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AGRO-FORESTRY AS AN EMERGING TREND FOR BOTH CLIMATE CHANGE ADAPTATION AND MITIGATION: A REVIEW

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Abstract: In tropical developing countries, agriculture represents the primary livelihood of rural people. Climate changes impact global farming productivity, including inadequate food security. Unwanted changes in climatic conditions e.g., severe droughts, flooding, diseases have an extensive impact on the agricultural system, triggering soil erosion, crop failure, biodiversity loss, reduction in soil moisture, crop damage by pests and the consequent economic losses. In the current scenario, agro-forestry is being recognized as an effective land management system for both climate change adaptation and mitigation, while addressing many of the challenges that smallholder farmers are facing. Climate adaptation at farm level and resilience at the landscape level is the need of the hour for sustainable livelihood. Water security through improved infiltration to soils and groundwater can be enhanced by agroforestry practices, thereby protecting water catchment and watersheds. Ecosystem services provided by such practices as climate buffering, enhanced soil fertility, erosion and flood control etc. are important for resilience to climate change, thereby reducing the vulnerability of local people. By storing increased amounts of carbon in the plant biomass both above and below the ground as well as in soil, agroforestry practice helps in carbon sequestration, in turn helps to combat global warming.

Keywords: Agro-forestry, Carbon sequestration, Climate change, Land degradation, Sustainable farming.

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INTRODUCTION

Agro-forestry is the cultivation and use of trees and shrubs with crops and livestock in the agricultural ecosystem. Agro-forestry seeks positive interactions between its components, aiming to achieve a more ecologically diverse and socially productive output from the land. The core idea of agroforestry is to select the appropriate tree, planting it in an optimal location, and ensuring it to serve the intended purpose. Agroforestry practices can be tailored to safeguard soil, animals, crops, and homes from extreme weather, enhance water quality, generate jobs and income, and produce a variety of products (such as food, fibre, bioenergy, wood, floral, and medicinal goods). They can also improve pollinator habitats, act as living snow fences by trapping snow and preventing road blockages, provide wildlife habitat and travel corridors, sequester carbon, reduce greenhouse gases, mitigate odours, and create aesthetically pleasing landscapes (USDA, 2025).

The global productivity of farm holds can be significantly affected by the current anthropogenic climate change that is occurring in the 21st century.

Agriculture, forestry and other land uses stand for 23% of the world's total emissions (Amy *et al.*, 2023). As the world's population continues to grow, the farmers are challenged to produce more and more by using sustainable farm practices with environmental ethics that mitigate climate changes (Kumar, 2019). Agro-forestry practices as a solution can be used both for climate change and food security, including intercropping of short and long-term trees with crops, inter cropping with leguminous plants during the fallow period. Agro-forestry can mitigate climate change through increasing carbon storage by capturing carbon from the atmosphere through photosynthesis and storing it in biomass and soil. Agro-forestry supports ecosystem services associated with trees, such as carbon and nutrient cycling in soils, water regulation and sediment flows (Colin, 2013; Campanhola and Pandey, 2019). However, due to environmental factors and diversity in agro-forestry practices, the carbon stocks stored in agro-forestry systems can vary.

There are a variety of complex agroforestry practices in different regions of world, modern agroforestry systems have a number of precursors, such as traditional systems across India (Murthy *et al.,* 2013), the Sahel (Waldron *et al.,* 2017), or the Javanese systems of pekarangan (combining agricultural and tree crops with livestock) and kebun-talun (rotational cultivation of agricultural and tree crops), shelterbelts, a linear planting of different trees to reduce wind speed; forest farming, these are natural forests whose canopies are used in order to grow high value crops in the understory; silvopasture, livestock and pasture production combined with trees; alley cropping, crops are grown in the alleyways of rows of widely spaced planted trees (Kurniawan and Kurniawan, 2022).

HUMAN-INDUCED CLIMATE CHANGE AND AGRICULTURAL ECOSYSTEM

Weather conditions strongly influence agricultural practices. Farmers are familiar with the seasonal variability of weather conditions. Local farmers are quite appropriate about the groups of crops which are productive under the current climate, but anthropogenic climate change is altering the seasonal climate away from current states. Moreover, excessive anthropogenic activities, pollution and climate change also influences biodiversity and overall sustainable development (Verma, 2021, Prakash and Verma, 2022; Singh *et al.,* 2023). Higher temperatures eventually induce weed and pest proliferation while reducing the land for beneficial crops. Greater

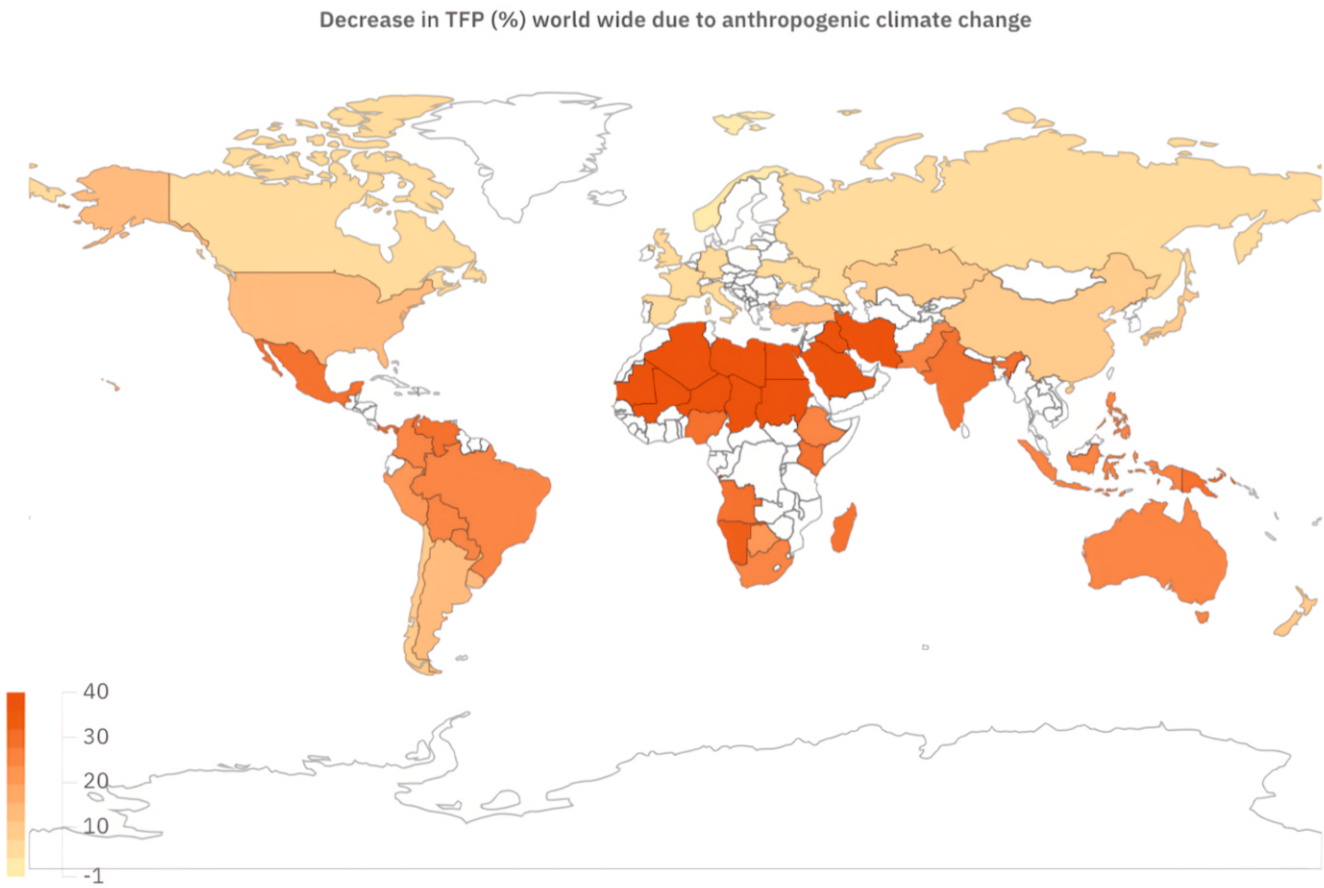

Fig. 1: Decrease in global Total Farm Productivity (TFP) due to anthropogenic climate change (Adapted and redrawn by Sumit Banerjee from Ortiz-Bobea *et al.*, 2021).

occurrence of drier and wetter conditions is already making it difficult and unpredictable for farmers to plan planting and harvesting, threatening the current production system and food as a result (SIWI, 2018). Without adaptation of proper procedures, agricultural productivity; farm economy and food security may remarkably be impacted by moderate levels of climate change. The global total farm productivity (TFP) has decreased by a mean 21% due to climate change impact (Fig. 1) (Vergolia, 2021).

Earth's estimated 25% ice-free land is subject to human induced land degradation and countries located in tropics are expected to be severely affected by climate change, as their large part of population depends on agriculture. Land degradation easily removes the carbon stored in soil in the form of organic matters. About 23% of the world's total GHGs (e.g. CO2, N2O, CH4...) come from agriculture, forestry and other land utilizations, such as deforestation, livestock production, soil, pollution and biodiversity degradation (IPCC, 2019).

POTENTIAL OF AGRO-FORESTRY

Agro-forestry provides several ecosystem services (Table 1). Intensification, diversification and buffering of trees in the farming system provide resilience to production under current climate variability as well as long-term climate change. This type of ecosystem has some advantages in production during drier and wetter years. Tree based systems have higher evapotranspiration rates than other productive systems; they maintain soil condition by pumping excess water out of the soil. It has the potential to prevent desertification and restore degraded soils. It enhances the micro-climate, soil fertility, nutrient cycling, biomass, carbon sequestration; it helps to reduce pressure from natural forests, which are the largest carbon sinks of terrestrial carbon. By using cocoa, coffee, nuts etc. farmers can improve livelihood. It can also help farmers reduce the economic recovery time of a natural disaster (Lin, 2007). It can increase employment opportunities as it increases the supply of wood and livestock in the market, which can trigger a substantial increase in the number of small-scale industries (Dhyani *et al.*, 2007).

Table 1: Ecosystem Services from Agroforestry (AF).

Ecosystem Service	Contribution of Agroforestry	Mechanism	Cases / Examples
Soil fertility	Nutrient cycling, organic matter addition	Leaf litter, N-fixing species	Cocoa-shade agroforestry (Lin, 2007)
Water regulation	Reduced runoff, infiltration improvement	Root systems, shading	Himalayan silvo-pastoral systems (Ilstedt *et al.*, 2007)
Biodiversity	Reduced runoff, infiltration improvement	Multi-strata vegetation	European and Indian home gardens (Torralba *et al.*, 2016)
Carbon sequestration	Above and below ground carbon storage	Photosynthesis → biomass, soil C	India, Africa (Mbow *et al.*, 2014)
Livelihood resilience	Food, fuel, fodder, diversified income	Multiple products from one system	Smallholder farms globally (Waldron *et al.*, 2017)

AGRO FORESTRY (AF) TYPES IN NON-FOREST AREAS

1. **Farm Forestry:** It is the practice of forestry in and around the farmlands integrated with other farm operations by farmers on their own land.

2. **Extension Forestry:** It is the practice of forestry in areas devoid of vegetation, situated in places away from forest areas to increase forest cover.

   a) **Mixed forestry:** It is the practice of forestry for raising fodder grass with scattered fodder trees, fruit trees and fuel wood trees on suitable lands.

   b) **Shelter belts:** It is a belt of trees and/or shrubs maintained for the purpose of shelter from wind, sun, snow drift, etc.

   c) **Linear strip plantations:** These are the plantations of fast-growing species on linear strips of land.

3. **Rehabilitation of the degraded Forests:** Ecological restoration of degraded forest area

which needs immediate attention and for meeting the socio-economic needs of the communities living in and around such areas.

4. **Recreation/Aesthetic Forestry:** It is the practice of forestry with the object of raising flowering plants mainly for recreation to develop or maintain a forest of high scenic value.

CLASSIFICATION OF AF SYSTEM

According to Nair (1987), agroforestry systems can be classified according to the following sets of basic criteria:

1. **Based on the nature of components, AF systems can be classified into the following categories:**
   a) **Agri silvicultural system (crops with shrubs, vines and trees):** This approach entails the intentional and thoughtful utilization of land for simultaneous cultivation of agricultural crops, encompassing tree crops and forest crops. The agroforestry systems encompass diverse practices, ranging from traditional '*taungya*' systems and alley cropping to functional plantings like windbreaks and riparian buffers. Diversifying the tree species improves forest resilience, due to their varying environmental tolerances. Multispecies forest fulfils the postulate of ecological insurance by spreading the potential risks due to climate change much better than monocultures. Such forests better cope with, for example, pest outbreaks, which are most often species-specific (Hlásny *et al.,* 2014). In the 21st century, changes in silvicultural actions are surely needed. Modifying and re-assessing silvicultural practices to ensure the forest continuity and sustainable use of forests will be a major challenge for foresters and forest owners (Szmyt and Dering, 2024).

   b) **Silvo pastoral system (trees with grazing land):** Silvo pastoral systems stand out as a leading agroforestry method that involves the integration of trees with forage and livestock production. This practice encompasses grazing livestock in wooded rangelands and incorporating trees into pastures to provide shade and timber. This system is categorized into three main types: Protein bank, Living fence of fodder trees and hedges, Trees and shrubs on pasture.

   c) **Agro-silvo pastoral System (trees along with crops and grazing land):**
   Home Gardens: This agroforestry practice is among the most ancient, prevalent in high rainfall regions of tropical South and Southeast Asia. It involves cultivating numerous species of trees, shrubs, vegetables, and other herbaceous plants in dense and multi-tiered spatial patterns. Waste materials from both crops and households are utilized as feed for animals and birds, while barn waste is utilized as fertilizer for crops.

   Woody Hedgerows: Within this system, diverse woody, quick growing bushes, and coppicing fodder plants are strategically planted to serve multiple purposes including browsing, mulching, green manure, and soil conservation, all aimed at producing food, fodder, fuel wood, and conserving soil.

   d) **Other Systems:**
   Apiculture with Trees: Within this approach, diverse tree species known for producing honey (nectar) and frequently visited by honeybees are strategically planted along boundaries intermingled with agricultural crops to facilitate honey production.

   Aqua forestry: This method involves growing fodder plants favoured by fish along boundaries and around fishponds. The leaves serve fish food, with the primary objective being fish production and stabilization of bunds around fishponds.

   Multipurpose wood lots: In this case, location-specific trees are either mixed or separately planted to serve many purposes such as timber, fodder, soil protection, and soil reclamation.

2. **Based on the arrangement of components, AF systems can be classified into the following categories:**
   a) **Spatial Arrangement:** Spatial arrangements range from dense mixed stands in home gardens to sparse mixed stands in silvo-pastoral systems. Plants may also be organized in micro- or macro-zonal strips, such as alternate rows.
   b) **Temporal Arrangement:** It takes diverse forms, such as shifting cultivation cycles (2-4 years of cropping followed by more than 15-year woody fallows) or silvo-pastoral grass rotations. These can occur concurrently, overlap (e.g. relay cropping), exist sequentially, or be interpolated.

Table 2: Types of Agroforestry Systems and their climate benefits.

Agroforestry Systems	Key Components	Benefits of Adaptation	Mitigation Benefits (Carbon, GHG)	Case Study
Agri-silviculture	Crops + Trees	Soil fertility, erosion control	Carbon sequestration in biomass	India (Murthy *et al.*, 2013)
Silvo-pastoral	Trees + livestock + forage	Shade, fodder security, resilience in drought	Soil carbon storage, reduced methane intensity	Latin America (Picasso and Pizarro, 2024)
Agro-silvo-pastoral	Trees + crops + grazing	Diversified income, reduced risk	Above and below ground carbon pool	Africa, South-East Asia (Awazi *et al.*, 2021)

3. **Functional basis:** It depends on the primary function or purpose of the system's woody components, such as shelterbelts, windbreaks, timber, and fuel wood. These AF systems can be categorized into the following groups:
   a) **Productive Functions:** These encompass various productive functions such as food, fodder, fuel wood, as well as other wood and non-wood products.
   b) **Protective Functions:** These encompass protective functions such as windbreaks, shelterbelts, soil conservation, moisture conservation, soil enhancement, and providing shade for crops, animals, and humans.

4. **Socio-economic basis:** The socio-economic foundation is determined by factors like input level, management intensity, and commercial objectives. AF systems can be categorized into 3 groups based on the socioeconomics of their components: Commercial systems, Intermediate systems, and Subsistence systems.

5. **Ecological basis:** The ecological framework is established based on environmental conditions, shaping AF systems accordingly. These systems can be categorized into the following groups:
   a) **Humid/sub-humid lowlands:** These hot, humid regions support evergreen vegetation as well as significant human populations. Agroforestry here varies widely, ranging from intensive plant cultivation in densely populated areas to tree-integrated rangelands in sparsely populated zones.
   b) **Semi-arid/arid lands:** In these regions rainfall is limited to certain months, with conditions such as a range in vapour pressure deficit (9 to 30 mb), high solar radiation (400-500 Cal cm^{-2} day^{-1}), wind velocity (20 km $hour^{-1}$), potential evapotranspiration (6 mm day^{-1}), and aridity index (70-74.8%).
   c) **Highlands:** Highlands, such as the Himalayas, feature immense biodiversity and diverse landscapes ranging from variable, high-altitude slopes to fertile valleys. Traditional agroforestry practices are well-established across these varying climatic zones.

BENEFITS OF AGROFORESTRY

1. **Environment Benefits:** There are several important environment benefits of intercropping trees with crops on farmlands (Table 2), both general and specific ecological benefits, which may include:
   a) Alleviation of forest pressure.
   b) Enhanced nutrient recycling facilitated by deep-rooted trees.
   c) Enhanced conservation of ecological systems.
   d) Mitigation of surface runoff, nutrient leaching, and soil erosion through the obstructive influence of tree roots and stems.
   e) Modification of microclimates by soil surface temperature reduction and diminished soil moisture evaporation via mulching and shading.
   f) Augmentation of soil nutrients through the deposition and decomposition of leaf litter.
   g) Enhancement of soil structure through continual organic matter addition from decomposed litter.

2. **Economic Benefits:** Agroforestry systems on croplands offer substantial economic advantages to farmers, communities, regions, or nations. These benefits may encompass:

a) Increased and sustained yields of food, fuelwood, fodder, fertilizer, and timber.
b) Decreased likelihood of total crop failure, which is common in single-cropping or monoculture systems.
c) Heightened levels of farm incomes owing to enhanced and consistent productivity.

3. **Social Benefits:** Beyond economic gains, social benefits arise from amplified crop and tree product yields and the sustainability of these products. These benefits include:
   a) Enhancement of income and sustained growth and employment to improve rural living standards.
   b) Enrichment of quality and diversity of food outputs to improvement in nutrition and health.
   c) Stabilization and advancement of upland communities by eliminating the necessity to relocate farm activities.

AGRO-FORESTRY AS AN ADAPTION AND MITIGATION STRATEGY

Agroforestry systems represent a powerful nexus of climate change mitigation and adaptation strategies, grounded in well-documented ecological principles (Fig 2). For mitigation, these systems act as significant carbon sinks by sequestering atmospheric CO_2 into both above-ground woody biomass and, more substantially, below-ground as stable soil organic carbon (SOC), with sequestration rates observed between 0.29 to 15.21 Mg C ha^{-1} yr^{-1} (Montagnini and Nair, 2004; Lorenz and Lal, 2014). Beyond just biomass, the continuous input of organic matter makes soil a dominant carbon reservoir in these systems (Montagnini and Nair, 2004). Furthermore, agroforestry alters biogeochemical cycles to reduce emissions of potent greenhouse gases; for instance, the integration of nitrogen-fixing trees can decrease the reliance on synthetic fertilizers, thereby lowering nitrous oxide (N_2O) emissions, while improved soil aeration can enhance the soil's capacity as a methane sink (Nair *et al.*, 2009).

Concurrently, for adaptation, the multi-strata canopy structure modifies the microclimate by intercepting solar radiation, which can reduce understory temperatures by up to 4°C and significantly decrease evapotranspiration rates (Jose, 2009). This biophysical regulation conserves soil moisture and enhances water-use efficiency, building resilience against drought and thermal stress. The inherent biodiversity

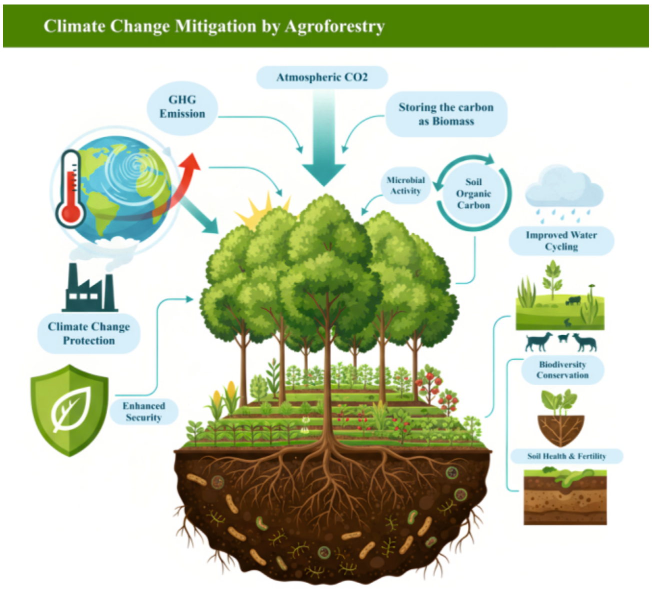

Fig 2: Role of agroforestry in climate change mitigation and carbon sequestration (Illustration created by Sumit Banerjee).

of these systems promotes greater productivity through mechanisms like niche partitioning and facilitation, allowing for more efficient use of resources such as light, water, and nutrients (Tscharntke *et al.*, 2012). This heightened biodiversity not only supports critical ecosystem services like pollination and natural pest control but also diversifies agricultural outputs, thereby enhancing food security and providing economic stability against the backdrop of a changing climate (Waldron *et al.*, 2017; Arya, 2024; Bhatt, 2024).

The increased ratio of GHGs in the atmosphere is increasing the global temperature. Agro-forestry seems to be a promising adaptation option for smallholder farmers to increase accessibility, production, livelihood and capturing atmospheric carbon as biomass. Recent scientific studies highlight the benefits of adapting agro-forestry practices in developing countries in Asia, Central and South America and Africa (Colin, 2013).

The United Nations Framework Convention on Climate Change (UNFCCC) and other international organizations and scientific panels are emphasizing the importance of using sustainable land management systems, such as agro-forestry generate multiple environmental and socio-economic benefits (e.g. FAO, 2019; IPBES, 2019; IPCC, 2019).

LIMITATIONS OF AGROFORESTRY

Agroforestry integrates trees with crops and livestock to address environmental and socio-economic objectives. Research suggests that it can prevent environmental degradation, enhance productivity, sequester carbon, and support ecosystems while providing economic benefits. However, the literature on these claims is not well documented. This study compiles and evaluates the evidence on agroforestry's impacts on ecosystem services and human well-being in high-income countries, identifying gaps in the existing research (Castle *et al.*, 2022).

1. **Environmental Aspect:** Trees may potentially compete with food crops for essential resources like space, sunlight, moisture, and nutrients, leading to a decrease in food crop yield. Harvesting trees could also cause damage to food crops, and trees might attract insect pests harmful to food crops. Additionally, fast-growing trees could quickly regenerate and overrun fields, displacing food crops entirely.

2. **Socio-economic Aspect:** The need for increased labour inputs could lead to occasional shortages in other farm tasks. Competition between food and tree crops might result in overall yields being lower than those of a single crop. Trees typically take a longer time to reach maturity and generate economic value. Farmers may resist replacing food crops with trees, particularly in areas where land is limited. Additionally, agroforestry is more intricate, less familiar, and harder to implement compared to single-crop farming.

By applying proficient management techniques, it becomes feasible to regulate any or all these factors. For instance:

a) Intercropping with legume trees with compact or sparse crowns to ensure adequate sunlight penetration for photosynthesis in the food crop.

b) Choosing deeply rooted tree species to facilitate the absorption of moisture and nutrients from the upper soil layer.

c) Increase the spacing between trees to mitigate their competitive impact on food crops.

CONCLUSIONS

Conventional agriculture germinates the seed of deforestation, but nowadays integrated agroforestry practices addressing environmental and socio-economic objectives can traverse the gap sorting out agriculture and forestry. These may help for diversifying and increase the sustainably and productivity of small hold farmers. It will add to the carbon sequestration and will aid to reduce significant amounts of CO_2 from the atmosphere. It is being practiced in different models in different countries worldwide, which helps to deal with the negative impacts of climate change which can't be done by traditional agricultural practices.

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