The Treesolution

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Content:

Introduction

In October 2016 Pieter Hoff's company Groasis was awarded National Icon by the Dutch Government[3]. His invention – the Growboxx® plant cocoon – is considered one of the 3 most innovative projects of the Netherlands. In 2008, he published "CO_2 , a gift from heaven", which he later renamed to "The Treesolution"[4]. In this book he promotes the concept of creating wealth through disconnection of CO_2 into valuable carbon products through agroforestry. In this paper we have attempted to validate and verify some of the concepts Pieter Hoff deals with in "The Treesolution" using the published scientific literature.

Concept

The Treesolution, in its essence, is a multi-faceted agroforestry approach to resolve a number of linked global problems including climate change, soil degradation, food scarcity, unemployment, associated poverty and rural-urban migration rates (figure 1). This article focusses mainly on the first two items, the other challenges are discussed briefly. One of the main principles behind the Treesolution is to reduce atmospheric carbon dioxide levels by the sequestration of carbon in the longer lasting soil carbon pools. By large-scale reforestation and afforestation, agroforestry can be implemented as a conduit to transfer carbon from the atmospheric pool to the pedological pool, while also increasing terrestrial biomass. At the same time, these systems sustain many ecosystem services such as increasing species diversity, enhancing wildlife habitats, fostering natural food webs, fostering water infiltration, improving soil and ecosystem health, augmenting long-term carbon sequestration. Additionally, agroforestry systems are able to provide a range of products, such as food, fodder, timber, fuel, and pollen for bees[5], hereby creating employment and wealth.

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[3] www.nationaleiconen.nl

[4] www.thetreesolution.com

[5] NAIR, PK Ramachandran, et al. Chapter five-carbon sequestration in agroforestry systems. *Advances in agronomy*, 2010, 108: 237-307.

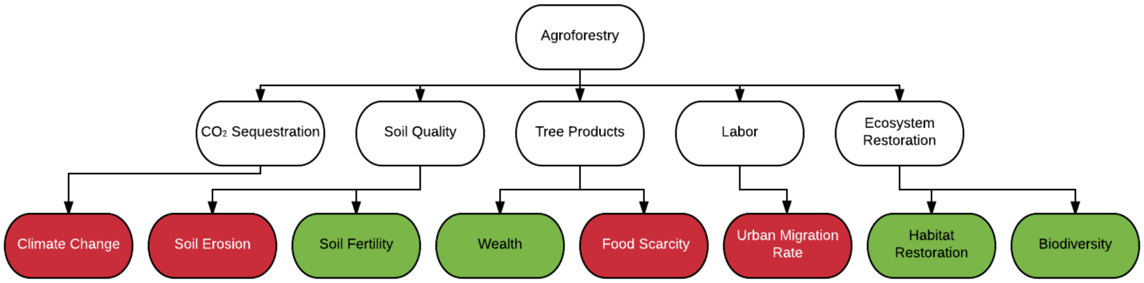

Figure 1. Agroforestry and its downstream effects on global challenges. Red boxes indicate a reduction, Green boxes indicate an increase.

Agroforestry has been demonstrated since the 1990's to be a promising mechanism of carbon sequestration in India, Mexico, Russia, Canada and sub-Saharan Africa amongst others[6]. Afforestation and reforestation have been recognized by the United Nations Framework Convention on Climate Change (UNFCCC) as an allowable method of carbon sequestration for carbon offset activities[7]. Because of the interconnection with food production, rural poverty, and environmental degradation, agroforestry is regarded as an overall sustainable method benefiting both humans and nature. Large-scale agroforestry will create employment in the agricultural sector, resulting in increased food production and a reduction in the rural-urban migration rate. This is especially poignant for farmers in developing countries who are affected by poverty and soil degradation.

A large problem of agroforestry practices in areas where groundwater levels are low, such as arid climates or on degraded land, has always been the need for uneconomical water management systems such as drip-irrigation. This, in combination with the water stress of many countries as reported by the United Nations, shows the need for innovations[8]. More than 1.5 billion people live in climates dependent on some kind of agroforestry system[9] and desertification is experienced on 33% of the global land surface, estimated to affect more than one billion people[10].

Previously, the reforestation of degraded arid soil was not economically viable since irrigation costs inhibited large-scale roll-out. The aforementioned mr. Hoff recently introduced a low cost solution. The Growboxx® plant cocoon is a plantation tool designed to circumvent expensive irrigation use. If trees are planted and grown with the Growboxx® plant cocoon, a reduction in water use of up to 90% is seen when compared to traditional systems[11]. Moreover, survival rates in excess of 95% have been realized using this tool. Effectively, deployment of the Growboxx® plant cocoon gives way to a realization of the Treesolution.

[6] PANDEY, Deep Narayan. Carbon sequestration in agroforestry systems. *Climate policy*, 2002, 2.4: 367-377.

[7] NAIR, PK Ramachandran, et al. Soil carbon sequestration in tropical agroforestry systems: a feasibility appraisal. *environmental science & policy*, 2009, 12.8: 1099-1111.

[8] WWAP (United Nations World Water Assessment Programme). 2016. The United Nations World Water Development Report 2016: Water and Jobs. Paris, UNESCO

[9] ZOMER, Robert J., et al. Trees on farm: analysis of global extent and geographical patterns of agroforestry. *ICRAF Working Paper-World Agroforestry Centre*, 2009, 89.

[10] ESWARAN, H., R. LAL and P.F. REICH. 2001. Land degradation: an overview

[11] www.groasis.com

Soil and land degradation

The ever-increasing need to sustain the human population and their livestock has led to an enormous expansion of land use as farmlands, pastures, and urban areas. In recent decades, the consequences of this activity have become more and more apparent, revealing the environmental impacts from land use on a global scale. Amongst these, deforestation has led to a significant loss of biodiversity and biomass, the rise of atmospheric carbon results in acidification of the oceans and loss of aquatic species, and the intensive use of land causes soil and land to degrade.[12,13,14].

The effect of this human activity is a profound decrease in soil quality and fertility. Up to 40% of croplands are experiencing a form of soil erosion or reduced fertility. However, land degradation proves a difficult term to define but often refers to a number of conditions such as desertification, salinization, erosion and compaction of soil, drop-off of groundwater levels or invasion of exotic species. This may hinder comparison between studies as different variables may have been studied. Most studies focus only on drylands, while others also include temperature and humid domains. It is however, broadly accepted that degradation pertains to a reduction in productivity of the land and soil as a result from human activity[15].

Global area of degraded land

As a result of these definition differences, figures of global area of degraded farmland vary wildly. In the scientific literature cited in this study a range from 1 to 6 billion hectares was noted[16]. Another factor that explains the discrepancy in these estimates is due to differences in methodology. At the low end, the Global Assessment of Soil Degradation (GLASOD) commissioned by the United Nations Environmental Program found that degraded land surface was about 1.2 billion hectares[17]. This study was criticized, however, due to its reliance on the subjective estimates by local 'experts' rather than experimentation Subsequently, at the high end, researchers commissioned by the Food and Agriculture Organization of the United Nations (FAO), expanded the GLASOD data by accounting for previously neglected impacts on surrounding lands, off-site effects such as sedimentation, and impacts on the economy as a whole[18]. They found that approximately 6 billion hectares were affected by land degradation. Alternatively, a 2008 assessment, using remote sensing rather than local experts, from the International Soil Reference and Information Centre shows that the total area of degraded land is as high as 3.5 billion hectares[19]. Other studies claim the area of degraded land to be around 1.9 billion hectares[20]. Lastly, the United Nations Environmental Program (UNEP) puts the global

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[12] TILMAN, David, et al. Forecasting agriculturally driven global environmental change. *Science*, 2001, 292.5515: 281-284.

[13] RASOOL, S. Ichtiaque; SCHNEIDER, Stephen H. Atmospheric carbon dioxide and aerosols: Effects of large increases on global climate. *Science*, 1971, 173.3992: 138-141.

[14] FOLEY, Jonathan A., et al. Global consequences of land use. *Science*, 2005, 309.5734: 570-574.

[15] KNIIVILA, Matleena. Land degradation and land use/cover data sources. *Working Document (Washington, Department of Economic and Social Affairs, Statistics Division, United Nations)*, 2004.

[16] GIBBS, H. K.; SALMON, J. M. Mapping the world's degraded lands. *Applied geography*, 2015, 57: 12-21.

[17] OLDEMAN, L. Roel. The global extent of soil degradation. 1994.

[18] BOT, Alexandra; NACHTERGAELE, F.; YOUNG, Anthony. *Land resource potential and constraints at regional and country levels*. Food & Agriculture Org., 2000.

[19] BAI, Z. G., et al. Global assessment of land degradation and improvement. 1. Identification by remote sensing. *Wageningen: International Soil Reference and Information Centre (ISRIC)*, 2008.

[20] BECKER, Klaus, et al. Carbon farming in hot, dry coastal areas: an option for climate change mitigation. *Earth System Dynamics*, 2013, 4.2: 237-251.

area of dryland at 40% of the earth total terrestrial surface, which again, is equal to 6 billion ha[21].

It is not unreasonable to assume that the total amount of degraded land may be somewhere in between these extremes. For now, this article will assume the total area of degraded land to be around 3.5 billion hectares, based on the remote sensing evidence from Bai *et. al.* (figure 2). To understand the impact of land degradation on the global environment and atmospheric carbon specifically, a closer look must be taken at how carbon is sourced and where it is stored.

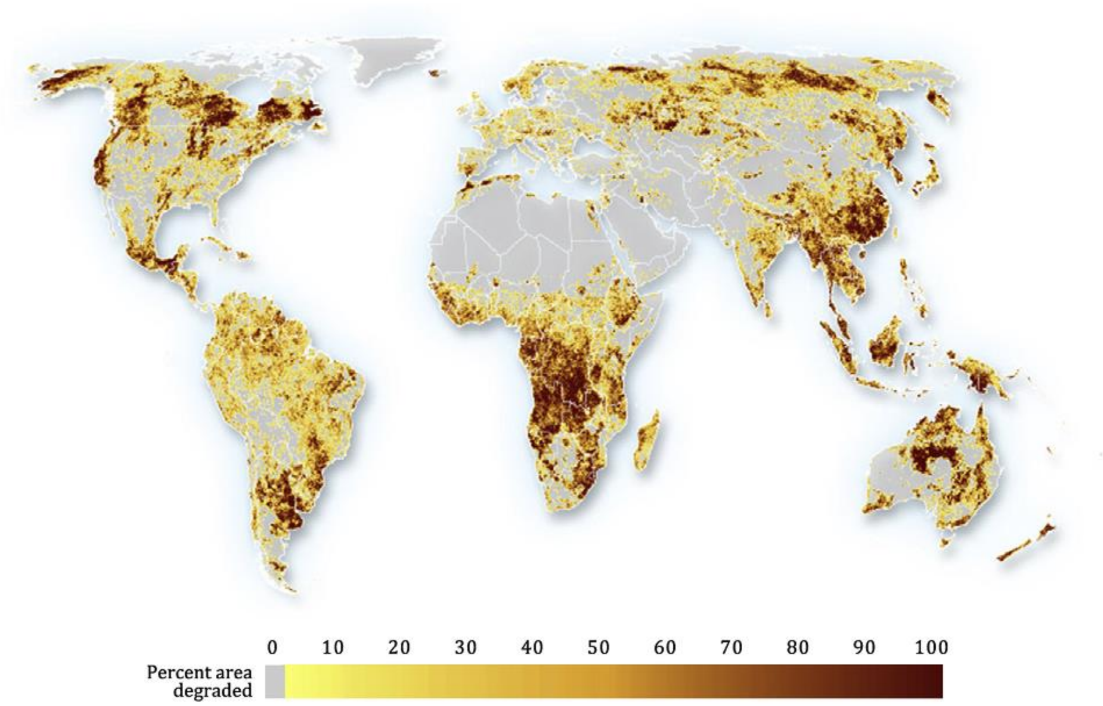

Figure 2. Map of global area affected by degradation, data from Bai *et. al.* 2008, adapted from Gibbs *et. al.* 2015.

The Carbon Cycle

The world's largest pool of carbon (not considering the earth's crust) are **the oceans** where carbon is stored mostly as dissolved inorganic bicarbonates and carbonates (36.000-38.000 Gt)[22], as shown in figure 3. The second largest is the **geological pool** at about 4.000 Gt of carbon, consisting of fossil fuels as coal, oil and natural gas[23].

The **soil or pedologic pool** to about one meter depth is a composite of **soil organic carbon** (SOC), including partly decayed vegetal and animal residues, humus, and micro-organisms, and **soil inorganic carbon** (SIC) containing carbonate minerals such as calcite, dolomite and gypsum, is the third largest pool of carbon with 2.500 Gt This global soil carbon pool includes about 1.550 Gt of SOC and 950 Gt of SIC.

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[21] MIDDLETON, et. al. The World Atlas of Desertification Millennium Ecosystem Assessment (2005a). Climate Change. Chapter 13 in: Ecosystems and Human Wellbeing: Current State and Trends, Volume 1. Island Press. 1997

[22] HOUGHTON, R. A. Balancing the global carbon budget. *Annu. Rev. Earth Planet. Sci.*, 2007, 35: 313-347.

[23] LAL, Rattan. Carbon sequestration. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 2008, 363.1492: 815-830.

At about 800-850 Gt, the **atmosphere** is the fourth largest pool of carbon, where it is stored as carbon dioxide[24]. Lastly, the **biotic pool** – all plant, animal, fungal and microbiotic matter – is estimated at 560 Gt of carbon and can therefore be seen as the fifth largest carbon pool. The soil and biotic carbon pools are together often referred to as the **terrestrial** carbon pool.

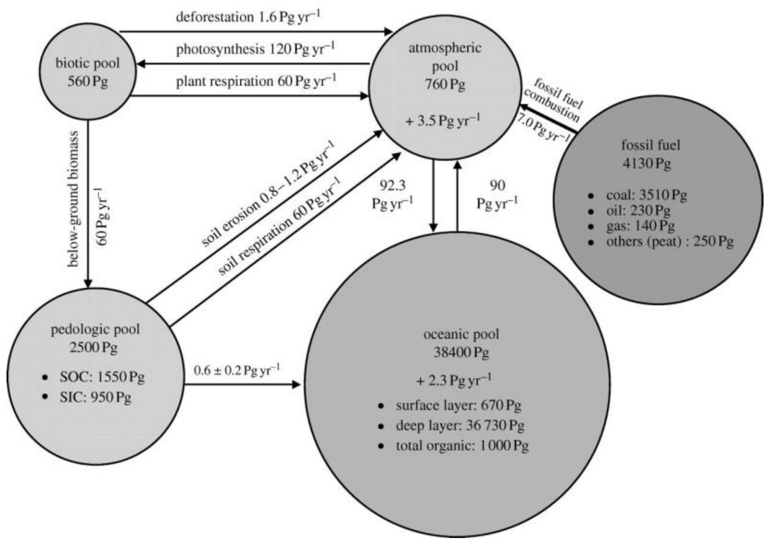

Figure 3. The Carbon Cycle and its various pools and fluxed. From Lal, 2008. The atmospheric carbon pool is adjusted in the text to more recent figures.

The total weight of pure carbon [thus solely carbon atoms] in the atmosphere is usually given at 850 Gt or around 400 (volume) ppm as of 2015[25]. Before the industrial age, the total atmospheric carbon pool was about 600 Gt or 280 ppm. This difference of 250 Gt of added carbon since the industrial revolution amounts to about 900 Gt of carbon dioxide (figure 4). This calculation is somewhat simplified as carbon is also released to the atmosphere as methane, but this is only a small fraction of the amount of carbon dioxide (1.8 ppm vs 400 ppm, respectively. The current annual increase in CO_2 is about 2 ppm/yr). To restore the concentration of carbon dioxide to pre industrial levels, we need to sequester 250Gt in the terrestrial carbon pool.

[24] OELKERS, Eric H.; COLE, David R. Carbon dioxide sequestration a solution to a global problem. *Elements*, 2008, 4.5: 305-310.

[25] Dlugokencky, E; Tans, P (6 May 2015). ESRL Global Monitoring Division. Earth System Research Laboratory. National Oceanic & Atmospheric Administration

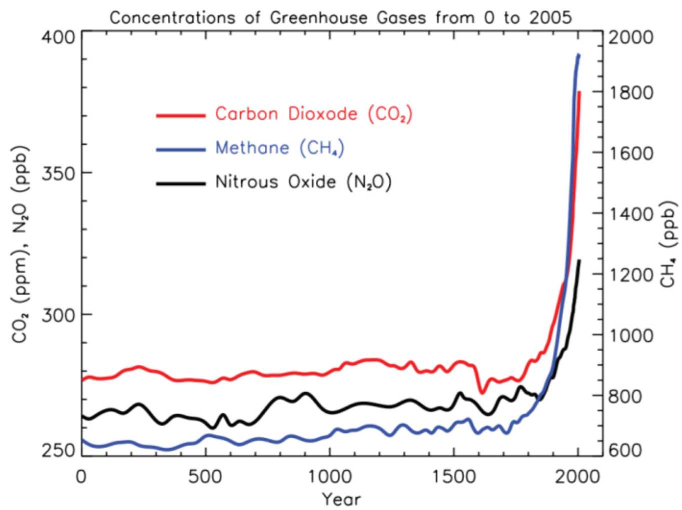

Figure 4. Historic rise in atmospheric carbon dioxide, methane and nitrous oxide concentration between 0-2005[26]. Note that CO_2 levels are in ppm, while methane and nitrous oxide are noted in ppb (parts per billion).

Annual emissions of carbon dioxide are over 35 Gt, equal to 9.5 billion metric tons of carbon (GtC), as of 2015. Of this 9.5 Gt only 40%-50%, or 3.8-4.3 Gt, will remain in the atmosphere[27] (figure 5). The rest is absorbed mostly by terrestrial and oceanic carbon sinks. However, due to deforestation practices and tilling of agricultural soil, biomass and SOC stocks have depleted, creating a soil carbon deficit. As a consequence, the ability of forest and soil to sequester carbon is diminishing.

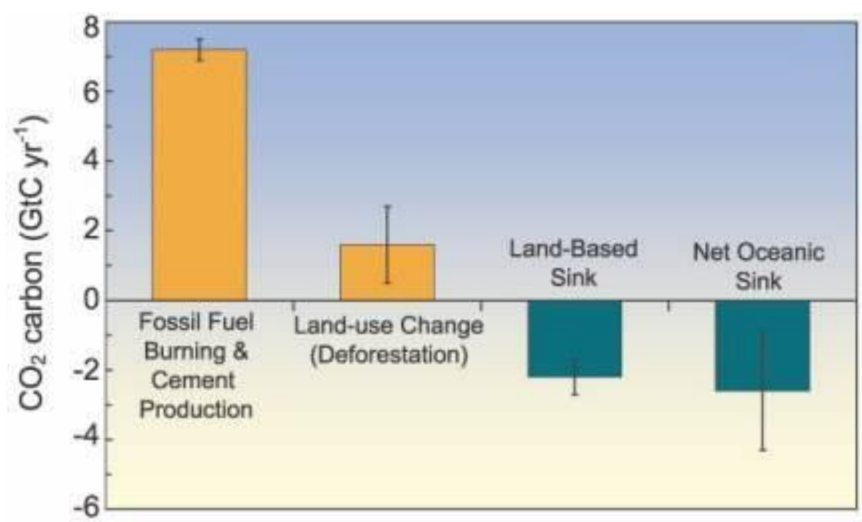

Figure 5. Carbon sources and sinks that contribute to increased atmospheric carbon dioxide concentrations. From IPCC, 2007[28]. Numbers in text are adjusted to current levels.

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[26] FORSTER, Piers, et al. Changes in atmospheric constituents and in radiative forcing. Chapter 2. In: *Climate Change 2007. The Physical Science Basis*. 2007.

[27] LAL, Rattan. Carbon sequestration. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 2008, 363.1492: 815-830.

[28] FORSTER, Piers, et al. Changes in atmospheric constituents and in radiative forcing. Chapter 2. In: *Climate Change 2007. The Physical Science Basis*. 2007

Conversely, this phenomenon presents an opportunity to restore carbon in soil through a variety of land management approaches, including agroforestry[29]. It is thus that long term carbon sequestration could be partly established by the build-up and reconstitution of degraded soils and their organic content. The allocation of carbon to above-ground sinks is another important sequestration option since, in absence of logging or forest fires, forests may sequester their carbon for hundreds of years[30].

Land Degradation and Atmospheric Carbon

Degradation of fertile land is a direct contributor to the increase of the concentration of carbon in the atmospheric pool. Deforestation impacts atmospheric carbon by decreasing the total biomass of carbon but also by decreasing its capacity to sequester carbon from the air. It has been estimated that deforestation accounts for up to 17% of anthropogenic carbon emissions[31]. Moreover, the effect of soil degradation is a reduction in the amount of soil organic carbon (SOC), such as humus. When the SOC pool is severely depleted the soil quality and fertility degrades, reducing biomass productivity and adversely impacting water levels. Conversion of ecosystems from natural to agricultural have caused depletion of the SOC pool by as much as 60% in temperate regions and 75% or more in the tropics[32]. This SOC is mostly released to the atmosphere as carbon dioxide.

SOC is a complex and heterogenous mixture of various types of carbon compounds that can differ in compostability. Some compounds are easily degraded by micro-organisms, while others may remain in the soil for long periods of time. The different soil compounds have distinctive turnover and residence times, leading to the concept that SOC can be seen as consisting of three distinct pools: an active labile pool with a mean residence time of 1-2 years, a slow pool which on average takes 25 years to decompose and a passive or recalcitrant pool with a turnover time of 100-1000 years[33].

SOC sequestration is achieved by storing carbon through the humification process that occurs in the surface layer of up to 1 meter depth. Soils in cultivated ecosystems contain a lower SOC pool than their natural ecosystem counterparts. The most rapid loss of the SOC pool occurs in the first 20–50 years of conversion of natural to agricultural ecosystems in temperate regions and 5–10 years in the tropics[34]. Global levels of SOC vary widely and depend, amongst others, on local climate and soil type. Deserts usually have SOC levels below 20 t/ha, tropical areas have between 80-160 t/ha and temperate regions have SOC levels between 160-200 t/ha but can be as high as 800-1200 t/ha as in some regions in Canada, Finland and Russia[35] (figure 6).

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[29] ONTL, Todd A.; SCHULTE, Lisa A. Soil carbon storage. *Nat. Educ. Knowl*, 2012, 3.10: 35.

[30] PANDEY, Deep Narayan. Carbon sequestration in agroforestry systems. *Climate policy*, 2002, 2.4: 367-377.

[31] BACCINI, A. G. S. J., et al. Estimated carbon dioxide emissions from tropical deforestation improved by carbon-density maps. *Nature Climate Change*, 2012, 2.3: 182-185.

[32] LAL, Rattan. Soil carbon sequestration impacts on global climate change and food security. *Science*, 2004, 304.5677: 1623-1627.

[33] TORN, Margaret S.; VITOUSEK, Peter M.; TRUMBORE, Susan E. The influence of nutrient availability on soil organic matter turnover estimated by incubations and radiocarbon modeling. *Ecosystems*, 2005, 8.4: 352-372.

[34] LAL, Rattan. World cropland soils as a source or sink for atmospheric carbon. *Advances in agronomy*, 2001, 71: 145-191

[35] ONTL, Todd A.; SCHULTE, Lisa A. Soil carbon storage. *Nat. Educ. Knowl*, 2012, 3.10: 35.

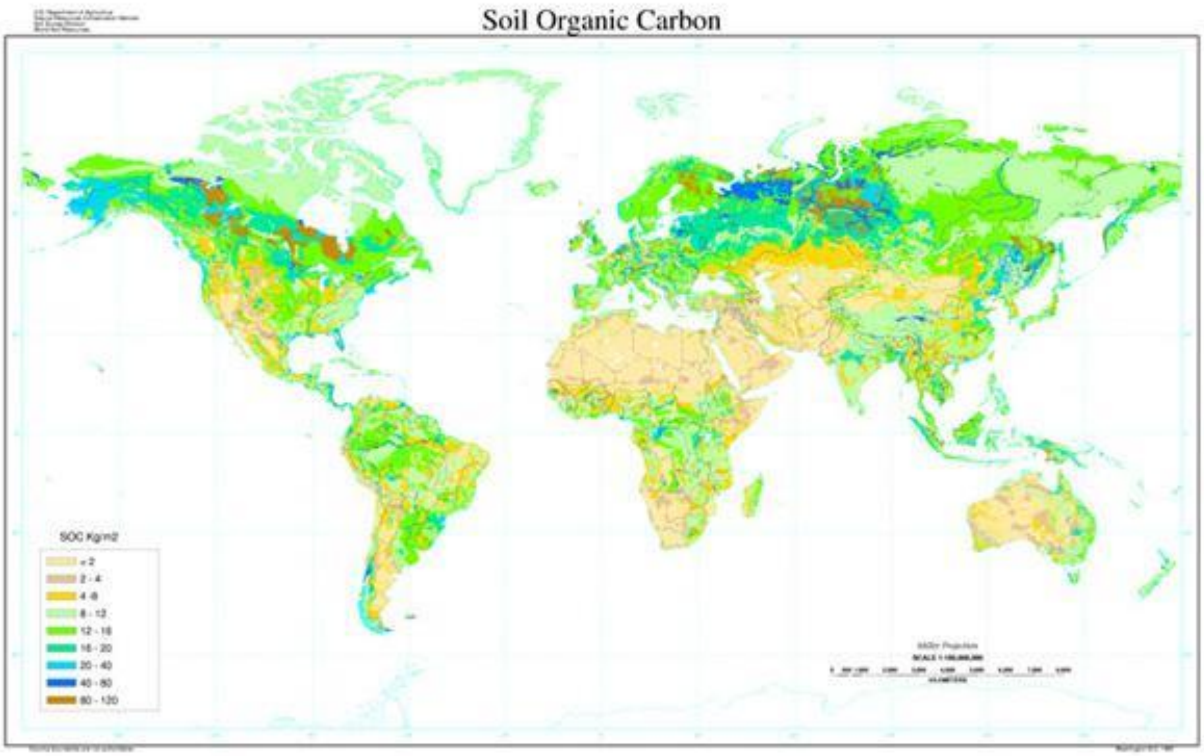

Figure 6. Soil Carbon Levels up to 1 meter depth. From USDA Natural Resources Conservation Service Soils[36]. 1 Kg/m^2 is equal to 10 t/ha.

[36] https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/use/?cid=nrcs142p2_054018

Carbon Sequestration and Allocation

Forests are capable of sequestering large amount of atmospheric carbon dioxide as above- and below-ground biomass by means of photosynthesis[37]. Carbon is assimilated in tree foliage to complex carbon-rich compounds such as glucose, cellulose, hemicellulose, starch and lignin and transported to all extremities of the tree for dissimilation to produce energy and for growth.

Much of the carbon captured from the atmosphere is, however, not sequestered for long periods of time. Firstly, a large part of captured carbon is almost immediately returned to the atmosphere due to autotrophic respiration. Additionally, some carbon will be lost as heterotrophic respiration when consumers eat parts of the tree. Secondly, carbon is sequestered in the stem, branches, leaves, fruits and roots but this carbon is only stored until trees are logged, burned in wildfires or the tree decomposes after death. Some of this carbon will remain in the soil, however, due to partial decomposition of detritus from litterfall and the root system, forming the humus layer.

Very important for the sequestration of carbon in soils for long terms, complex mycorrhizal interactions, which are found in over 90% of plant species, cause for an exchange of nutrients and minerals with symbiotic fungi[38]. Mycorrhizal symbiosis has even been identified as one of the most important global predictors of below-ground carbon storage, more than net primary production (NPP), temperature, precipitation and soil clay content[39]. While many fungal species are net contributors to the emission of carbon dioxide to the atmosphere, as they act as decomposers of organic matter, some mycorrhizal fungi are able to sequester carbon in the soil[40,41]. Moreover, plants and trees that have been colonized by these types of fungi have been found to grow faster[42]. A portion of the tree's sequestered carbon is allocated to the hyphae - the fine filamentous roots - of the mycorrhizal fungi, and may in this way be deposited to the soil where it is decomposed by micro-organisms. This humic carbon may consist of remnants from cell walls such a chitin, polysaccharides or other complex and random carbon compounds. Since these compounds can vary widely in composition, they are not easily targeted by decomposing microbes - thus remaining in the soil for years[43]. In recent years, it has become clear that it is in fact this symbiosis that sequesters carbon for long periods of time - decades to decennia. It has recently been shown that at least 50%-70% of accumulated carbon content in humus in boreal forests is derived from below-ground root inputs rather than from above-ground litter fall[44].

Carbon Sequestration Potential

The sequestration and allocation of carbon in tree systems is a complex issue and the subject of

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[37] UNWIN, Gregory Leonard, et al. Principles and processes of carbon sequestration by trees. *Technical Paper-Research and Development Division, State Forests of New South Wales*, 2000, 64.

[38] WANG, B.; QIU, Y.-L. Phylogenetic distribution and evolution of mycorrhizas in land plants. *Mycorrhiza*, 2006, 16.5: 299-363.

[39] AVERILL, Colin; TURNER, Benjamin L.; FINZI, Adrien C. Mycorrhiza-mediated competition between plants and decomposers drives soil carbon storage. *Nature*, 2014, 505.7484: 543-545.

[40] TRESEDER, Kathleen K.; HOLDEN, Sandra R. Fungal carbon sequestration. *Science*, 2013, 339.6127: 1528-1529.

[41] MOHAN, Jacqueline E., et al. Mycorrhizal fungi mediation of terrestrial ecosystem responses to global change: mini-review. *Fungal Ecology*, 2014, 10: 3-19.

[42] HOEKSEMA, Jason D., et al. A meta-analysis of context-dependency in plant response to inoculation with mycorrhizal fungi. *Ecology letters*, 2010, 13.3: 394-407.

[43] ALLISON, Steven D. Brown ground: a soil carbon analogue for the green world hypothesis?. *The American Naturalist*, 2006, 167.5: 619-627.

[44] CLEMMENSEN, K. E., et al. Roots and associated fungi drive long-term carbon sequestration in boreal forest. *Science*, 2013, 339.6127: 1615-1618.

continuous research[45]. It is dependent on many factors such as plant species, soil type, nutrient supply, temperature, and mycorrhizal activity. A 1999 study on tropical, temporal and boreal forests found that respectively 45%, 48% and 52% of the gross carbon captured by photosynthesis from tree foliage is distributed to the root system[46]. The remaining carbon is lost as respiration or allocated to above-ground biomass. However, it is important to note that not all of this carbon in sequestered in the roots and turned into SOC when the tree dies. The built-up of soil is a slow process compared to biomass as micro-organisms can decompose a large part of the carbon contained in the soil. Some practices such as no tillage and mulching of branches have been shown to positively influence SOC built-up[47].

Reforestation of degraded farmland and/or wasteland increases the carbon pool in the above-ground biomass and replenishes the soil carbon pool. Until the soil reaches a new equilibrium between the input of carbon through litterfall and root growth and the output of carbon through respiration the carbon stock accumulates. This equilibrium depends on various factors including the input of organic material and the rate of decomposition, but also mineralization[48]. There is however ongoing debate whether soils, even in old forests, are really in equilibrium as is often assumed in soil equilibrium models, and there is evidence that shows that SOC builds up beyond what those models predict[49].

The average rate of soil carbon sequestration is 0.3 tC/ha/yr[50]. Contrarily, observed rates of SOC sequestration in agricultural and restored ecosystems range from 0 to 0.15 tC/ha/year in dry and warm regions[51], and 0.1 to 1 tC/ha/year in humid and cool climates[52]. Due to tilling of the land, SOC will not accumulate on long time-scales in agricultural systems. Agroforestry systems, where there is no or hardly any tilling of the soil, can therefore steadily accumulate SOC over time. On average, reforestation increases the total carbon stock by 18%, but is dependent on location, method of farming, growth rate and tree species, amongst others. For agroforestry systems other than reforestation, such as extensive tree-intercropping systems of (semi)-arid lands and species-intensive multistrata shaded perennial systems, the suggested ranges of carbon sequestration reach from 0.05 to 0.01 tC/ha/yr to 0.0.25 tC/ha/yr, respectively[53]. This also stresses the need for adaptation of reforestation and afforestation practices.

Recently, a study using *Jatropha curcas* as carbon farming plantations, by Becker *et al.*, found that those bushes could capture 17-25 tonnes of carbon dioxide per hectare per year[54]. This

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[45] NAIR, PK Ramachandran, et al. Soil carbon sequestration in tropical agroforestry systems: a feasibility appraisal. *environmental science & policy*, 2009, 12.8: 1099-1111

[46] MALHI, Y.; BALDOCCHI, D. D.; JARVIS, P. G. The carbon balance of tropical, temperate and boreal forests. *Plant, Cell & Environment*, 1999, 22.6: 715-740.

[47] HAVLIN, J. L., et al. Crop rotation and tillage effects on soil organic carbon and nitrogen. *Soil Science Society of America Journal*, 1990, 54.2: 448-452.

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[49] WUTZLER, T.; REICHSTEIN, M. Soils apart from equilibrium? consequences for soil carbon balance modelling. *Biogeosciences Discussions*, 2006, 3.5: 1679-1714.

[50] JANDL, Robert, et al. How strongly can forest management influence soil carbon sequestration?. *Geoderma*, 2007, 137.3: 253-268.

[51] ARMSTRONG, R. D., et al. Using zero tillage, fertilisers and legume rotations to maintain productivity and soil fertility in opportunity cropping systems on a shallow Vertosol. *Animal Production Science*, 2003, 43.2: 141-153.

[52] LAL, Rattan. Soil carbon sequestration impacts on global climate change and food security. *Science*, 2004, 304.5677: 1623-1627

[53] NAIR, PK Ramachandran, et al. Soil carbon sequestration in tropical agroforestry systems: a feasibility appraisal. *environmental science & policy*, 2009, 12.8: 1099-1111.

[54] BECKER, Klaus, et al. Carbon farming in hot, dry coastal areas: an option for climate change mitigation. *Earth*

was based on the observation that a hectare of dry, coastal land planted with approximately one thousand bushes would acquire 180 tonnes of total dry above-ground biomass over 20 years, excluding fruits and litter. Given that approximately half of the total biomass of these trees consist of carbon, this amounts to a net carbon sequestration of 5-7 tonnes per hectare per year (mass of CO_2 = 3.67 * mass of C). This estimation did not take into account the possible sequestration of carbon in the soil.

Indeed, this corresponds well with what other research has found. Other studies on perennial desert trees, found similar sequestration rates between 2.5-12 tC/ha/yr[55]. A study on maturing pines found a sequestration rate of 3-4.5 tC/ha/yr[56]. Montagini *et. al.* reported biomass growth in agroforestry systems at rate between 3-7 tC/ha/yr[57]. A study on poplar plantations found a sequestration rate of 5-7 tC/ha/yr[58]. Kongsager *et. al.* studied the rate of carbon uptake in cocoa, orange, rubber and oil palm plantations and reported rate of 2-5 tC/ha/yr, depending on species and age[59]. Lastly, Klein and Hoch reported a biomass increase of about 4 tC/ha/yr in *pinus halipensis* samples in a semi-arid forest[60].

From this evidence, we conclude that about 4 tC/ha/yr (equivalent to 15 tCO_2/ha/yr) should, on average, be a reasonable and attainable sequestration rate. The studies on sequestration potential point towards the ability of forest systems to acquire on average this amount in above-ground biomass. The accumulation of SOC is a less rapid process with a median reported sequestration rate of about 0.3 tC/ha/yr. The process of reducing the concentration of atmospheric carbon should therefore be a combination of large-scale reforestation, thereby mitigating (at least partially) the amount of annual carbon dioxide input, together with a gradual increase in SOC, sequestering carbon from the atmosphere over long periods of time. Reforestation of the 3.5 billion hectares of degraded, and otherwise useless, land would then result, even at the lowest observed sequestration rate of 2 tC/ha/yr, in a full compensation of the annual increase in atmospheric carbon of 3.8 Gt, though aforementioned considerations must be kept in mind. Moreover, 1 Gt of carbon per year will be built up as SOC, restoring ecosystem function and soil quality. Above-mentioned papers also stress the need for the afforestation of perennial trees rather than annual plants. Many annual crops, such as maize, can capture more carbon than forest systems, but they are harvested and their biomass usually decomposes very rapidly, effectively returning this sequestered carbon back to the atmosphere[61]. Hence they are useless for mitigation of carbon emissions.

Some critics have argued that the introduction of such a carbon sink would not be enough to stabilize the mixing ratio of carbon dioxide at current levels[62]. Heimann, in his critique, argues

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System Dynamics, 2013, 4.2: 237-251.

55 MAGNUSSEN, Steen; REED, David. Modeling for estimation and monitoring. *Knowledge reference for national forest assessments*, 2004, 111.

56 OREN, Ram, et al. Soil fertility limits carbon sequestration by forest ecosystems in a CO2-enriched atmosphere. *Nature*, 2001, 411.6836: 469-472.

57 MONTAGNINI, Florencia; NAIR, P. K. R. Carbon sequestration: an underexploited environmental benefit of agroforestry systems. *Agroforestry systems*, 2004, 61.1-3: 281-295.

58 FANG, Shengzuo; XUE, Jianghui; TANG, Luozhong. Biomass production and carbon sequestration potential in poplar plantations with different management patterns. *Journal of environmental management*, 2007, 85.3: 672-679.

59 KONGSAGER, Rico; NAPIER, Jonas; MERTZ, Ole. The carbon sequestration potential of tree crop plantations. *Mitigation and Adaptation Strategies for Global Change*, 2013, 18.8: 1197-1213.

60 KLEIN, Tamir; HOCH, Günter. Tree carbon allocation dynamics determined using a carbon mass balance approach. *New Phytologist*, 2015, 205.1: 147-159.

61 LIGUORI, GIORGIA; GUGLIUZZA, GIOVANNI; INGLESE, PAOLO. Evaluating carbon fluxes in orange orchards in relation to planting density. *The Journal of Agricultural Science*, 2009, 147.06: 637-645.

62 HEIMANN, Martin. Comment on “Carbon farming in hot, dry coastal areas: an option for climate change mitigation” by Becker et al.(2013). *Earth System Dynamics*, 2014, 5: 41-42.

that this carbon sink would not stabilize atmospheric carbon dioxide concentration as is not taking into account the more complex dynamics of the carbon cycle. This means that, although a large (>10 Gt/yr) carbon sink would reduce the atmospheric growth rate, a far larger amount of carbon is needed to stabilize the carbon level in the atmosphere. The well-established Bern model used by the International Panel for Climate Change (IPCC) shows that a reduction of the total emissions of 75% is needed over 20 years.

It is indeed true, as other modern climate models also show (for example from US Climate Change Science Program) that the introduction of such a carbon sink would cause a decline in the increase of the atmospheric carbon fraction but is ultimately not sufficient to stabilize the carbon concentration[63]. This is especially true in the most pessimistic models, where the predicted annual carbon emission levels rises to 30 GtC/yr (110 $GtCO_2$/yr) by the year 2100 (figure 7b). As can be seen in figure 7b, there will be a delay in the rise of carbon dioxide concentrations over the next 80 years compared to the business-as-usual projections (i.e. doing nothing at all, figure 7a), but ultimately the concentration will rise again, if nothing is done about the emissions. Even if we stabilize the carbon emissions at current levels (figure 7c) but do not introduce an additional global carbon pool, the atmospheric carbon concentration will rise significantly in the coming century.

If we can however, and stabilize our carbon output to about 15 GtC/yr by 2100, and introduce a 10 GtC/yr carbon sink, than that would indeed slow the atmospheric carbon growth rate to zero, stabilizing at around 400-410 ppm[64] (figure 7d). Although it may not be sufficient to reduce atmospheric carbon dioxide, in our view, and that of others, carbon sequestration by geoscale agroforestry is currently the only viable way to mitigate the amount of emissions[65].

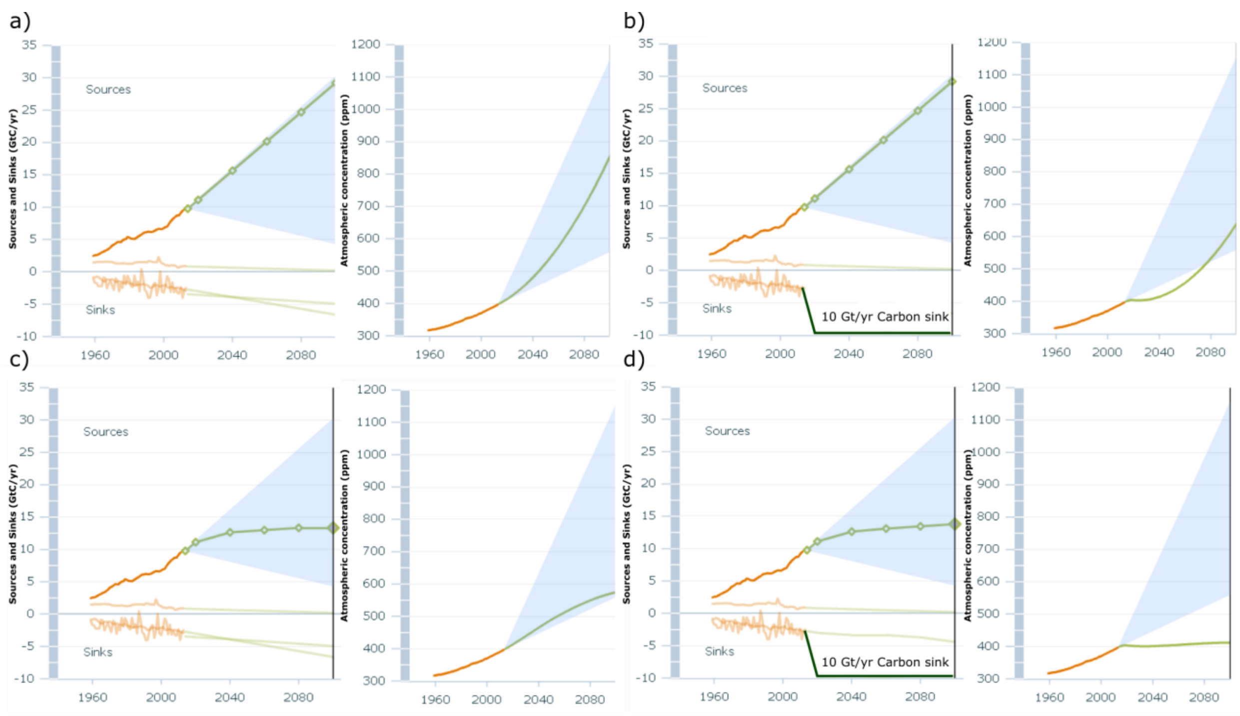

Figure 7. Projections (left panels) and outcomes (right panels) of various carbon dioxide concentration scenarios.

[63] FLUX, CARBON; YEAR, IN GIGATONS PER. Carbon sequestration to mitigate climate change. 2008.

[64] http://carboncycle.aos.wisc.edu/carbon-budget-tool/

[65] RAMACHANDRAN NAIR, P. K.; MOHAN KUMAR, B.; NAIR, Vimala D. Agroforestry as a strategy for carbon sequestration. *Journal of plant nutrition and soil science*, 2009, 172.1: 10-23.

Orange lines represent measured data, light blue planes show the range of predictions, light green lines represent projections of carbon emissions (left panels) and outcomes for CO_2 concentrations (right panels), dark green lines represent the introduction of a large carbon sink. a) If emissions continue to rise and no preventive measures are taken. b) If emissions continue to rise and a 10 Gt/yr carbon sink is introduced. c) If carbon emissions stabilize and no extra carbon sink is introduced. d) If emissions are stabilized and a 10 Gt/yr carbon sink is introduced. Based on a model by prof. G.A. McKinsley[66].

Lastly, recent studies have shown a pause in the increased growth rate of carbon dioxide, even though anthropogenic emissions are ever-increasing, remaining at 2 ppm/yr[67]. This is due to increased uptake of carbon dioxide from terrestrial ecosystems, i.e. forests, and oceans, effectively enhancing the carbon sink. A change in the net residual terrestrial carbon sink, which is the net capture of carbon in the terrestrial biosphere after accounting for effects of land-use change, can affect the amount of anthropogenic emissions in the atmosphere and thus the annual growth rate of atmospheric carbon dioxide. The increased uptake of carbon dioxide by forests is two-fold. Firstly, there is a widely-reported increase in plant growth due to an increase in carbon dioxide levels, called the CO_2 fertilization effect[68]. The effect of CO_2 fertilization has even caused a doubling in carbon uptake in the last fifty years (from 1-2 GtC/yr to 2-4 GtC/yr). Secondly, global temperatures over vegetated land have not been increasing as fast in the last decade as before. This slowdown in global terrestrial warming has led to a slowdown in global ecosystem respiration. Therefore, since gross primary production in plants has been increasing due to carbon dioxide fertilization and ecosystem respiration has been slowing, this resulted in an increase of the net primary production of the terrestrial biosphere. Additionally, the warming that has occurred has expanded the growing season, adding to the effect of increased growth.

Conclusion

The solution to the world's carbon crisis is two-sided. There is a widely-held view that carbon sequestration is an absolutely necessary component in resolving global warming and thus climate change. Stabilizing or even reducing our carbon emissions is another major objective in this fight. It will not be possible to either stabilize or reduce the carbon fraction in the atmosphere if carbon emissions rise with current trends, associated with the rise in global population. It will also not be possible to stabilize or reduce our carbon emissions by only using replacement and reduction exercises without technological breakthroughs. The introduction of a large additional carbon sink can help to neutralize the excess carbon dioxide emissions. If we can stabilize the growth rate at the current level of 35 $GtCO_2$/yr, we would still see an annual increase in the carbon dioxide concentration of 2 ppm/yr, it will just not be an accelerated increase. To actually stabilize the carbon concentration in the atmosphere, meaning no annual increase, we must also sequester as much carbon from the atmosphere as we emit. These two components go hand in hand.

In our opinion, replantation of forests on difficult to access arid and degraded land and agroforestry on arid and degraded farmlands are the prime candidates for large-scale carbon sequestration, especially since other carbon capture technologies are largely still in their infancy and time is of the essence[69,70]. Our research shows that reforestation of 3.5 billion hectares of

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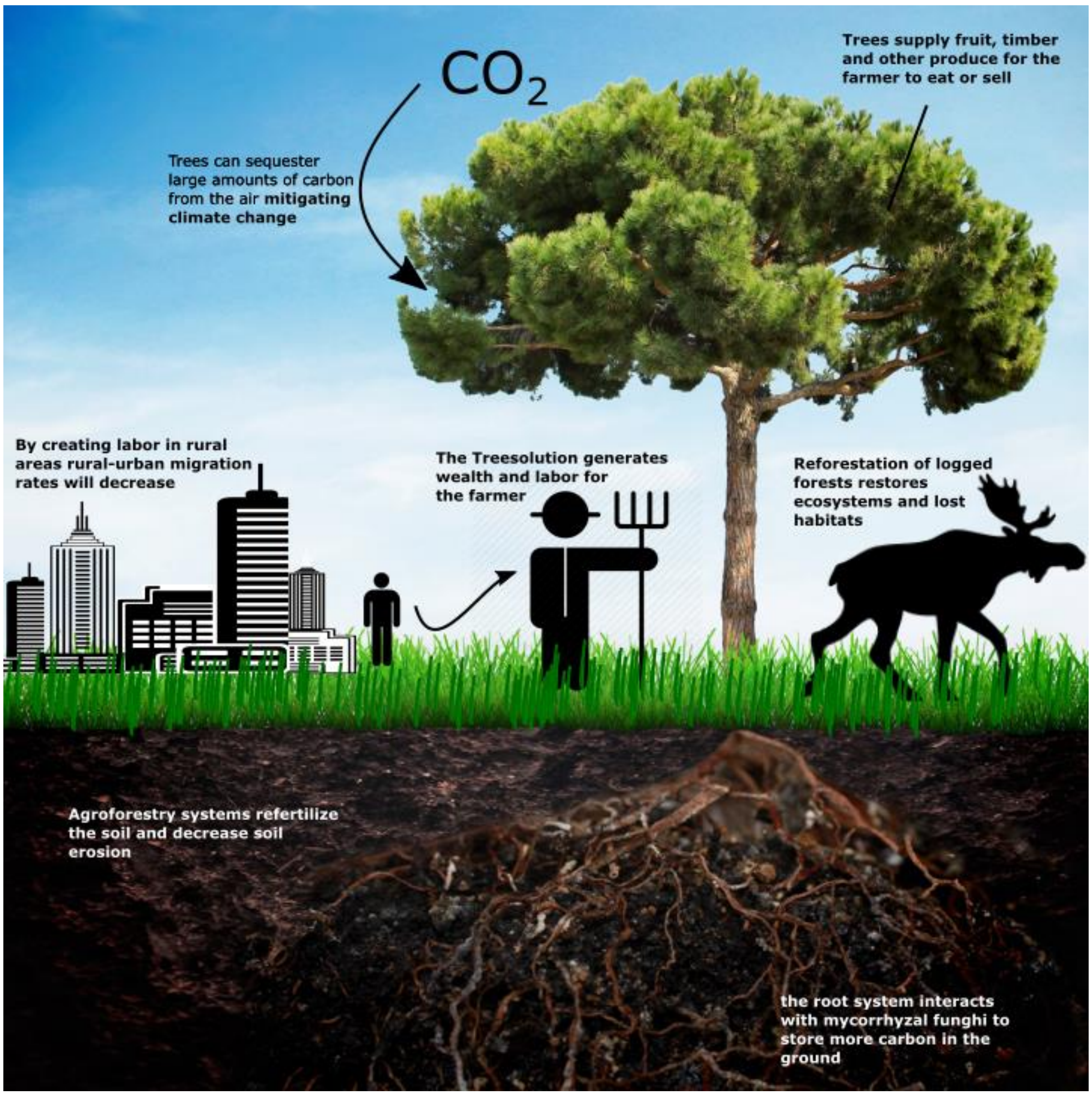
[66] http://carboncycle.aos.wisc.edu/carbon-budget-tool/

[67] KEENAN, T., et. al. Recent pause in the growth rate of atmospheric CO_2 due to enhanced terrestrial carbon uptake, *Nature Communications,* 2016, 7: 1-9

[68] DONOHUE, Randall J., et al. Impact of CO2 fertilization on maximum foliage cover across the globe's warm, arid environments. *Geophysical Research Letters*, 2013, 40.12: 3031-3035.

[69] BOOT-HANDFORD, Matthew E., et al. Carbon capture and storage update. *Energy & Environmental Science*, 2014, 7.1: 130-189.

degraded lands with perennial, deep-root desert trees has the potential to store at least 7 GtC/yr, and tentatively 14 GtC/yr, as biomass and approximately 1 GtC/yr as soil organic carbon, thus restoring soil quality and fertility. This is enough sequestration potential to offset the current carbon emissions at the low end and, at the high end, should even be enough to reduce the net atmospheric carbon concentration if emissions are stabilized. Moreover, reforestation promises a range of other greatly beneficial aspects such as ecosystem and habitat restoration, increased soil fertility and ground-water levels, reduced soil erosion and economic benefits including food security and labor for impoverished people. The Treesolution, as defined by Pieter Hoff, is therefore an essential CO_2 mitigating methodology that at the same time is able to create wealth.



The Treesolution

[70] MCGLASHAN, Niall, et al. High-level techno-economic assessment of negative emissions technologies. *Process Safety and Environmental Protection*, 2012, 90.6: 501-510.