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RESEARCH ARTICLE

From Carbon Neutral to Carbon Positive: A Framework for Sustainable and Economically Viable Agriculture

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Abstract – Human activities have greatly raised global temperatures by producing greenhouse gases such as carbon dioxide, methane, and nitrous oxide, posing several environmental issues. Addressing these difficulties, we propose a scalable methodology for increasing CO_2 absorption by reforestation on privately owned agricultural land. This strategy focuses on planting commercially valuable and high carbon-sequestering trees, such as mulberry, fig, olive, linden, almond, and hemp, on a one-hectare area. The design features ten rows of trees with hemp planted between them to maximise land utilisation and revenue creation. Economic predictions indicate a yearly income of € 41.064 per hectare from plant-based goods and € 992,40 from carbon credits, totalling € 42.056,40. The net CO_2 absorption per hectare is 16,54 tonnes per year. This approach helps farmers financially while simultaneously helping to minimise climate change by balancing emissions and absorption. Diversifying crops improves resistance to market variations, while hemp boosts soil fertility and rotational crops. This method, which balances environmental and economic stability, demonstrates that sustainable practices may generate revenue. Based on Siena's previous successes in reaching carbon neutrality, this approach provides an effective strategy for achieving positive carbon results that may be applied in a variety of climates and locations. Implementing such initiatives is crucial for sustainable growth, reducing our environmental footprint, and ensuring a resilient future.

Keywords – Global warming, bioeconomy, sustainable development, carbon neutral, GHG, sustainable model, farmer, carbon credit, agriculture, crop rotation, SDGs

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1. INTRODUCTION

1.1 Introduction to global warming and human contribution

Human activities have significantly contributed to the rise in average global temperatures over the last century by emitting greenhouse gases such carbon dioxide, methane, and nitrous oxide (YUE & GAO, 2018). This condition, known as "Global Warming," is characterised by an unprecedented increase in the Earth's average surface temperature, which is mostly caused by greenhouse gas emissions from fossil fuel combustion (Hansen et al., 2000). According to NASA, the global average surface temperature rose by 0.6 to 0.9 degrees Celsius (1.1 to 1.6 ° F) between 1906 and 2005, with the rate of increase essentially tripling in the last 50 years (Hansen et al., 2010). Temperatures will inevitably rise in the foreseeable future. Rising temperatures have numerous consequences, including soil deterioration, decreased agricultural production, desertification, biodiversity loss, ecosystem degradation, limited freshwater resources, ocean acidification, stratospheric ozone depletion, and deforestation (A. Nastis, 2012; Godbold & Calosi, 2013; Hafizur Rahman & Rahman, 2011; Lal, 2012). Global warming poses a huge threat to water and food supplies, potentially destabilising agricultural sectors already overburdened by droughts or heavy rainfall (Charles et al., 2010; Ciampittiello et al., 2024).

Furthermore, elevated temperatures may promote the spread of new infections, vectors, or hosts, demanding increased pesticide and fertiliser use in agriculture (Rossati, 2017).

1.2 Deforestation as a Driver of Local and Global Climate Alterations

Agricultural lands account for approximately 38% of the Earth's land surface, and the overall increase in atmospheric CO_2 is strongly linked to deforestation, which causes both local and global climate alterations (Foley et al., 2005). Currently, population growth and the subsequent extension of agricultural lands are the principal drivers of deforestation, a trend that is expected to continue throughout the current century. Following land clearance, crops and marginal lands, which humans use for food and raw materials, frequently replace trees, resulting in a lower carbon density per unit area than forests. Crompton et al. examined how deforestation in tropical regions contributes to regional climate change, as well as how different spatial arrangements of cleared and forested lands affect temperatures, using remotely sensed forest loss and land surface temperature (LST) data from maritime Southeast Asia. As expected, deforestation increases LST. Surprisingly, the study found that fragmented landscapes caused by forest loss, where forest and non-forest areas are intertwined, have a lower temperature increase. Thus, widening the forest-non-forest boundary may help to decrease temperature rise. Another significant finding was that deforestation-induced temperature increments extend up to 6 km from the deforested locations. Even land clearance carried out by small-holder agriculture can impact local climate (Crompton et al., 2021).

1.3 Urbanization and Carbon Sequestration Loss

The rate of deforestation is closely tied to the growth of urban areas, and it's projected that by 2030, roughly 60% of the world's population will reside in cities (Rydin et al., 2012). While urbanization serves as vital living space for humans, it also serves as an increasingly significant source of carbon emissions. Consequently, human activities constitute the primary driver of carbon sequestration loss, which occurs through actions that directly or indirectly influence tree growth characteristics, conditions, and mortality (Longobardi et al., 2016).

1.4 The potential of global tree restoration

Afforestation has emerged as a powerful technique for reducing global climate change, due to forests' capability to store huge quantities of carbon. Furthermore, alterations to forest cover can cause either warming or cooling by altering the passage of energy and water between the Earth's surface and the atmosphere, which underpins the biogeophysical impacts (Bastin et al., 2019). The obtained data highlights the potential for climate change mitigation through global tree regeneration, emphasising the urgent need for action. Tree restoration remains one of the most effective ways to fight climate change. Under current climate conditions, there is sufficient capacity to support 4,4 billion hectares of canopy cover. It surpasses the current 2,8 billion hectares of canopy cover by 1,6 billion hectares (Bastin et al., 2019). However, much of the area suitable for tree cover around the world is currently being used for human development and agriculture, both of which are required to maintain an ever-increasing human population. Failure to depart from the current track could reduce worldwide potential canopy cover by 223 million hectares by 2050, with the majority of losses concentrated in the tropics. More than half of the tree restoration potential is concentrated in six countries: Russia (+151 million hectares), the United States (+103 million hectares), Canada (+78,4 million hectares), Australia (+58 million hectares), Brazil (+49,7 million hectares), and China (+40,2 million hectares), some of which are experiencing significant development and urbanisation (Bastin et al., 2019). As a result, there is an urgent need to change existing practices and implement more effective and sustainable land management solutions.

1.5 Exploring green solutions: a case study of Politec Technology S.r.l

Politec Technology S.r.l., an Italian company, provides an example demonstration of how businesses may address global warming and offset CO_2 emissions. They first measured their Carbon Footprint and then established plans to offset their emissions through tree planting efforts. The carbon footprint represents the total volume of greenhouse gases directly or indirectly associated with a product's lifecycle (Wiedmann & Minx, 2007). While greenhouse gases naturally present in the Earth's atmosphere have historically mitigated atmospheric temperature by retaining solar energy, excessive production of these gases has resulted in climate change. The greenhouse gases covered by the Kyoto Protocol include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), sulphur hexafluoride (SF_6), and perfluorocarbons (PFCs). The primary references utilized for calculating the Carbon Footprint are UNI 14064 and UNI 14067. Although there is no explicit regulation in Italy regulating carbon footprint estimation, other countries have implemented rules for this purpose. Politec Technology S.r.l. decided to follow the PAS 2050 standard produced in the UK by the Department for Environment, Food, and Rural Affairs (DEFRA). The company's carbon footprint was evaluated to establish the equivalent CO_2 emissions that required compensation. Given nature's ability to mitigate the consequences of significant greenhouse gas emissions via CO_2 sequestration, reforestation appears to be an efficient CO_2 offset. A study conducted at the Institute of Biometeorology of Bologna analyzed 31 tree and shrub species, evaluating parameters such as CO_2 sequestration, potential absorption of gaseous pollutants, potential particulate capture, VOC emissions, and ozone formation potential. The study identified acer platanoides, betula pendula, and quercus cerris as the top three plant species suited for the company's territory. Similar analyses should be conducted by all companies seeking to offset their CO_2 emissions and achieve carbon neutrality globally.

1.6 Carbon Neutrality in Siena

The province of Siena holds the distinction of being the first in Italy to achieve carbon neutrality. In 2001, the province started on an extensive effort to examine emissions balance, recognising its strategic relevance from both political and environmental perspectives (Caro et al., 2014). The SPin-Eco Project was launched the same year, with the goal of performing an environmental study that covered the entire province of Siena, it is presented as an example of a local environmental sustainability assessment. The study included scientific examination of numerous environmental sustainability indicators, such as Ecological Footprint, Greenhouse Gas Inventory, Extended Exergy Analysis, Emergy Evaluation, Life Cycle Assessment (LCA) and Remote Sensing. Concurrently, the Province of Siena pursued environmental certification ISO 14001, being the first Italian province to do so (Pulselli et al., 2008). In 2007, the REGES project, in conjunction with the University of Siena, was initiated with the goal of reducing greenhouse gas emissions. The methodology for calculating emissions follows the IPCC Guidelines for National Greenhouse Gas Inventories (Bastianoni et al., 2014). The areas considered for emissions include energy (electric energy, petroleum products, waste-to-energy), industry (landfill, composter, wastewater), and agriculture (land use, farming). Forest absorption is taken into account for carbon absorption. The gases considered are CO_2, CH_4, and N_2O. This system enables the annual measurement of net emissions in the province. The data evaluation revealed steady improvement over the years (Bastianoni et al., 2014). Hence, the target of achieving net zero emissions was accomplished four years ahead of schedule, in 2011. In 2016, the balance of greenhouse gases, measured as Gross Emissions minus Forest Absorption, showed an unprecedented 108% reabsorption rate (Caro et al., 2014).

1.7 Principles and Transformational Potential of the Bioeconomy

These core principles of resource optimisation, waste reuse, and the implementation of emission-reduction technologies are all consistent with bioeconomy practices. The bioeconomy has the capacity to generate long-term systemic transformation and transition, solving critical economic, societal, and environmental concerns for EU Member States (MS) (Bugge et al., 2016). At the local level, improving and proposing strategies for the circular bioeconomy can boost the production of environmentally friendly and digital products. This can, in turn, promote job creation and sustainable socio-economic growth. In the aftermath of COVID-19, the bioeconomy holds particular promise for aiding sustainable recovery and development by providing locally sourced sustainable biomass to support bio-based industries.

1.8 National Bioeconomy Strategies and Ongoing Challenges

It is increasingly important to develop and implement National Bioeconomy Strategies. These strategies should be regularly updated to align with national priorities, the European Green Deal (EGD), Sustainable Development Goals (SDGs), and COVID-19 recovery efforts (Stephenson & Damerell, 2022). The development of bioeconomy solutions provides a new and actionable method for facilitating the transition to a sustainable, climate neutral economy. Policymakers at the highest levels of each Member State must demonstrate a long-term commitment and political will to support and implement bioeconomy initiatives. Sustainability implementation requires adherence to rules and multi-step systems that are constantly improved through "good practice" - better organisation achieved through the design and development of national bioeconomy strategies and action plans, stakeholder engagement, and robust monitoring, self-monitoring, and implementation processes. Given the huge advantages of achieving goals related to biodiversity conservation in agriculture, sustainable food production, and climate change mitigation, it is clear that current aid disproportionately benefits a small fraction of farmers, while ignoring inland areas and smaller farms.

1.9 Policy and support mechanisms

To address this disparity and give support, the Common Agricultural Policy (CAP) has been updated multiple times, with the most recent version approved and slated to take effect from 2023 to 2027. The most recent edition of CAP includes five forms of direct payments: basic income support, redistributive support, support for young farmers, climate and environmental initiatives, and coupled income support. The CAP represents a close cooperation between agriculture and society, encouraging collaboration between Europe and its farmers (Dwyer et al., 2007). Furthermore, at the local level and in relation to the proposed work, CAP might provide an extra incentive for the availability of private lands for involvement in sustainable activities (Barrett et al., 2021).

1.10 Purpose of the model

The literature confirms that greenhouse gas emissions into the atmosphere are the principal cause of global warming. This occurrence has serious consequences, including altering water supply and food production, negatively hurting the agricultural industry (Schmidhuber & Tubiello, 2007). Deforestation emerges as a key contribution to the rise in atmospheric CO_2 levels, which is compounded by ongoing land urbanisation (Seto et al., 2012). These tendencies are predicted to cause significant increases in global temperatures. To address these difficulties, global tree restoration emerges as a promising alternative, with the capacity to reverse these processes and restore optimal environmental conditions (Bastin et al., 2019). The province of Siena set a pioneering example by becoming Italy's first to achieve carbon neutrality (Caro et al., 2014). The goal of this research is to establish a model that can be applied on a larger scale to improve CO_2 absorption by balancing emissions and absorption. This concept focuses on planting trees on privately owned land, with a special emphasis on free and exploitable plots where such efforts can be successfully implemented.

2. MATERIALS AND METHODS

2.1 Model design

This model aims to create a scalable model to enhance CO_2 absorption by balancing emissions and absorption, focusing on planting trees on privately owned, free, and exploitable plots. Thus, the model's goal is not just to cut emissions, but also to offer farmers with additional economic benefits by planting various types of trees and bushes on their private land. The proposed model has the following design:

- Total area: 1 hectare (10.000 m²);
- Tree area: 0,3 hectare (3.000 m²);
- Hemp area: 0,7 hectare (7.000 m²);
- Number of tree rows: 10 rows, spaced 10 meters apart;
- Hemp cultivation area: between the tree rows, with 7 meters of cultivation space;
- Tree spacing: 4 meters apart within the rows;
- Hemp plant spacing: 1,5 meters apart;
- Total plants: 48 plants, including both trees and hemp.

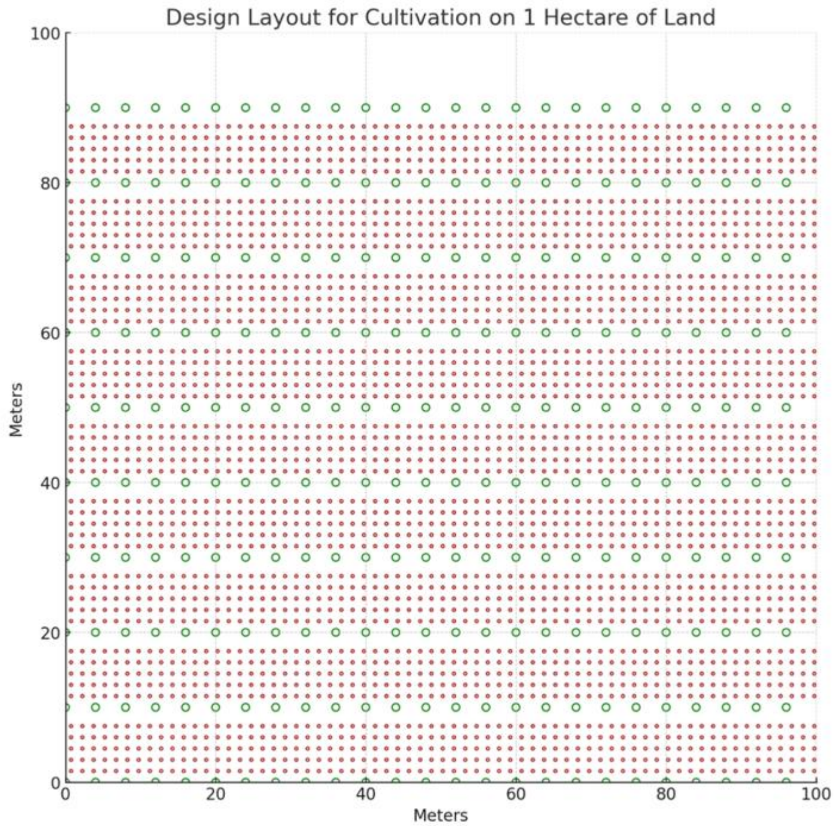

Figure 1 Representative design of the proposed sustainable model; Green circles represent the trees, positioned 4 meters apart within the rows; Brown circles, represent the hemp plants, spaced 1,5 meters apart. These plants are cultivated in the space between the tree rows, in a 7-meter-wide area.

2.2 Species selection

Species were chosen based on their capability for CO_2 absorption and the economic value of their products. The selected plants include:

- Mulberry (*Morus nigra*);
- Fig (*Ficus carica*);
- Olive (*Olea europaea*);
- Linden (*Tilia cordata*);
- Hemp (*Cannabis Sativa*);
- Almond (*Prunus dulcis*).

2.3 Selection criteria

Several variables were reviewed and assessed to help guide the selection process, including yield per hectare, economic yield, trees per hectare, purchasing price, and CO_2 sequestered.

The selection of these kinds of plants is based not only on their carbon sequestration capabilities, but also on their ability to produce valuable products, ensuring income for private individuals. While there may have been species with better carbon sequestration capacity, they were excluded for practical reasons. These limits include difficulties in maintenance or compatibility with row agriculture models, uncertainty about profitability for growers, and practical issues such as space constraints for hemp cultivation or tractor passing. The chosen plants have a high carbon sequestration capacity while also allowing the land to be used for additional purposes, changing the model from an ideal concept to a viable one. In this model, carbon sequestration is more than just an abstract concept; it is an additional source of revenue for private persons that benefits both them and the community. The approach evaluates the potential benefits of sustainable, non-intensive land use strategies that maintain soil fertility, which are supported by crop rotation and the addition of hemp. It's important to note that the model doesn't hypothesize maximum profits but rather average gains, which can vary based on additional elements introduced under the trees.

2.4 Model yield calculation

The yield from the model is calculated as the sum of incomes generated from each plant species per hectare, along with carbon credits obtained for sequestering carbon, considering emissions from tractors used in cultivation

3. RESULTS

According to the approach provided, the calculated profits from each plant per hectare and year are as follows:

- Mulberry: € 7,200;
- Fig: € 12,000;
- Olive: € 1,584;
- Linden: € 1,920;
- Almond: € 2,880;
- Hemp: € 12,600;
- Almond: € 2,880.

The total of this amount comes to €41.064. Furthermore, the overall CO_2 absorption is predicted to be 19,4 tonnes per hectare per year, with tractors' emissions deducted, yielding a net absorption of 16,54 tonnes. Given the current value of €60 per tonne of CO_2 absorbed, the total carbon credits equal €992,40, which must be added to the income from plant products. The value of carbon credits is assessed in our study, taking into account its fluctuation and susceptibility to a variety of factors such as demand and supply dynamics, government policies, and international climate accords. As a result, the total annual income per hectare is €42.056,40.

Table 1 - Average estimations for various species (mulberry, fig, olive, linden, hemp, and almond) in an agricultural plantation. Data are presented as the mean of multiple sources and are variable based on features such as geographical location, tree variety, source (nursery, internet store, farmer), condition, and maintenance. * The economic yield in euros per kilogram of an adult hemp plant varies considerably depending on the derived product (Fiber: €1/kg; Seeds: €3/kg; Seed oil: €20/kg)

	Mulberry	Fig	Olive	Linden	Hemp	Almond
Trees per hectare	400	300	300	300	5000	300
Economic yield (€/kg)	6	5	2	12	8*	9
Yield per hectare	10	15	5	1	10	2
CO_2 sequestration (t/ha)	7.5	10	10	20	15	10
Price for tree (€)	40	60	90	75	5	75

4. DISCUSSION

The suggested model, offers significant benefits to the farmer, allowing them to potentially earn €41.064 per year in addition to revenues from other activities, while also achieving a net absorption of 19,40 tons of CO_2 annually. CO_2 exchanges can be measured using two fundamental methodologies: whole-system balance and small chamber enclosures. The first one is able to establish the NEP (Net Ecosystem Production) of an ecosystem by means of the "Giant cylinder" (Lovett et al., 2006) and the "Aerodynamic analysis of the boundary layer" (Ghadimi et al., 2012). The second one is able to analyze separately the individual components contributing to the budget; the summation of individual streams (all carbon losses), subtracted from the value of gross photosynthesis (PPL) allows to obtain the balance of the carbon. Furthermore, to mitigate the effects of global warming, companies can implement strategies to reduce carbon emissions, including the use of carbon credits. With each credit certifying the reduction of one tonne of CO_2 equivalent, the farmer could potentially earn an additional €992,40 by selling absorbed CO_2 in the form of carbon credits, resulting in a total revenue of €42.056,40 per hectare per year.

The economic yield varies according to the use that is made of the plant and its components, for instance the gain varies if the fruit is dry or fresh. Therefore, the revenue is not immutable, but it is variable and depends on different factors. Fresh figs are sold at €5/kg, whereas dried ones cost €17/kg. Fresh mulberry berries cost €6/kg while dried ones cost €10/kg; moreover, the mulberry has an excellent potential as a biorefinery: its leaves have a digestibility between 75 and 90%, they have been used as a silkworm food, but they are also an excellent fodder for mammals. The high content of polyphenolic compounds and the relative antioxidant activity of *Morus nigra* underline the nutraceutical qualities of its fruits: it can be considered a very interesting raw material for food applications, food supplements, juices and beverages (Kostić et al., 2013).

Almonds shelled cost €15/kg. About olives, the average cost of oil in Tuscany is €12-13/ kg. In this case the gain from the olive trees depends on the use that the farmer makes of them. Regarding the linden, its main economic yield concerns honey. The cost of honey is €15/kg. However, the linden tree can also bring a gain from flowers and leaves because they can be used for herbal teas. The economic return of a mature hemp plant differs significantly based on the derived product, such as fiber, seeds, or seed oil. Hemp provides positive support to rotational crops. After cultivation, the soil is left in optimal conditions, given the high shading capacity that suppresses weeds. The findings are, for example, demonstrable in rotation with wheat, which has crop increases up to 20%. Hemp is also useful for reclaiming land polluted by heavy metals through a process called phytoremediation (Piotrowski et al., 2011).

Another key aspect of this model is that a differentiated crop is used instead of monoculture. Taking the olive tree as an example, it can happen that for a year all the olive trees get sick and using a monoculture the consequences in economic terms for the agricultural entrepreneur would be devastating. If, on the other hand, a differentiated crop is used, as proposed in this model, the farmer will still have a profit from other crops. Thus, differentiated cultivation makes the farmer resilient. In the development of this model, the valorisation of the landscape aspect is taken into account. Cultivation on rows that follow the contour lines facilitates the management of rainwater, increasing the infiltration and enhancing soil fertility (Lei et al., 2021). In addition, it is possible to evaluate and integrate in the model various cultivation options along the rows, under the canopy of the trees, for example artichokes, berries or sea buckthorn, the latter is a spontaneous plant belonging to the Elaeagnaceae family. Adding more plants between the rows means increasing both CO_2 absorption and economic yield. Indeed, economic yield and CO_2 absorption in this model are estimated not at their maximum value. This model aims to provide a feasible, profitable, and easily applicable solution for agricultural entrepreneurs, leveraging private farm settings where farmers can closely monitor plant growth and management, ensuring the success of reforestation initiatives.

5. Conclusions

Carbon sequestration must be integrated into agricultural production in order to assure sustainability and economic viability. The model's strength rests in its comprehensive approach, which considers both carbon sequestration and economic output as interconnected components. By combining these elements, the model creates a firm foundation for sustainability that is both practical and effective. Built on Siena's carbon neutrality record, the model offers as a template for converting from "carbon neutral" to "carbon positive" without sacrificing economic viability. It provides a framework for combining environmental responsibility and financial stability, demonstrating that sustainability and profitability are compatible.

Furthermore, the model's versatility allows for customisation based on climate, assuring its application across a wide range of regions. The ability to choose appropriate plants for the system maintains its effectiveness independent of environmental circumstances. The switch to "carbon positive" is essential for all human activities because it is consistent with the principles of sustainable development. By lowering our environmental footprint and optimising resource utilisation, we can achieve a more sustainable and resilient future. The model described here serves as a useful tool for facilitating this shift, providing a path towards balancing environmental stewardship with economic development.

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