coarse fragments (%) content modelled by multivariate additive regression splines (Topsoil physical properties for Europe, 2016)

The Alps, Pyrenees, Iberian mesas, Apennines, and Balkans have the highest concentration of coarse fragments. In areas of shallow water deposition along the southern border of the North and Baltic Seas, there is very little coarse fragmentation.

Bulk density (BD) is calculated as in following Equation 22.

$$BD = \frac{bulk\ soil\ mass\ (g) - coarse\ fragment\ mass\ (g)}{bulk\ soil\ volume (cm^3) - coarse\ fragment\ volume\ (cm^3)} \qquad \text{Equation 22}$$

Bulk density is a value that ranges from roughly 0.85 g/cm^3 in a freshly tilled soil to 1.60 g/cm^3 in a compacted, root-limited soil. In most row-crop landscapes that are not freshly tilled, median bulk densities of the top 30 cm will range from 1.0 to 1.35 g/cm^3. Bulk density can be changed by management. To sample bulk density, it needs to be collected a known mass of soil and calculate the oven-dry soil mass. While there are multiple ways to collect a known soil mass, the most common involve inserting a large soil core into the ground and extracting the soil from the core. Because these soil cores need to be large, also method to drive the soil into the ground such as a slide hammer or hydraulic coring machine is needed. The main challenge to bulk density sampling is to avoid compacting the soil while collecting the sample so that artificially high bulk density readings will be avoided (Morgan & P. Ackerson, 2022).

Applications for bulk density can be found in almost all soil research and analysis. The interest in bulk density, especially of surface layers, has increased due to current efforts in soil quality, soil sufficiency, and sequestration of carbon. Since collecting soil sample and calculating it may take time and source of money, the bulk density data map shown in Figure 22 which is published by European Soil Data Center (ESDAC) can be used as another solution to reach bulk density date to related land (Topsoil physical properties for Europe, 2016).

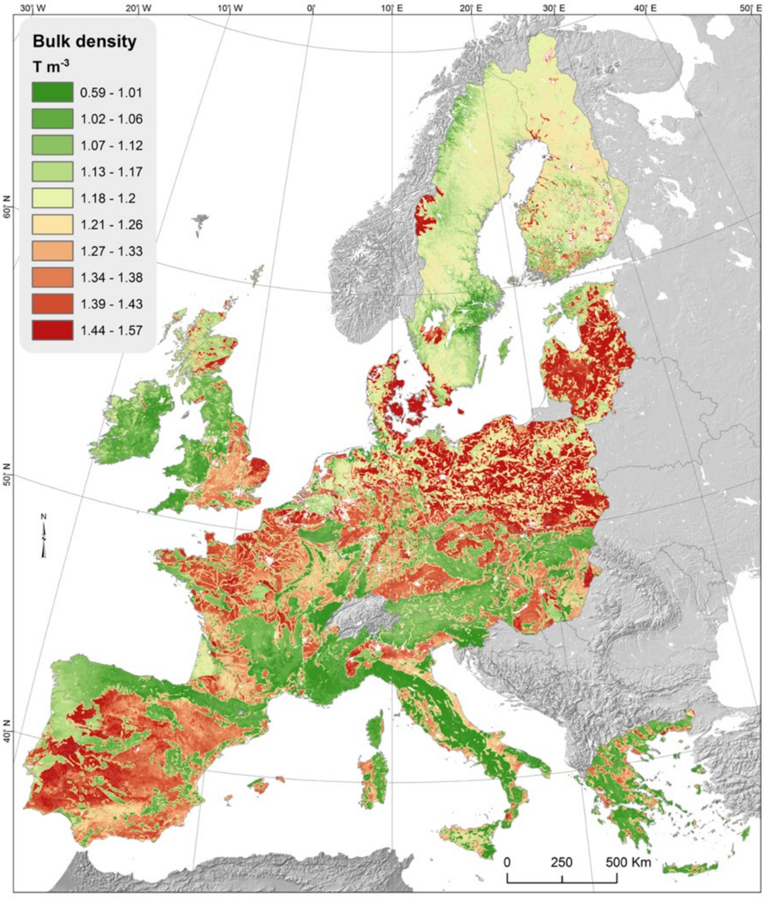

Figure 22. Bulk density derived from soil texture datasets (Topsoil physical properties for Europe, 2016)

The research results emphasize the importance of soil organic carbon stock maps for environmental management and research by offering useful information on them. These maps provide comprehensive information on the organic carbon content of soil at various depths and geographical locations, making it possible to track carbon stocks, evaluate changes over time, and comprehend the effects of land management techniques and climate change on soil health. The information displayed on the maps is essential for several tasks, such as monitoring greenhouse gas emissions, assessing soil quality, and assessing carbon sequestration. High-resolution maps of the soil organic carbon stock at the regional and global levels are helpful for making educated decisions about climate change mitigation and sustainable land use, as well as improving our understanding of soil carbon dynamics. Simulated SOCS in the top-soil layer (0–30 cm) of European agricultural soils is shown in Figure 23.

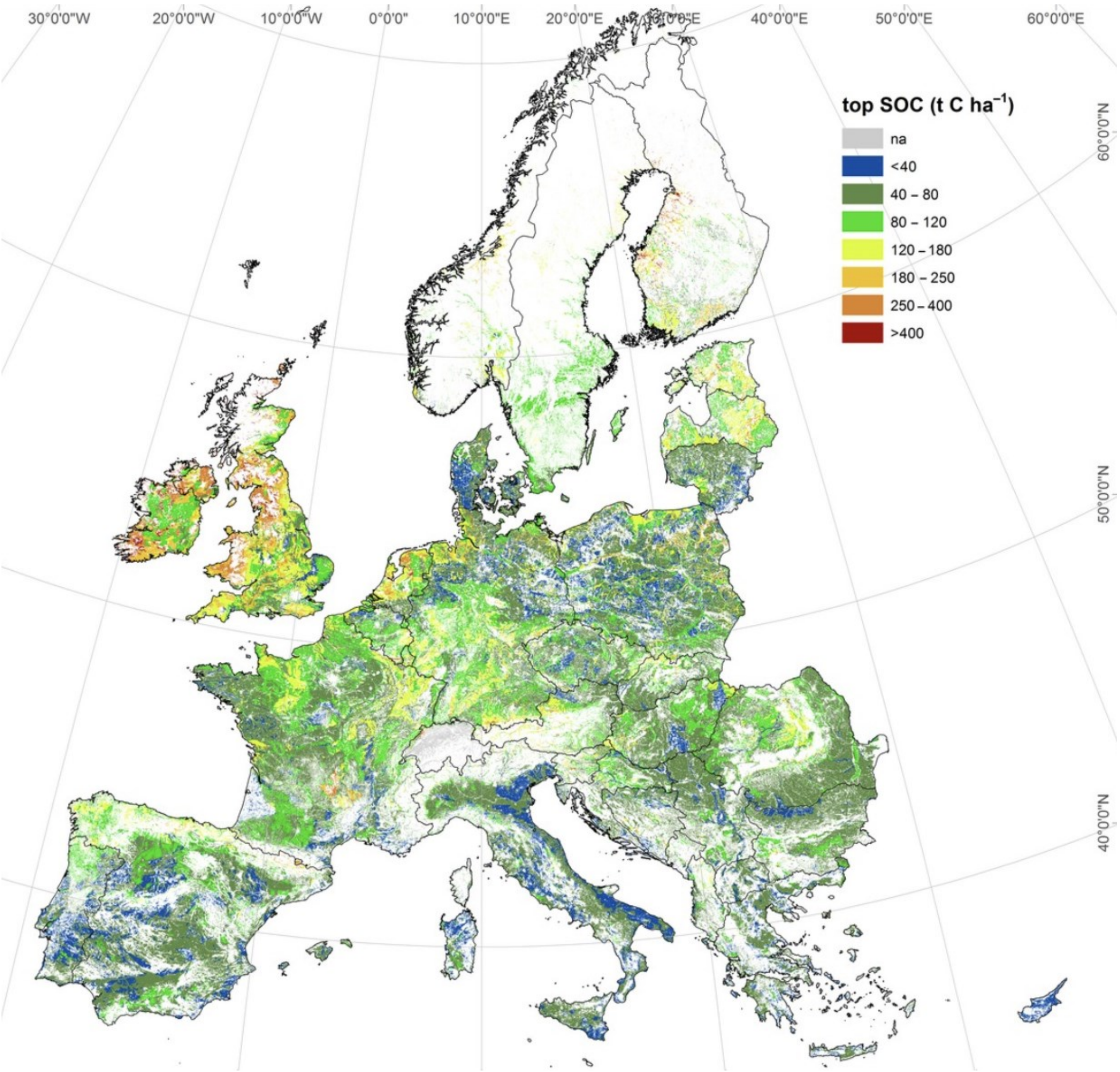

Figure 23. Simulated SOCS in the top-soil layer (0 - 30 cm) of European agricultural soils (Topsoil physical properties for Europe, 2016)

Since the unit of SOCS is Mg C/ha to find the SOCS per tree and for the sake of the summation to find total Carbon sequestration following unit conversion must be held.

$$\frac{Mg\ C}{ha} * \frac{1\ ha}{number\ of\ trees\ per\ hectare} * \frac{1000\ kg}{1 Mg} = \frac{kg\ C}{tree}$$

7.2.5. STEP 5: Determination of Total Carbon Sequestration

Total carbon sequestration is the summation of carbon sequestration by the above and below ground parts and carbon sequestration by soil. Therefore, the total carbon sequestration of the tree is calculated as Equation 23.

$$\boldsymbol{W(total - carbon) = W(carbon) + SOCS}$$ Equation 23

W total-carbon = Total carbon sequestration (kg/tree)

7.2.6. STEP 6: Determination of the Total Weight of CO_2 Sequestered in the Tree

Until this step all the calculations have the unit for C sequestration. C to CO_2 involves using the molecular weights of carbon and carbon dioxide. This conversion is essential in calculating the amount of CO_2 that can be sequestered or released based on the carbon content.

- Molecular weights:

  Carbon (C)= 12 g/mol

  Carbon dioxide (CO_2) = 44 g/mol

- Conversion Factor

  The ratio of the molecular weight of CO_2 to the molecular weight of C is:

  $$\frac{44\ g/mol}{12\ g/mol} = 3.67$$

  This means that for every unit of carbon, there are 3.67 units of CO_2.

- Conversion Formula

  $$CO_2(weight) = C(weight) * 3.67$$

  To sum up, last step of calculation methodology is shown in Equation 24.

$$\boldsymbol{W(carbon\ dioxide) = W(total - carbon) * 3.67}$$ Equation 24

7.3. Efficiency of the Plantation of Trees

A number of variables, including species selection, management techniques, site circumstances, and long-term sustainability, affect how effective tree plantings are, especially when it comes to carbon sequestration and ecological advantages. In this part of the thesis, example calculation of above-mentioned methodology will be used to see the efficiency of planting trees. As a plantation site Veneto, Italy is chosen. For the calculation of the efficiency, 1 hectare of land is thought to be planted in Padova. This land should be preferred with no plantation to see exact efficiency of trees; thus, plantation will be done in arid area.

After the decision of the city where plantation will be held, type of trees and number of trees are chosen. Oak and Pine are two of the most abundant tree types in Veneto region, and they have a great potential to absorb CO_2 and fast-growing pace. The ideal number of trees to plant per hectare depends on a number of variables, including the species, planting goals, and site circumstances. A typical oak and pine tree spacing may be 3 meters by 3 meters, resulting in about 1,111 trees per hectare. (Spacing of plantings, n.d.)

$Spacing: 3m\ x\ 3m$

$Trees\ per\ hectare$: 10,000 square meters / (3m $*$ 3m) $\approx$ 1,111 trees

Lower densities are frequently employed for ecological restoration or conservation in order to replicate natural forest conditions and increase biodiversity. Experts estimate that if tree-planting initiatives are properly designed and include sufficient aftercare, a survival percentage of 90–95% can be predicted. This suggests a 5–10% mortality rate for well-planned projects (Gatten, 2022). A 10% potential tree mortality rate will be used to plant 1,111 trees per hectare, and calculations will be made for 1000 trees which is the number of trees calculated with survival percentage, including 500 white oak tree and 500 eastern white pine trees. Two different types of trees are chosen to see the ability of the calculation method to be applicable for different tree types. The trees are chosen to be planted will be 20-year-old young oak and pine trees. They reach full maturity at the age of 35 – 40, and after this maturity age, the growth rate of the trees is very low. That's why the project year for trees planted has been determined as 20 years until they reach full maturity. As a result of the calculations made using the methodology, the amount of CO_2 that 1 tree will absorb every year will be calculated by taking the average of the total CO_2 emissions of both types of trees.

7.3.1. Oak Tree

The white oak is regarded as the king of oaks, despite the fact that the oak tree family contains several other species. Its wood's strength and durability are the reason for this. White oak tree (known as Quercus Alba) is an excellent large, durable shade tree which reaches 60 to 100 feet (18 – 30 m) in height with a large, rounded canopy when it is open grown (Kilgore, 2024). The average height of a 20-year-old oak tree can vary depending on the species and environmental conditions. Typically, an oak tree can grow around 20 to 30 feet (6 – 9 m) tall in its first 20 years of growth. Growth rates and heights can differ widely even within species due to environmental factors like sunlight, rainfall etc., so these are the approximate ranges found in the related sources. The growth rate was kept constant during the calculation due to the difficulty of estimating height over the years due to the fact that growth may vary in each year depending on the variables.

Figure 24. Oak tree growth chart for height based on years

It was decided that the height of the tree on the day it was planted would be 25 feet (7.62 m), and it is assumed that in average the height of the trees in their 40 ages would be 80 feet (24.4 m). Therefore, growth rate is decided as 2.89 feet (0.88 m) each year and shown in Figure 24.

Other than height of the White Oak Tree, its diameter at breast height (d.b.h.) is another important parameter for the calculation of total biomass. To measure the d.b.h. the methodology explained in the previous part should be applied. In forests it is tall and straight with few or no lower branches and, the trunk in 20 years old tree can be between 6 to 12 inches (15 – 30 cm) and for the mature tree in 40 – 60 years old tree could be around 12 to 24 inches (30 – 60 cm) in d.b.h.

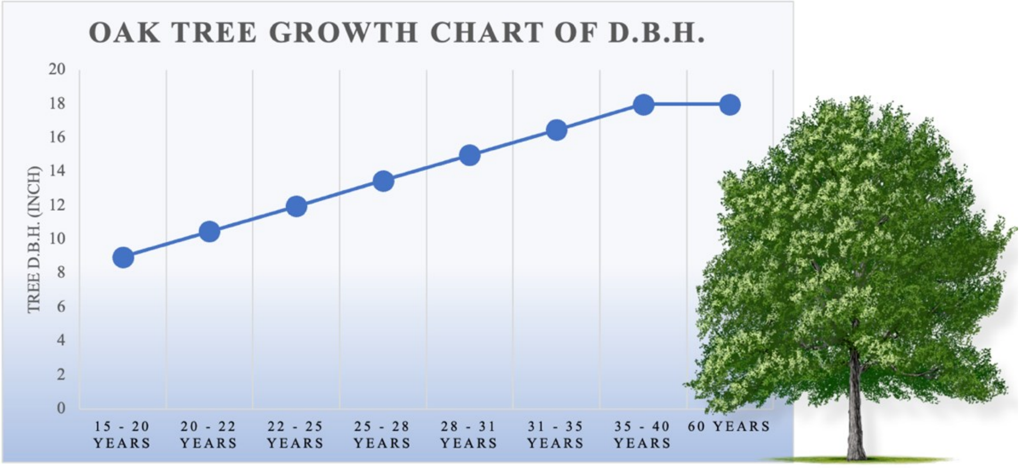

Figure 25. Oak tree growth chart for D.B.H. based on years

It was decided that the d.b.h. of the tree on the day it was planted would be 9 inch (22.86 cm), and it is assumed that in average the d.b.h. of the trees in their 40 ages would be 18 inch (45.72 cm). Therefore, growth rate is decided as 0.473 inch (1.2 cm) each year and shown in Figure 25 (Daniel P. Bebber , n.d.).

It is important to keep in mind that this calculation methodology gives the total CO_2 absorption until that year. Therefore, to find the amount of CO_2 absorption between the age of 20 to 40 years old, the total emission amount in the first 20 years, which is not included in the calculations, must be subtracted from the total emission amount in the 40th year.

- For the calculations of first 20 years:

STEP 1: Calculation of the Total Biomass of the Tree

D (d.b.h.) = 9 inch

H (height of the tree) = 25 feet

$$\boldsymbol{W\ (above - ground) = 0.25 * D^2 * H\ (for\ trees\ with\ D < 11)}$$

W (above – ground) = 0.25 * 9^2 * 25= 506.25 pounds

$$\boldsymbol{W\ (below - ground) = W\ (above - ground) * 0.25}$$

W (below – ground) = 506.25 * 0.25= 126. 56 pounds

$$\boldsymbol{W\ (total\ biomass) = W\ (above - ground) + W\ (below - ground)}$$

W (total biomass) = 506.25 + 126.56 = *632.81 pounds*

STEP 2: Determination of the Dry Weight of the Tree

$$\boldsymbol{W(dry\ weight) = 0.725 * W(total\ biomass)}$$

W (dry weight) = 0.725 * 632.81 = 458.79 pounds

STEP 3: Determination of the Weight of Carbon in the Tree

$$\boldsymbol{W(carbon) = W(dry\ weight) * 0.50}$$

W (carbon) = 458.79 * 0.50 = 229.39 pounds

229.39 pounds = 104 kilogram

STEP 4: Determination of the Soil Organic Carbon Stock of Tree

$$\boldsymbol{SOCS = OC * BD * (1 - CF) + SD * 0.1}$$

To calculate the soil organic carbon stock, BD and CF are decided by using maps. Since the plantation are in Padova, in the map Padova location is chosen.

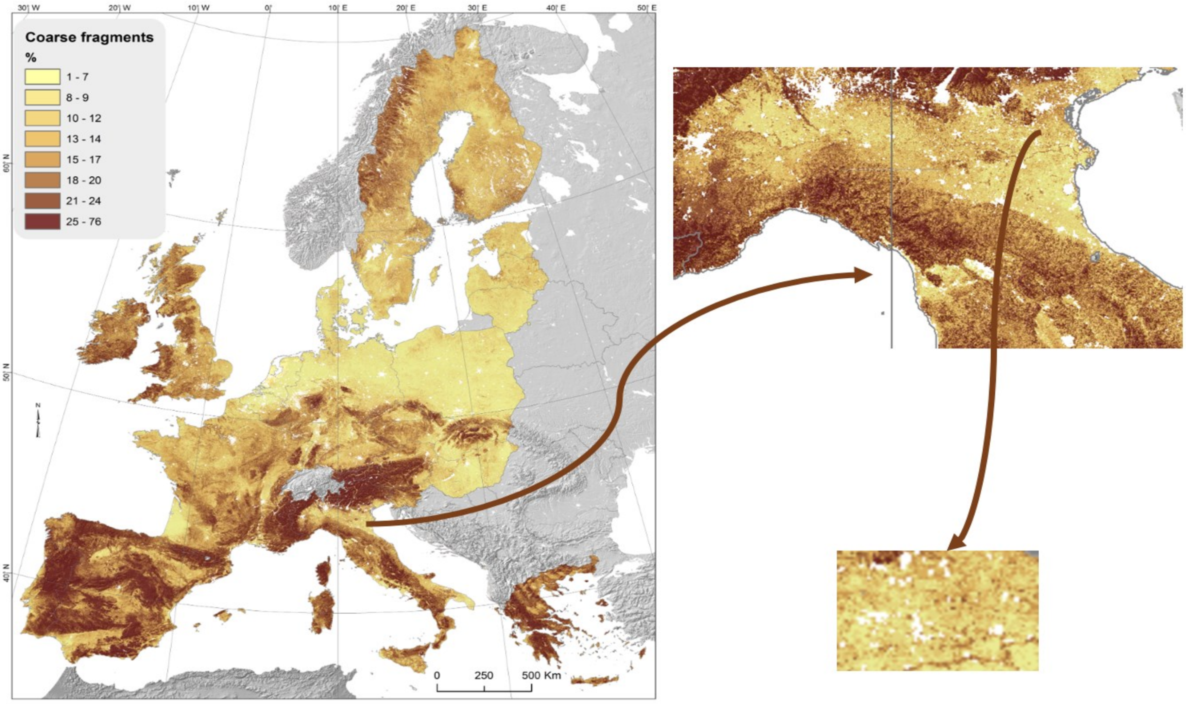

Figure 26. Coarse fragments of Padova

From the coarse fragments (%) map, location of the Padova's coarse fragment is like shown in Figure 26. Depending on the coloration, coarse fragments of Padova looks like between 1% to 12%. During the calculation, average which is 6.5% will be used.

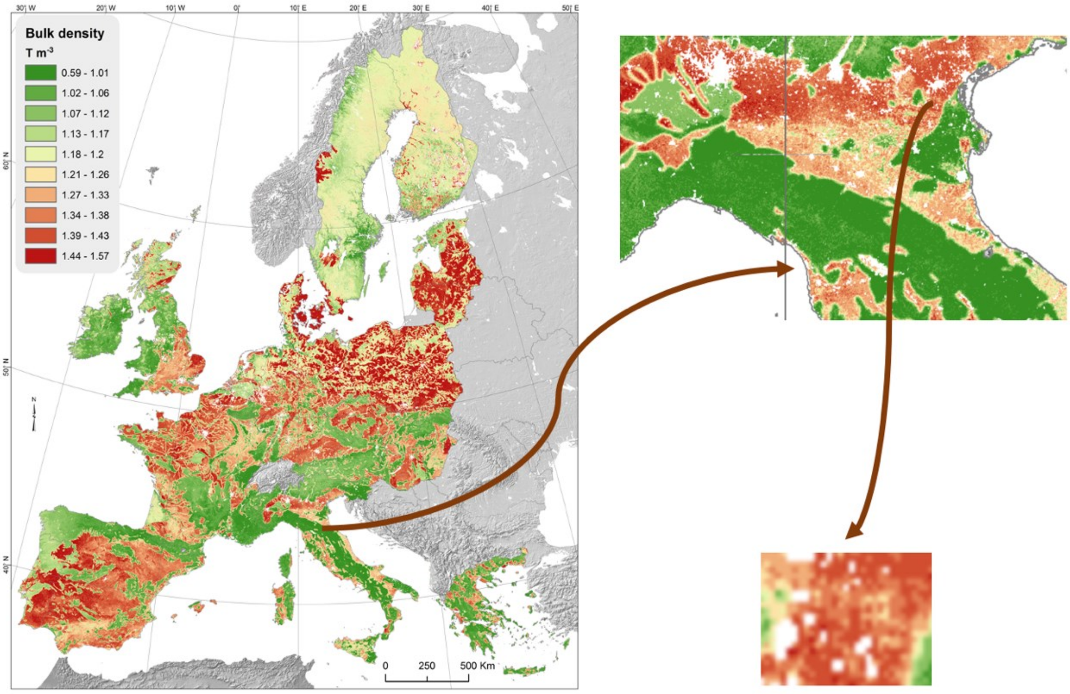

Figure 27. Bulk density (T/m^3) of Padova

From the bulk density (T/m^3) map, location of the Padova's bulk density is like shown in Figure 27. Depending on the coloration, bulk density of Padova looks like between 1.27 T/m^3 to 1.43 T/m^3. During the calculation, average which is 1.35 T/m^3 will be used.

However, since calculation and measurements of carbon concentration (OC) in soil want source, energy, money and time, SOCS map also can be used to see directly SOCS of Padova easily, like shown in Figure 28.

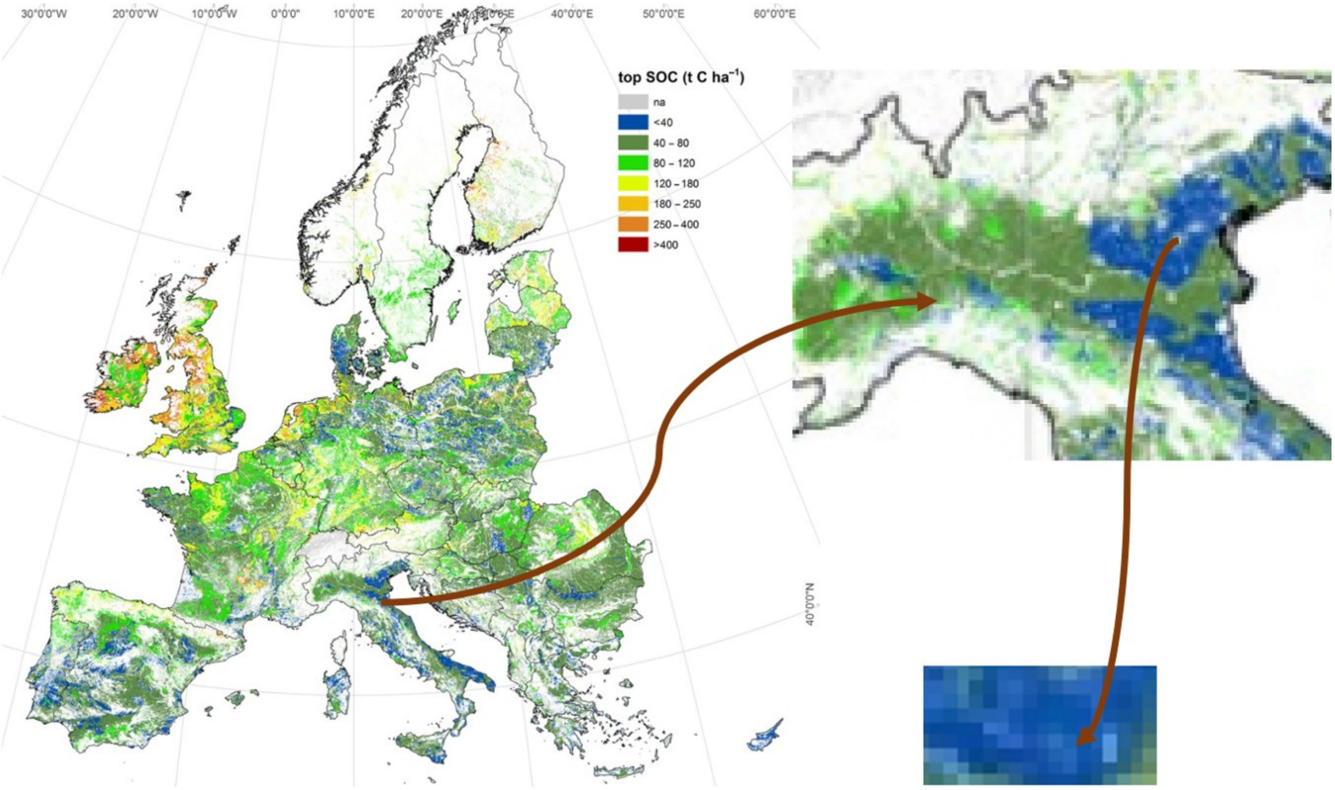

Figure 28. Simulated SOCS in the top-soil layer (0-30 cm) of Padova

Depending on the coloration, SOCS of Padova looks like <40 t C/ha. During the calculation, 20 t C/ha will be used.

$$SOCS = \frac{20\ t\ C}{ha} * \frac{1\ ha}{1000\ trees} * \frac{1000\ kg}{1\ t} = 20\ \frac{kg\ C}{tree}$$

STEP 5: Determination of Total Carbon Sequestration

$\boldsymbol{W(total - carbon) = W(carbon) + SOCS}$

W (total-carbon) = 104 kg C/tree + 20 kg C/tree = 124 kg C/tree

STEP 6: Determination of the Total Weight of Carbon dioxide Sequestered in the Tree

$\boldsymbol{W(carbon\ dioxide) = W(total - carbon) * 3.67}$

W (carbon dioxide) = 124 kg C/tree * 3.67 = 455 kg CO_2/tree (in total first 20 years)

- For the calculations for 40 years:

STEP 1: Calculation of the Total Biomass of the Tree

D (d.b.h.) = 18 inch

H (height of the tree) = 80 feet

$$\boldsymbol{W\ (above - ground) = 0.15 * D^2 * H\ (for\ trees\ with\ D \geq 11)}$$

W (above – ground) = 0.15 * 18^2 * 80 = 3888 pounds

$$\boldsymbol{W\ (below - ground) = W\ (above - ground) * 0.25}$$

W (below – ground) = 3888 * 0.25= 972 pounds

$$\boldsymbol{W\ (total\ biomass) = W\ (above - ground) + W\ (below - ground)}$$

W (total biomass) = 3888 + 972 = *4860 pounds*

STEP 2: Determination of the Dry Weight of the Tree

$$\boldsymbol{W(dry\ weight) = 0.725 * W(total\ biomass)}$$

W (dry weight) = 0.725 * 4860 = 3523.5 pounds

STEP 3: Determination of the Weight of Carbon in the Tree

$$\boldsymbol{W(carbon) = W(dry\ weight) * 0.50}$$

W (carbon) = 3523.5 * 0.50 = 1761.75 pounds

1761.75 pounds = 799 kilogram

STEP 4: Determination of the Soil Organic Carbon Stock of Tree

From the previous part,

SOCS = 20 kg C/tree

STEP 5: Determination of Total Carbon Sequestration

$$\boldsymbol{W(total - carbon) = W(carbon) + SOCS}$$

W (total-carbon) = 799 kg C/tree + 20 kg C/tree = 819 kg C/tree

STEP 6: Determination of the Total Weight of Carbon dioxide Sequestered in the Tree

$$\boldsymbol{W(carbon\ dioxide) = W(total - carbon) * 3.67}$$

W (carbon dioxide) = 819 kg C/tree * 3.67 = 3005.73 kg CO_2/tree (in total for 40 years)

Between the years 20 to 40, the total CO_2 absorption by Oak trees is:

3005.73 – 455 = *2550.73 kg CO_2/tree*

127.53g CO_2/tree/year

7.3.2. Pine trees:

The Eastern White Pine or Pinus strobus is a coniferous evergreen tree. Within 20 years, these trees grow to 25 feet (7.62 m). Mature trees vary in height based on their growing conditions and other factors. On average, white pines may grow 50 to 80 feet (15.24 – 25 m) tall. (Pinus strobus, n.d.) The growth rate was kept constant during the calculation due to the difficulty of estimating height over the years due to the fact that growth may vary in each year depending on the variables.

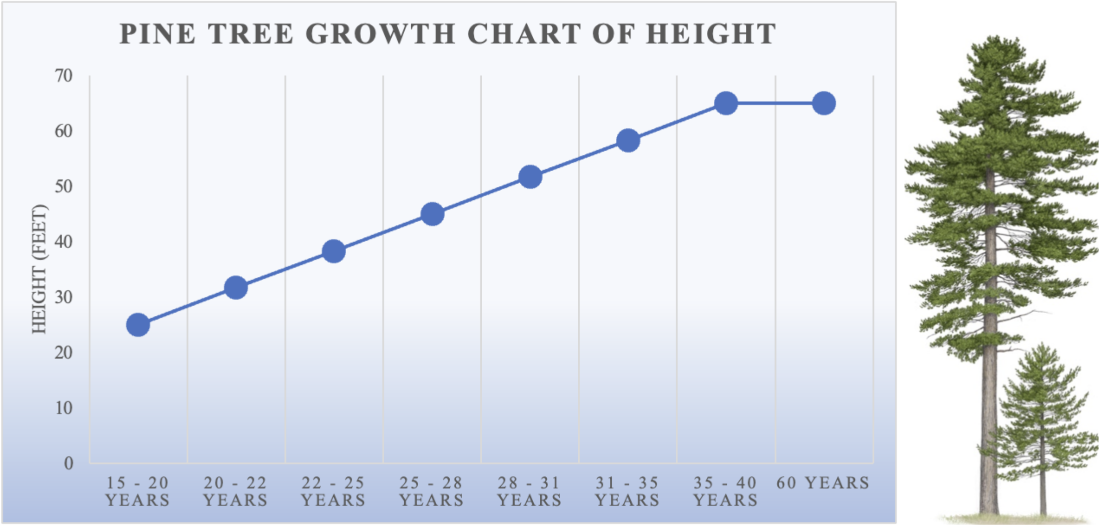

Figure 29. Pine tree growth chart for height based on years

It was decided that the height of the tree on the day it was planted would be 25 feet (7.62 m), and it is assumed that in average the height of the trees in their 40 ages would be 65 feet (19.8 m). Therefore, growth rate is decided as 2.1 feet (0.64 m) each year and shown in Figure 29.

Other than height of the Pinus strobus, its diameter at breast height (d.b.h.) is another important parameter for the calculation of total biomass. To measure the d.b.h. the methodology explained in the previous part should be applied. 20 years old trees' d.b.h. might be around 8 to 12 inches (20 to 30 cm), and when they grow up until 40 years their d.b.h. can reach around 18 to 24 inches (45 to 60 cm) (Bebber, 2002).

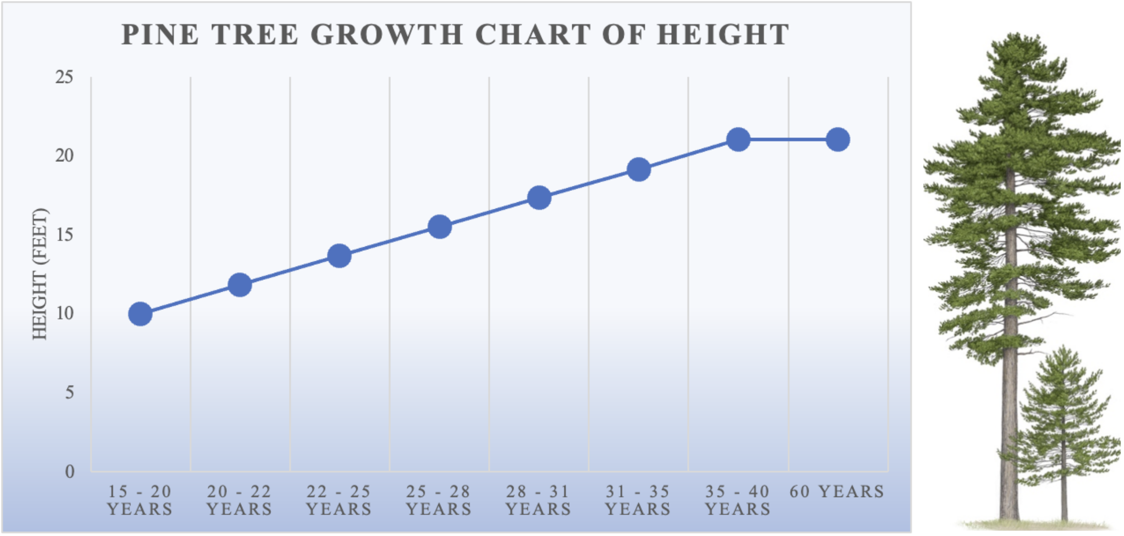

Figure 30. Pine tree growth chart for D.B.H. based on years

It was decided that the d.b.h. of the tree on the day it was planted would be 10 inch (25.4 cm), and it is assumed that in average the d.b.h. of the trees in their 40 ages would be 18 inch (53.37 cm). Therefore, growth rate is decided as 0.578 inch (1.47 cm) each year, and shown in Figure 30.

The calculation is how it has done for the oak tree which is the first 20 years will be subtracted from 40th year calculation.

- For the calculations of first 20 years:

STEP 1: Calculation of the Total Biomass of the Tree

D (d.b.h.) = 10 inch

H (height of the tree) = 25 feet

$$\boldsymbol{W\ (above - ground) = 0.25 * D^2 * H\ (for\ trees\ with\ D < 11)}$$

W (above – ground) = 0.25 * 10^2 * 25= 625 pounds

$$\boldsymbol{W\ (below - ground) = W\ (above - ground) * 0.25}$$

W (below – ground) = 625 * 0.25= 156.25 pounds

$$\boldsymbol{W\ (total\ biomass) = W\ (above - ground) + W\ (below - ground)}$$

W (total biomass) = 625 + 156.25 = *781.25 pounds*

STEP 2: Determination of the Dry Weight of the Tree

$$\boldsymbol{W(dry\ weight)\ =\ 0.725\ *\ W(total\ biomass)}$$

W (dry weight) = 0.725 * 781.25 = 566.4 pounds

STEP 3: Determination of the Weight of Carbon in the Tree

$$\boldsymbol{W(carbon) = W(dry\ weight) * 0.50}$$

W (carbon) = 566.4 * 0.50 = 283.2 pounds

283.2 pounds = 128.45 kilogram

STEP 4: Determination of the Soil Organic Carbon Stock of Tree

From the previous part,

SOCS = 20 kg C/tree

STEP 5: Determination of Total Carbon Sequestration

$$\boldsymbol{W(total - carbon) = W(carbon) + SOCS}$$

W (total-carbon) = 128.45 kg C/tree + 20 kg C/tree = 148.45 kg C/tree

STEP 6: Determination of the Total Weight of Carbon dioxide Sequestered in the Tree

$$\boldsymbol{W(carbon\ dioxide) = W(total - carbon) * 3.67}$$

W (carbon dioxide) = 148.45 kg C/tree * 3.67 = 544.81 kg CO_2/tree (in total first 20 years)

- For the calculations for 40 years:

STEP 1: Calculation of the Total Biomass of the Tree

D (d.b.h.) = 21 inch

H (height of the tree) = 65 feet

$$\boldsymbol{W\ (above - ground) =\ 0.15 * D^2 *\ H\ (for\ trees\ with\ D \geq 11)}$$

W (above – ground) = 0.15 * 21^2 * 65 = 4299.75 pounds

$$\boldsymbol{W\ (below - ground)\ = W\ (above - ground)\ *\ 0.25}$$

W (below – ground) = 4299.75 * 0.25= 1074.93 pounds

$$\boldsymbol{W\ (total\ biomass) = W\ (above - ground) +\ W\ (below - ground)}$$

W (total biomass) = 4299.75 + 1074.93 = *5374.68 pounds*

STEP 2: Determination of the Dry Weight of the Tree

$$\boldsymbol{W(dry\ weight)\ =\ 0.725\ *\ W(total\ biomass)}$$

W (dry weight) = 0.725 * 4860 = 3896.64 pounds

STEP 3: Determination of the Weight of Carbon in the Tree

$$W(\boldsymbol{carbon}) = W(\boldsymbol{dry\ weight}) * \mathbf{0.50}$$

W (carbon) = 3896.64 * 0.50 = 1948.32 pounds

1948.32 pounds = 883.74 kilogram

STEP 4: Determination of the Soil Organic Carbon Stock of Tree

From the previous part,

SOCS = 20 kg C/tree

STEP 5: Determination of Total Carbon Sequestration

$$W(\boldsymbol{total - carbon}) = W(\boldsymbol{carbon}) + \boldsymbol{SOCS}$$

W (total-carbon) = 883.74 kg C/tree + 20 kg C/tree = 903.74 kg C/tree

STEP 6: Determination of the Total Weight of Carbon dioxide Sequestered in the Tree

$$W(\boldsymbol{carbon\ dioxide}) = W(\boldsymbol{total - carbon}) * \mathbf{3.67}$$

W (carbon dioxide) = 903.74 kg C/tree * 3.67 = 3316.72 kg CO_2/tree (in total for 40 years)
Between the years 20 to 40, the total CO_2 absorption by Oak trees is:

3316.72 – 148.45 = *3168.27 kg CO_2/tree*
158.41 kg CO_2/tree/year

Table 15. Summary of calculations

SUMMARY		
	White Oak Tree	**Eastern White Pine Trees**
CO_2 Sequestration (kg CO_2/tree/year)	127.53	158.41
CO_2 Sequestration (kg CO_2/year)	63,765	79,205
Total CO_2 Sequestration in 1 year (kg CO_2/year):	***142,970***	
CO_2 Sequestration (kg CO_2 in 20 years)	1,275,300	1,584,100
Total CO_2 Sequestration in 20 years (kg CO_2):	***2,859,400***	

As can be seen from Table 15 after the calculations it is found that when 500 oak and 500 pine trees are planted in 1 hectare (with survival rate), while individual oak tree absorbs 127.53 kg CO_2/year, individual pine tree absorbs 158.41 kg CO_2/year in average. Thus, in total for a year 500 oak and 500 pine trees absorbs 142,970 kg CO_2/year, and after 20 years total CO_2 absorption in 1 hectare is 2,859,400 kg CO_2/year.

7.4. Economic Analysis

Due to technical, political, and socioeconomic issues like the challenges of developing measurement techniques, the transient nature of carbon in forests, the high opportunity costs associated with land, and the costs associated with transactions, the use of carbon sequestration projects to mitigate climate change are limited to a small portion of their potential biological capacity. Furthermore, it has become difficult to compare estimates from various projects and research due to actual costs varying widely by woodland type, site conditions and operations that may be undertaken. For the purpose of creating suitable laws and incentives to carry out these activities widely enough to result in a noticeable reduction in greenhouse gasses, the supply costs of carbon sequestration activities must be understood and examined within their socioeconomic environment. Goal of this part of the thesis is to provide understanding of the variables influencing supply costs and possible market-based mechanism implementation by analyzing the carbon sequestration costs of agroforestry. The fundamental procedures for conducting a financial assessment of an investment in plantation projects are provided.

To guarantee that all relevant expenses are taken into account in the assessment, classifying costs helps in the systematic identification and formalization of plantation costs. The financial expenses associated with afforestation projects are divided into three categories. The investor's situation determines which classification type is best. Firstly, if an investor does not already own the property where trees are to be planted, traditional factors of production might be appropriate. In most cases, if property is already owned and most activities will be carried out by contractors or outside management businesses, physical location of expenses is appropriate. Finally, when operations are expected to be completed by hand, cost variability might be most appropriate (Hardaker, Financial evaluation of afforestation projects - basic steps, 2021).

The contractor's fees will account for the majority of the cost of an ARPs. Finding typical contractor fees for forestry activities might be challenging. Financial planning cannot easily access these charges, unlike budgeting data for agricultural businesses. Table 16 lists some reasonable estimates of what contractors should charge for standard forestry operations. Site maps, species selections, an operating plan, and work schedules are all included in a management plan. Usually, a forestry specialists help with the writing of this. Labor and capital costs are variable. While ground preparation (drainage), ground preparation (mounding), fencing, spot spraying, trees for planting, hand planting, replacing dead trees, weeding with herbicide and roading are varies depending on scale; mensuration and marking (thinning), mensuration (clear fell), harvesting and extraction to roadside and supervising harvesting varies depending on production. Woodland management plan and grant application, land purchase and management costs and insurance fees are fixed costs.

Table 16. Typical forestry cost (Hardaker, Financial evaluation of afforestation projects - basic steps, 2021)

Category	***Typical cost (£)***	***Timing***
Woodland management plan and grant application	3,000 to 6,000	Prior to planting
Land purchase	8,500 (poor) to 19,500 (prime) per hectare	Prior to planting
Ground preparation (drainage)	90 – 110 per hectare	Year 1
Ground preparation (mounding)	300 – 400 per hectare	Year 1
Fencing	4 – 11 per meter	Year 1
Spot spraying	80 – 100 per 1000 trees	Year 1
Trees for planting	200 – 400 per 1000 trees	Year 1
Hand planting	350 – 600 per 1000 trees	Year 1
Replacing dead trees	200 – 350 per hectare	Year 2-3
Weeding with herbicide	75 – 130 per hectare	Year 1-4
Roading	13,000 to 30,000 per km	Mid rotation
Mensuration and marking (thinning)	0.75 – 1 per m3	Prior to thinning
Mensuration (clear fell)	300 – 400 per hectare	Prior to harvesting
Harvesting and extraction to roadside	10 – 15 per m3	End of rotation
Supervising harvesting	2-5% of timber revenues	End of rotation
Management costs and insurance fees	60 – 90 per hectare	Annual

Grants for planting must be accompanied by authorized management plans; these plans also eliminate the requirement to apply for felling licenses. Clearing the area to plant trees is part of ground preparation. Depending on how well the facility is maintained, the fees will change. Preparing a grassland will usually be less expensive than preparing a location with dense vegetation cover. Upland terrain may need drainage, which can be accomplished with burying pipes or a subsoiler. To prepare an elevated, freely draining area of bare soil for planting tree seedlings, mounding is utilized. It is essential to protect the crop from herbivore damage with fencing while creating some woods for the production of commercial timber. The least expensive alternatives will usually keep livestock out, while the most expensive options will keep deer and small herbivores like rabbits out. Spot spraying reduces competition with tree seedlings by clearing a weed-free space for tree planting. Chemicals and the spraying process will usually be included in the price of this. "Beating up" refers to the process of replacing dead trees, which is normally necessary once in the second year and again in the third. The price of replacing trees will vary according to the quantity needed. Access roads must be built to provide access for timber vehicles in order to produce timber for commercial use. The price of this will differ based on how easily accessible road stone is and how many culverts are needed. Trees usually need to be tagged and measured, a process known as mensuration, prior to a thinning sale in which only a fraction of the trees are felled at an intermediate period in the rotation. Similarly, the volume of timber will need to be measured for a clear-felling sale where all of the timber is sold standing in the woodland. A forest agent typically performs this, and the price of forest mensuration varies greatly and rises in proportion to the crop's value. After the woodland is developed, it will need to be managed and maintained on a yearly basis. This will include maintenance costs for fences, pest control, preventing fires, management fees, and insurance premiums for commercial timber production. It's important to conduct a comprehensive cost analysis that takes into account all relevant factors and considers the full lifecycle of the afforestation project. Additionally, cost-effectiveness analysis can help prioritize interventions and optimize resource allocation to maximize the environmental, social, and economic benefits of afforestation initiatives (Hardaker, Evaluating the financial costs of forestry, 2021).

8. CONCLUSION

BECCS, DAC and tree planting represent three distinctive approaches to carbon sequestration, each with unique advantages and challenges. One of the main differences is the costs for these solutions to mitigate carbon emissions from the atmosphere as shown in Table 17. BECCS integrates the production of bioenergy with carbon capture and storage technologies, enabling the simultaneous generation of renewable energy and the removal of CO_2 from the atmosphere.

During the process, biomass, such as agricultural residues or dedicated energy crops, is converted into energy, and the CO_2 emitted is captured and stored underground or utilized in various products. This method has the potential to sequester up to 1573 gCO_2eq/KWh, making it a highly effective tool for negative emissions. However, the efficiency of BECCS is limited by the availability of sustainable biomass feedstocks and the infrastructure required for capturing and storing the carbon. BECCS cost estimates are dependent on numerous factors and assumptions and are therefore fundamentally quite uncertain. The IEA GHG study indicates that an ETS certificate price of biomass co-fired plant with capture is 65-76 €/tCO_2 (€238-278/tC) for dedicated biomass plant, with reference to the EU ETS (Emissions Trading Scheme).

Table 17. Costs for BECCS, DAC and planting trees

COSTS FOR BECCS, DAC AND PLANTING TREES			
METHODS			COSTS
BECCS	Biomass co-fired plant with capture		65 – 76 €
DAC	Capital Cost + Operational Cost	Liquid Solvent DAC	113 – 267 €
		Solid Sorbent DAC	17 – 995 €
DAC	Energy Sources	Solar	398 – 638 €
		Wind	333 – 527 €
		Natural Gas	81 – 211 €
		Coal	81 – 211 €
		Nuclear Power	342 – 573 €
Plantation		Woodland Management	3523 – 7046 €
		Roading (per km)	15267 – 35232 €
		Expenses Per Hectare	10834 – 8784 €
		Expenses Per 1000 Trees	740 – 1292 €

In contrast, DAC is a technology that directly captures CO_2 from ambient air through chemical processes, irrespective of the source of the emissions. This technology holds the potential for removing billions of tons of CO_2 annually, offering a highly scalable solution. Despite its significant potential, DAC currently faces high capital and operational costs, ranging from 17 € to 995 € per ton of CO_2 removed. Also, its energy sources need is another cost, ranging from 81 € to 638 €. As a technology still in its early stages, DAC is undergoing rapid advancements with increasing investments aimed at reducing costs and enhancing efficiency.

Tree planting, the oldest and most natural form of carbon sequestration, involves the cultivation of new trees or the reforestation of degraded areas to absorb CO_2 through photosynthesis. While initial costs can be high, the long-term benefits of enhanced carbon sequestration and ecosystem services make afforestation and reforestation a viable and sustainable approach to climate mitigation. The environmental benefits of tree planting extend beyond carbon sequestration, contributing to biodiversity enhancement, soil health improvement, and the provision of ecosystem services. However, its effectiveness is based on factors such as species selection, growth rates, and climatic conditions. Additionally, tree planting requires significant land resources, and takes a long time to have a major influence on carbon sequestration.

From a financial point of view, BECCS offers two benefits: it produces renewable energy and facilitates carbon sequestration. The projected costs per ton of CO_2 eliminated range from 65 to 76 €. BECCS may become financially feasible as a result of this integration, particularly in areas with developed carbon capture and storage infrastructure and bioenergy businesses. On the other hand, because DAC requires a lot of energy to capture CO_2, even though it has high scalability and flexibility, it currently has higher costs. But with time, it is anticipated that these prices would decrease due to greater investment and advancements in technology, improving its economic viability. Tree planting stands out for its low to moderate costs and potential to provide additional benefits which can bolster its economic viability, particularly in rural and developing areas.

In conclusion, each of these carbon sequestration methods—BECCS, DAC, and tree planting—presents unique strengths and challenges. BECCS offers a valuable integration of renewable energy and carbon removal but is constrained by biomass availability and land-use considerations. DAC provides a flexible and highly scalable solution for carbon removal at a high cost and energy demand. Tree planting, though requiring substantial land and long timescales, offers cost-effective carbon sequestration alongside significant environmental benefits. To effectively mitigate climate change, a combination of these approaches with regulations on CO_2 emissions are crucial for mitigating climate change by limiting greenhouse gas outputs, thereby reducing the overall warming of the planet.

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