Carbon Cycle

Anthropogenic Activities Resulting in its Non-Sustainable State, Resilience Measure towards Restoration

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Abstract: Carbon cycle is one of the most important Biogeochemical Cycle on earth. It is the basic element of all life forms on earth. Human activities have a tremendous impact on the carbon cycle. Burning fossil fuels, changing land use, and using limestone to make concrete all transfer significant quantities of carbon into the atmosphere. Carbon in the atmosphere combines with oxygen to become carbon dioxide, which is a greenhouse gas. Greenhouse gases absorb and then re-emit energy back to the Earth. The more carbon dioxide there is in the air, the warmer the temperatures on land and in the oceans. As a result, the amount of carbon dioxide in the atmosphere is rapidly rising; it is already greater than at any time in the last 3.6 million years. Scientists believe this warming is responsible for increasingly destructive storms, desertification, and rising sea levels. In this paper various aspects of carbon cycle is discussed and a sustainable resilient approach is proposed to reverse the carbon cycle to the safest reservoir of carbon i.e. land.

Keywords: Carbon Cycle, Deforestation, Global Warming, Carbon Fertilizer, Carbon Capture Storage, Geological Sequestration, Biological Sequestration, Rewilding

Introduction: According to Irish scientist John Tyndall “Thus the atmosphere admits of the entrance of the solar heat; but checks its exit, and the result is a tendency to accumulate heat at the surface of the planet.” He stated that any change in the amount of water vapour or carbon dioxide in the atmosphere could change the climate. His work therefore set a foundation for our understanding of climate change and meteorology.

The amount of carbon in the Earth and its atmosphere is constant. Like all elements, it’s neither created nor destroyed. Similar to Hydrological cycle, the carbon cycle is another cycle which circulates within Earth’s systems. Carbon moves between different spheres on planet Earth, these spheres include the atmosphere, the biosphere, the lithosphere, the hydrosphere and the cryosphere. Though oceanic carbon sink is having 50 times more reserve of CO_2 than atmospheric sink, but for human sustainability atmospheric sink plays a major role.

When carbon is held in these spheres we consider them to be carbon pools, also called stocks or reservoirs because they act as storage houses for large amounts of carbon. Net Carbon sinks are those pools where more carbon is added than leaves. Net carbon sources are those pools where more carbon leaves than is added.

Carbon Sink = Inputs of carbon $>$ Outputs of carbon

Carbon source = Inputs of carbon

Any movement of carbon between the reservoirs is called a flux. These fluxes vary in timescale from seconds to thousands of years. They can also result in feedback loops just like within the water cycle. If all sources are equal to all sinks, the carbon cycle can be said to be in dynamic equilibrium or in balance and there is no change in the size of the pools over time.

For example, over long periods of geologic time carbon dioxide returns to the atmosphere by decomposition of limestones sub ducted to the Earth's deep interior, releasing the carbon dioxide through gases dissolved in magmas that rise to the surface. Tectonic uplifting of carbonate rocks also causes them to be exposed to the atmosphere. Weathering processes release the trapped carbon, which can then pass into the oceans within precipitation. This carbon can then be taken up by sea creatures who use it in their shells. Their shells sink to the ocean bed upon death and are compressed into calcium carbonate rocks and the cycle begins again.

Store of Carbon	% of total carbon	Forms of carbon
Lithosphere	99.985	Sedimentary rocks like limestone Organic carbon Hydrocarbons such as fossil fuels Marine sediments
Hydrosphere	0.0076	Carbonate ions Bicarbonate ions Dissolved CO_2
Pedosphere (soils)	0.0031	Soil organisms Plant remains
Cryosphere	0.0018	Frozen mosses Methyl clathrates
Atmosphere	0.0015	Gaseous carbon
Biosphere	0.0012	Living plants and animals

Table 1: Global Carbon Reserve *Source: IPCC Report*

Literature Review:

Major Stores of Carbon: The quantities of carbon in the Earth's major carbon pools can be enormous, the United Nations Intergovernmental Panel on Climate Change, IPCC use Gigatonnes of carbon dioxide equivalent GtC to measure the stores of carbon. One GtC is a billion tonnes and can also be referred to as a Petagram.

The Atmosphere and Carbon: The atmosphere is a small store of carbon relative to the other stores. It contains approximately 750 GtC, the majority of which is in the form of CO_2, with much smaller amounts of methane, CH4 and various other compounds. Despite the small size of the store, carbon in the atmosphere is of great importance because of its influence on the greenhouse effect and climate. The relatively small size of the atmospheric Carbon pool also makes it more sensitive to disruptions caused by an increase in sources or sinks of Carbon from the Earth's other pools. Carbon in the atmosphere is measured in parts per million. Deforestation and fossil fuel combustion have added to this store to a great extent. As per the data revealed by the Mauna Loa Observatory atmospheric research facility the CO_2 concentrations is over 400ppm against less than 280 ppm pre industrial revolution era.

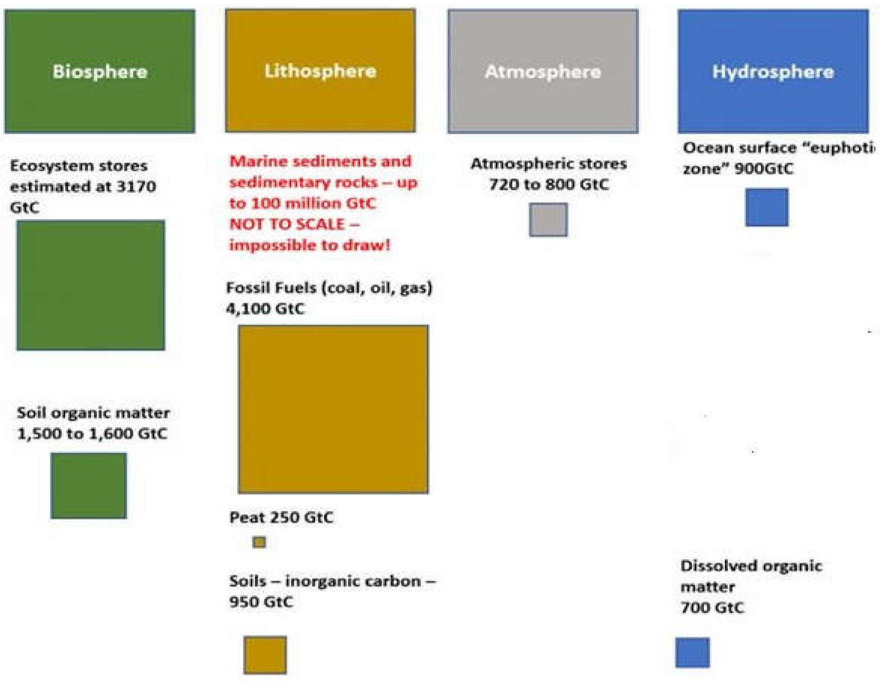

Figure 1: Earth's Carbon Reserve *Source: IPCC Data Bank*

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The carbon cycle describes the movement of carbon in its various forms between the different spheres – between the Atmosphere, Hydrosphere, Biosphere and lithosphere. It is described in the diagram above. Carbon can take many pathways through the stores and moves over different timescales. According to NASA's Earth observatory, through a series of chemical reactions and tectonic activity, carbon takes 100-200 million years to move between rocks, soil, ocean, and atmosphere in the slow carbon cycle. On average, 10–100 million metric tons of carbon move through the slow carbon cycle every year.

For example, carbon can end up in the atmosphere from many other sources. Carbon can arrive from erupting volcanoes, decaying vegetative matter, respiration from the biosphere and oceans, weathering of rocks and the burning of fossil fuels. However, carbon can leave the atmosphere in many ways too. It can enter the oceans via diffusion and the plants in the biosphere by photosynthesis.

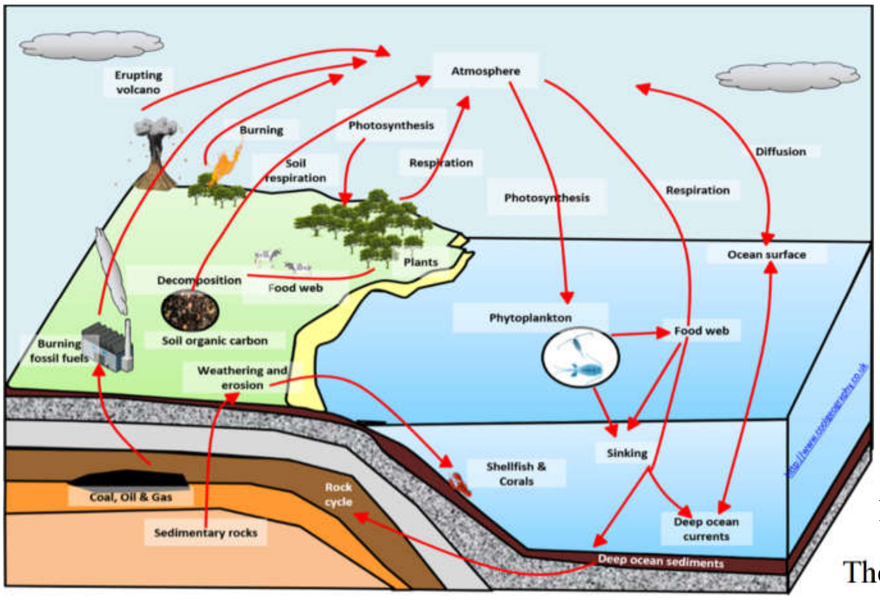

Figure 3: Earth's Carbon Dioxide Cycle *Source: FAO Data Bank*

Changes in the carbon cycle over time

Changes in the carbon cycle over time, to include natural variation, including wild fires, volcanic activity and human impact including hydrocarbon fuel extraction and burning, farming practices, deforestation, land use changes.

The Carbon cycle and the location of carbon has changed over vast periods of time. Current concentrations of CO_2 is over 409 ppm on the 15th of December 2018. This is despite the fact that for the 400,000 years prior to the industrial revolution CO_2 level never went above 300ppm. Carbon can change locations from other stores too, as climate changes the amount of vegetation can change which either locks up carbon in the biosphere or releases it. Some

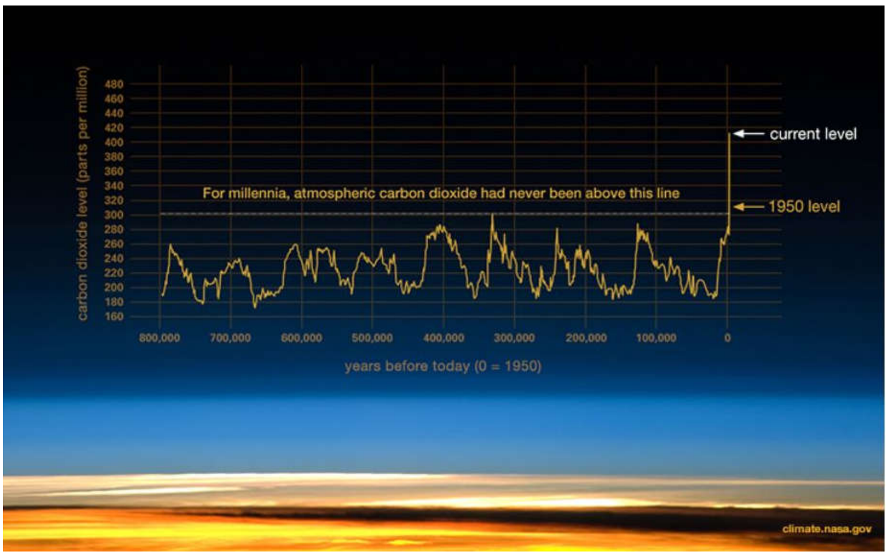

Figure 2: Atmospheric Carbon Concertation *Source: NASA-Climate.org*

carbon can be locked up over long periods of time during Geological sequestration as hydrocarbons and sedimentary rocks are formed on the sea bed only for that carbon to be released later by weathering after tectonic uplift of those rocks.

Anthropogenic changes or human factors, such as hydrocarbon fuel extraction and burning, farming practices, deforestation and land use changes that are increasingly changing the balance within the Carbon Budget.

Human Impacts on the Carbon Cycle

Farming: Agriculture or farming can have a significant impact upon the carbon budget. Farming is essential for life on earth as it provides people with the food they need, but with increasing numbers of people on the planet and modern agricultural methods the impact upon the environment can be large. Farming impacts upon the carbon budget in the following ways;

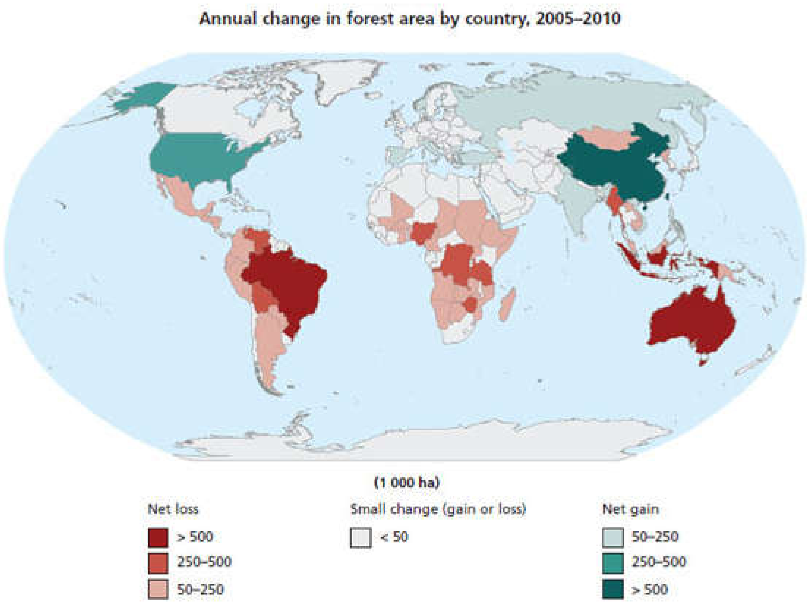

Figure 4: Global Forest Cover Loss Source: WHO/INT/GHO Databank

1. People have cleared vast areas of natural biomes and replaced them with crops and pasture. In Tropical forests the process of slash and burn releases huge amounts of stored carbon. In many European countries vast areas of deciduous forest is cleared to make way for farms.
2. Peat lands, wetlands have been drained and used for farmland. In doing so, methane is released as organic matter that was previously stored and in anaerobic conditions can now decay. There has been a huge increase in stock densities of animals such as cattle and chickens as global demand for animal products increases. These animals produce huge amounts of methane during their digestive processes and this is released into the atmosphere. Up to 60% of all agricultural emissions of carbon come from this pastoral farming. Researchers at the University of Oxford found that cutting meat and dairy products from your diet could reduce an individual's carbon footprint from food by up to 73 per cent.
3. Rice paddies produce methane. This potent greenhouse gas is emitted from flooded rice fields as bacteria in the waterlogged soil produce it in large quantities.
4. Ploughing of field releases carbon. According to the United Nations Food and Agriculture Organisation, Carbon emissions from agriculture have increased from 4.6 to 5.0 Gt CO_2 eq. in 2000, 5.3 Gt eq. in 2011, and 7.8 Gt eq. in 2019 per year, forestry and other land uses emitted 10Gt CO_2 eq. in 2010 but only stored 2Gt CO_2 eq.

Fossil fuel extraction and Burning Fossil Fuels effectively lock up carbon in the form of hydrocarbon within the lithosphere over long periods of time. Humans have been extracting hydrocarbons to produce energy and heat for centuries. The rate of extraction and burning has increased over time shifting carbon stores from the lithosphere to the atmosphere and this poses significant problems for the delicate climate balance of our planet. This is because carbon dioxide is released in the burning of hydrocarbons which contributes to climate change and global warming. The extra carbon dioxide in the air acts as a greenhouse gas and effectively traps heat within the Earth's atmosphere. Human activities are responsible for almost all of the increase in greenhouse gases in the atmosphere over the last 150 years.

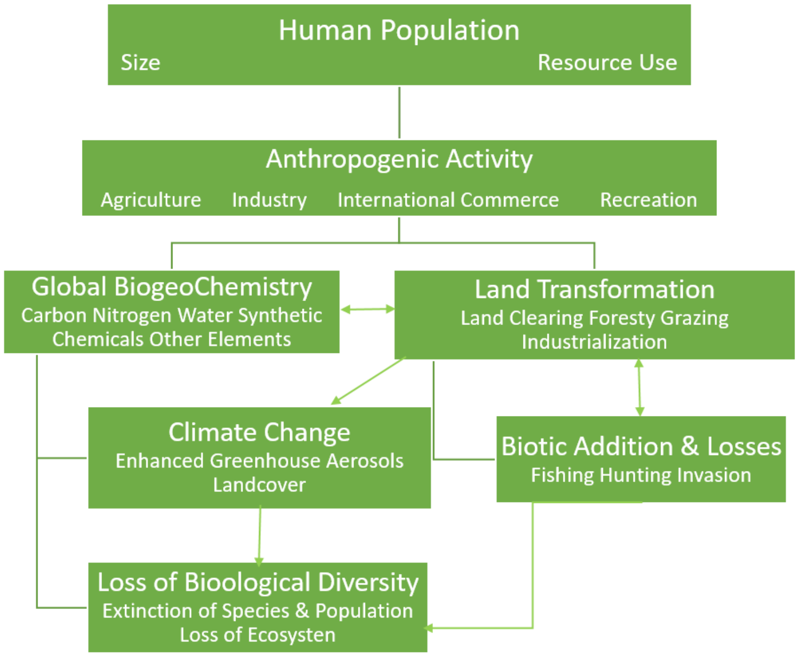

Figure 5: Human Intervention and Changes in Bio-Diversity

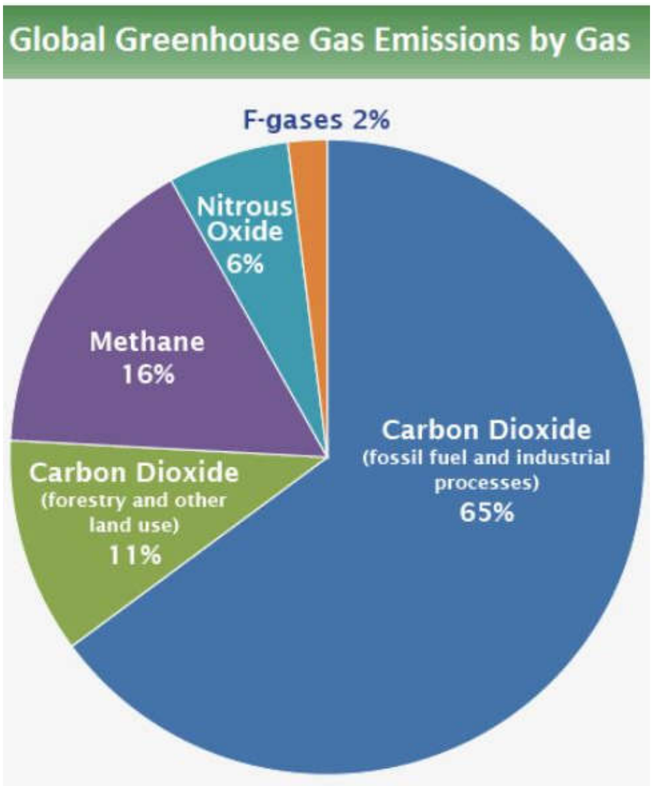

Figure 6: Global CO2 Emission Source: IPCC Data Bank

Global carbon (C) emissions from fossil fuel use were 9.795 (Gt) in 2014. Fossil fuel emissions, including cement production accounted for about 91% of total CO_2 emissions from human sources in 2014. This portion of emissions originates from coal (42%), oil (33%), and gas (19%), cement (6%) and gas flaring (1%). Countries such as China and the USA dominate CO_2 emissions from these sources.

Cement manufacture: Cement is a vital material used to bind building materials together. China alone makes and uses 45 percent of worldwide output. The manufacture of cement creates greenhouse gases both directly through the production of carbon dioxide when calcium carbonate is thermally decomposed, producing lime and carbon dioxide, and also through the use of the energy needed to make cement, particularly from the combustion of fossil fuels. Cement plants account for 5 percent of global emissions of carbon dioxide, the main cause of global warming.

Land use Changes: Changes in land use are responsible for about 9% of all global CO2 emissions.

Deforestation: Deforestation is the widespread removal of forest cover for other land uses. This happens globally and much attention is currently on tropical forests, but deciduous and boreal forests also store a lot of carbon and are used as a wood stock. In tropical regions there is particular focus because of the rates of forest clearance and the abundance of carbon stored per hectare. Similarly, small scale farmers can use a process known as slash and burn to remove an area of forest to create a small holding to be farmed by themselves and their family.

Deforestation impacts the carbon budget because of the following reason:

1. The biomass store of trees and plants is removed and replaced by something inferior in terms of carbon storage

2. Clearing forests speeds up the decay of leaf litter on the forest floor, releasing even more carbon to the atmosphere, along with burning of the same.

4. Soil carbon is exposed to the atmosphere, speeding up soil erosion, removal of carbon into the hydrosphere by rainwater and rivers and even the release of stored soil carbon through decomposition into the atmosphere.

Recall from the water cycle that this deforestation process also damages the forest water cycle and can result in these environments being significantly damaged. Some dry out so much that they are more at risk of wild fires which alters the carbon budget further.

According to carbonfootprint.com "Around 13 Million hectares of forests lost per annum between 2000 and 2010 and as well as the ecological impact, rainforest deforestation

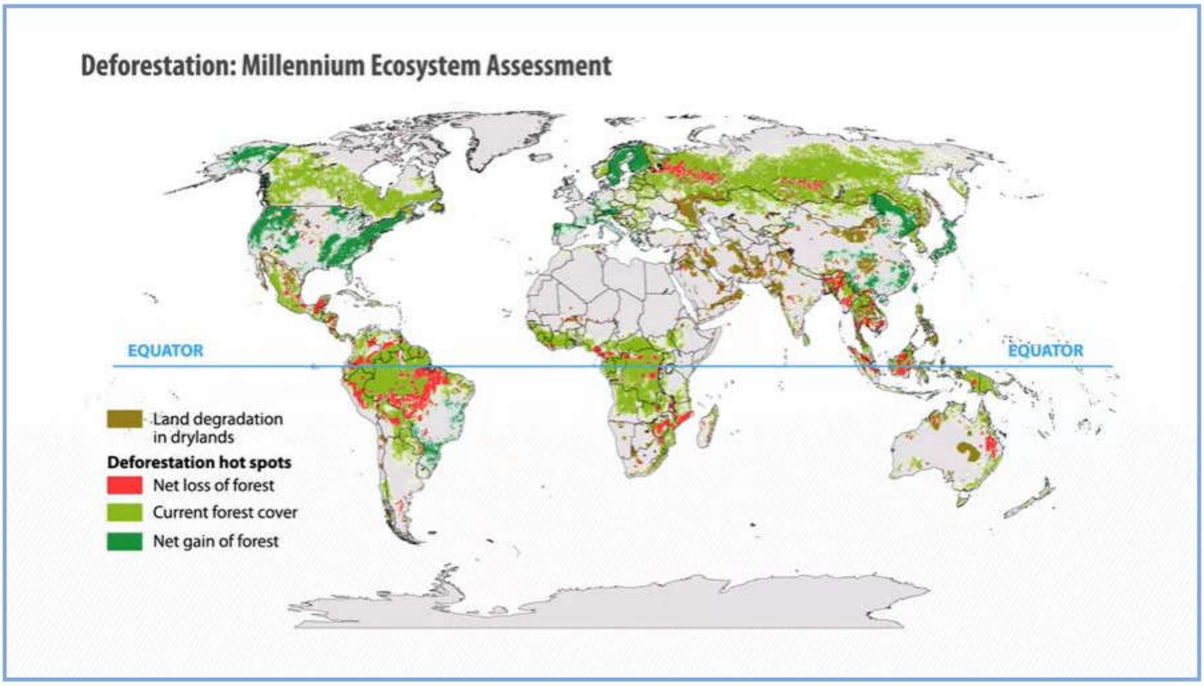

Figure 7: World's Deforestation Map *Source: WHO Data Bank*

jeopardises people's livelihoods." Deforestation accounts for a staggering 15% of Global Greenhouse Gas (GHG) emissions plus there is the loss of the carbon sink in the biosphere.

In 1990 forests made up 31.6 percent of the worlds land areas, or some 4,128 million hectares, this has changed to 30.6 percent in 2015, or some 3,999 million hectares which is following a declining trend.

Urban growth: More and more people are living in the World's urban areas. Half of the world's population lives in cities, a share that is likely to reach 70 percent in 2050. Cities are major contributors to greenhouse gas emissions. This is because;

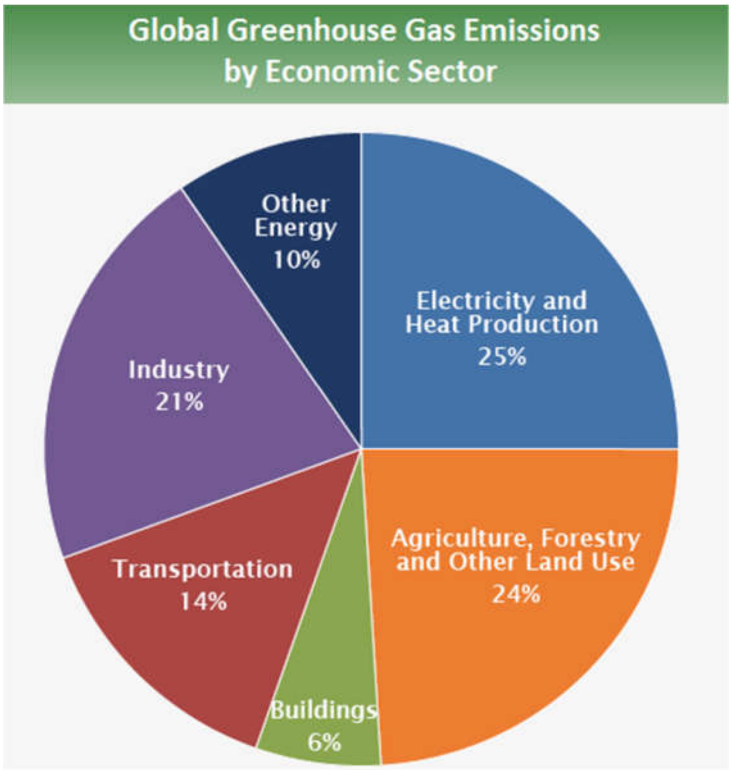

Figure 8: Global Greenhouse Gas Emission Sector Source: IPCC Data Bank

1. Cities consume as much as 80 % of energy production worldwide, due to the many industrial activities that take place within them.

2. As development proceeds, greenhouse gas emissions are driven less by industrial activities and more by the energy services required for lighting, heating, and cooling.

3. Massive quantities of cement production which is one of the key component of urbanization contributes largely to greenhouse gas emission.

It is observed that, rich cities with higher PPP use more energy than poor cities and therefore emit more greenhouse gas emissions.

• The International Energy Agency estimates that cities in 2006 emitted 19.8 gigatonnes of CO_2 from energy use, which was 71 percent of global energy-related GHG emissions.

• By 2030, this number is expected to increase to 30.8 Gt CO_2 or 76 percent of global energy-related emissions.

• The 50 largest cities, with more than 500 million urban citizens, generate about 2.6 GtC of CO_2 equivalent GHG emissions, more than all countries apart from the United States and China.

Carbon Budget & Impacts of Carbon Cycle

The carbon budget and the impact of the carbon cycle upon land, ocean and atmosphere, including global climate.

Population (millions)	GHG emissions (million tCO_2e)	GDP (billion US$ PPP)
1. China: 1,192	1. United States: 7,107	1. United States: 14,202
2. India: 916	2. China: 4,058	2. 50 Largest Cities: 9,564
3. 50 Largest Cities: 500	3. 50 Largest Cities: 2,606	3. C40 Cities: 8,781
4. C40 Cities: 393	4. C40 Cities: 2,364	4. China: 7,903
5. United States: 301	5. Russian Federation: 2,193	5. Japan: 4,354
6. Indonesia: 190	6. Japan: 1,374	6. Top 10 GHG Cities: 4,313
7. Brazil: 159	7. Top 10 GHG Cities: 1,367	7. India: 3,388
8. Russian Federation: 142	8. India: 1,214	8. Germany: 2,925
9. Top 10 GHG Cities: 136	9. Germany: 956	9. Russian Federation: 2,288
10. Japan: 128	10. Canada: 747	10. United Kingdom: 2,176

Table 2: World's Carbon Budget *Source: World Bank Data*

The Carbon Budget: A budget takes into account what goes into a system and what goes out. In terms of a carbon budget this would include how much carbon is emitted by various processes, such as combusting fossil fuels compared to what can be absorbed by nature or captured by people. This can be calculated using a carbon footprint calculator. Carbon footprint is defined as the total amount of greenhouse gases produced to directly and indirectly support human activities, usually expressed in equivalent tons of carbon dioxide, CO_2.

We could consider the carbon budget at various scales;

1. Individually – how much carbon is produced by our activities such as heating our home, the food we eat, how we get around, less how much carbon is absorbed by the plants in our gardens, our use of renewable energy like solar etc.

2. Businesses – Amount of carbon which is produced to run any business operation.

3. Nations – as part of international agreements countries must consider how much carbon is produced in their country compared to how much is absorbed in biological and geologic sequestration, or captured using technology.

4. Globally – this is the scale we need to address, as the carbon system is interconnected and global, so changes to the budget in one part of the world will have impacts upon other parts of the world. Since many of the carbon emissions have occurred in wealthier countries they have a bigger impact on other countries. Many of these are human induced or anthropogenic changes resulting from human activity since the industrial revolution.

The global carbon budget and climate change: In 2015, the countries that signed the UN Framework Convention on Climate Change adopted a target to stop the average global temperature from rising before it reaches 2°C above pre-industrial levels.

This goal can be met if cumulative emissions of carbon do not exceed 1 trillion tonnes of carbon (GtC). However, out of that 1 trillion tonnes of carbon 535 GtC have already been emitted during industrial times. This leaves only 465 GtC to stay within the agreed limits.

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Many developing countries also support a reduction in the target to keep global average temperature increases below 1.5°C above pre-industrial levels.

Impact of the changing carbon budget on the land: The changing carbon budget can have significant impacts upon the land.

Carbon Fertilization: It is thought that plants on land have taken up approximately 25 percent of the carbon dioxide that humans have put into the atmosphere. Overall, the world's plants have increased the amount of carbon dioxide they absorb since 1960 although the amount they absorb varies from year to year. Only some of this increase occurred as a direct result of fossil fuel emissions.

NASA have found that increased amounts of atmospheric carbon dioxide means more carbon is available to convert to plant matter in photosynthesis. This means that plants were able to grow more. This extra growth is referred to as carbon fertilization. This extra growth is not boundless however, as plants also need water, sunlight, and nutrients, especially nitrogen. If a plant doesn't have one of these things, it won't grow regardless of how abundant the other necessities are. This means that the amount of extra carbon taken in from place to place on earth varies according not just too how much extra carbon there is but also factors such as water and nitrogen availability

Land use Decisions: Agriculture has become much more intensive, so we can grow more food on less land. In high and mid-latitudes, some abandoned farmland is reverting to forest, and these forests store much more carbon, both in wood and soil, than crops would.

In many places, we prevent plant carbon from entering the atmosphere by extinguishing wildfires. This allows leaf litter and woody material, which stores carbon to build up. All of these land use decisions are helping plants absorb human-released carbon in the Northern Hemisphere.

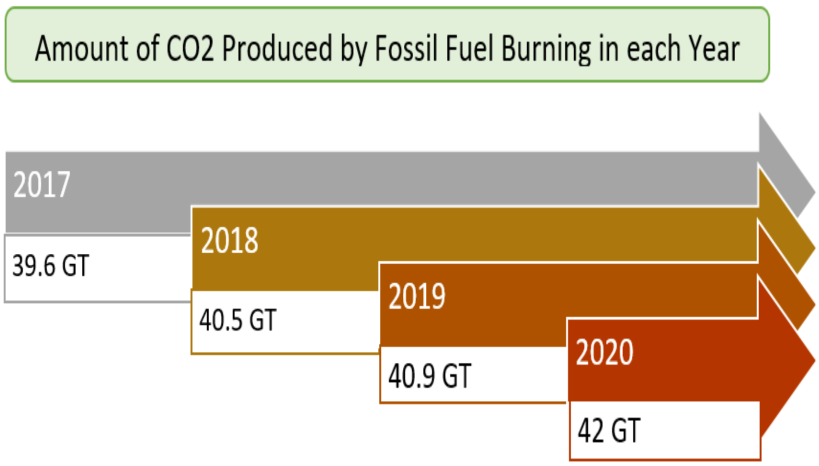

Figure 9: Amount of CO2 Produced by Burning Fossil Fuel

However, this balance could be changing as more forest fires appear to be occurring releasing this stored carbon. According to NASA "In the far north, where an increase in temperature has the greatest impact, the forests have already started to burn more, releasing carbon from the plants and the soil into the atmosphere. Tropical forests may also be extremely susceptible to drying. With less water, tropical trees slow their growth and take up less carbon, or die and release their stored carbon to the atmosphere."

In the tropics forests are being removed, often through fire via slash and burn, and this releases carbon dioxide.

Global warming and the Land: Other impacts of the global warming element of changing carbon budgets can occur and impact upon the terrestrial environment.

1. Carbon dioxide increases temperatures, extending the growing season and increasing humidity. This has led to some additional plant growth. However, warmer temperatures also stress plants. With a longer, warmer growing season, plants need more water to survive. Scientists are already seeing evidence that plants in the Northern Hemisphere slow their growth in the summer because of warm temperatures and water shortages.
2. Higher temperatures can “bake” the soil, this allows the rate at which carbon seeps out to

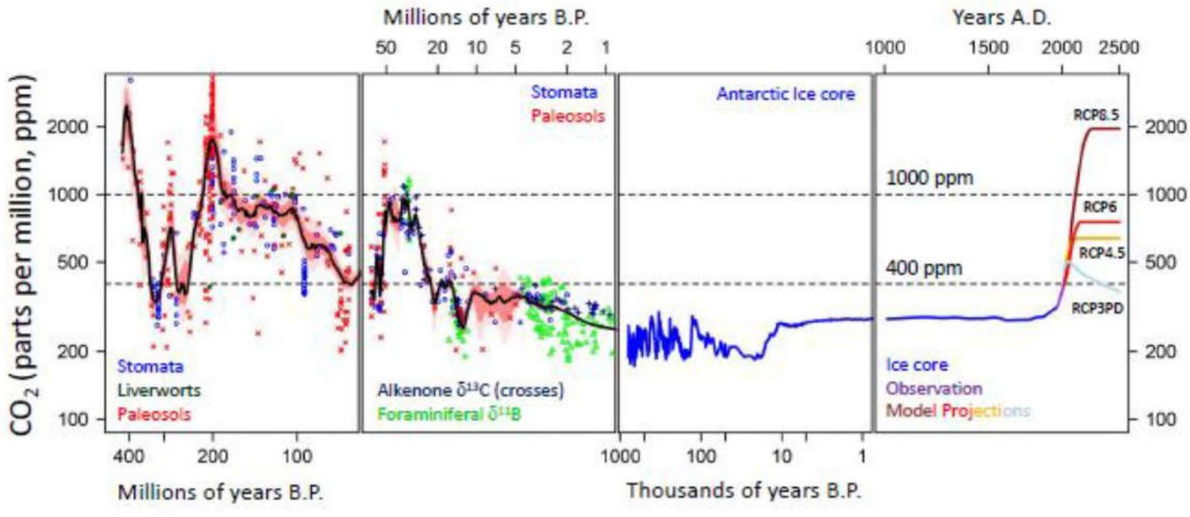

Figure 10: World's CO2 Concertation *Source: World Bank Data*

increase in some places.

3. The permanently frozen soil, the permafrost is thawing. Permafrost contains rich deposits of carbon from plant matter that has accumulated for thousands of years because the cold slows decay. When the soil warms, the organic matter decays and carbon in the form of methane and carbon dioxide seeps into the atmosphere.

Human interventions in the carbon cycle designed to influence carbon transfers and mitigate the impacts of climate change.

Mitigation: Mitigation refers to efforts to cut or prevent the emission of greenhouse gases – this would limit the magnitude of future warming. Mitigation can also include new attempts to actually remove carbon currently in the atmosphere.

Climate change adaptation is different, this is how people can manage unavoidable impacts of climate change.

Mitigation involves:

- Using new technologies
- Using clean energy sources
- Changing people's behaviour
- Making older technology more energy efficient

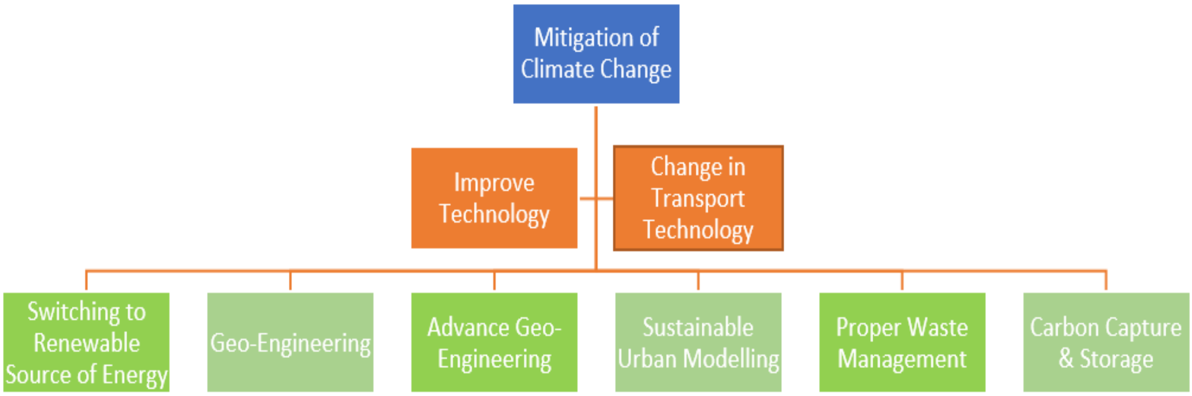

Figure 11: CO_2 Mitigation Procedure

Carbon Capture and Storage (CCS): Carbon Capture and Storage - CCS is a technology that can capture up to 90% of the carbon dioxide emissions produced in anthropogenic activities from the use of fossil fuels burning. This prevents the carbon dioxide from entering the atmosphere.

CCS involves:

1. Capture technologies allow the separation of carbon dioxide from gases produced in electricity generation and industrial processes by one of three methods: pre-combustion capture, post-combustion capture and oxy-fuel combustion.

2. Transport the CO_2 by pipeline or by ship for safe storage. Millions of tonnes of carbon dioxide are already transported annually for commercial purposes by road tanker, ship and pipelines

3. The carbon dioxide is then stored in carefully selected geological rock formation that are typically located several kilometres below the earth's surface.

Geological Sequestration

Forest Landcover Restoration Scheme	CO_2 Removal Rates Over 20 Year
Planted Forest & Woodland	4.5 to 40.7 t CO_2/ha/year
Mangrove Restoration	23.1 t CO_2/ha/year
Natural Regeneration	9.1–18.8 t CO_2/ha/year
Agroforesty	0.8 - 15.6 t CO_2/ha/year

Figure 12: Forest Land cover Restoration Scheme

New technologies are emerging to fix carbon deep under the ground in a process known as Geologic sequestration. In Iceland a new process is taking place to fix carbon in the abundant Basalt rocks there. It starts with the capture of waste CO_2 from the steam used in the geothermal power plant there, which is then dissolved into large volumes of water. The fizzy liquid is then piped to the injection site 2km away. Then it is pumped 1,000m beneath the surface. Here, chemical reactions will solidify the CO_2 into rock in a matter of months - thus preventing it from escaping back into the atmosphere for millions of years. The carbon forms calcites within the pores of the basalt rock.

Other schemes involve actually removing carbon currently in the atmosphere, using Carbon dioxide removal, CDR technologies. These include bio-energy with carbon capture and storage, biochar, ocean fertilization, enhanced weathering, and direct air capture when combined with storage.

Biological Sequestration: Biological sequestration involves the net removal of CO2 from the atmosphere by plants and micro-organisms and its storage in vegetative biomass and in soils.

This offers many potential advantages:

1. This process can sequester relatively large volumes of carbon at comparatively low cost

2. Protecting or improving soils, water resources, habitat, and biodiversity

3. It can also generate rural income

4. This promotes more sustainable agriculture and forestry practices

This means new sinks can be created, for example, afforestation or rewilding which is under taken in many parts of Europe can capture carbon.

Result & Findings:

Afforestation leading to Rewilding: It is been a worldwide question across scientist and research scholars that, how much CO_2 can be absorbed by tree, while discussing CO_2 absorption by trees, it is important to consider that elemental carbon locked within the tree differs from carbon dioxide absorbed from the atmosphere, also all trees absorb the same amount of CO_2. The quantity depends on several factors such as the height of the tree, the amount of foliage and of course the species of tree. An oak tree for example will absorb more than a cactus.

Figure 13: Futuristic Urban Plan with Urban Rewilding Scheme (Green circles represents increased intensity of Carbon absorbing tree plantation)

The average Pine tree absorbs about 10 kilograms of CO_2 per year. Assuming that the standard measurements of tree plantings are about 1000 trees can be in one hectare. If a tree absorbs 10 kg per year, the acre will absorb a total of 10,000 kg or 10 tons per year.

How many trees to offset 1 ton of CO_2

The number of trees corresponds with the type of tree and the measurement time. A Melia tree can absorb 0.04 tons daily. To absorb one ton per day, approximately 25 trees are required.In the case of the Aleppo pine, which absorbs 50 tons per year; an average of 1 ton per day requires eight trees. On average, a Pine tree can absorb 0.13 tons per day, in which case 8 trees absorb 1.04 tons/day.

The Stone Pine requires a slightly larger quantity than its colleague Aleppo. This pine can absorb an average of 27 tons per year, which leads to 0.07 tons per day. It takes 14 trees to consume approximately 1 ton.

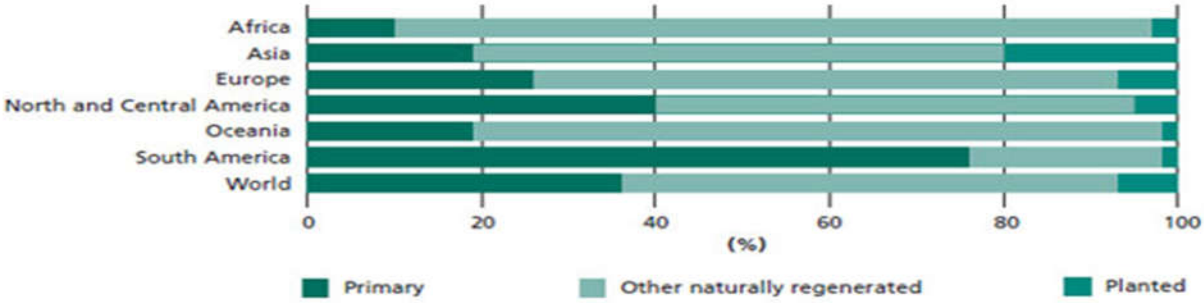

Figure 14: Afforestation drive across World *Source: United Nation & Global Engagement Data Bank*

Another wonder tree, Redwood with the highest carbon dioxide absorption capacity and it is capable of decreasing air pollution to a great extent. Studies have shown that a Redwood plantation can absorb carbon dioxide from 2,700 vehicles in a year. Apart from these, Acacia and Jacaranda also contribute largely in CO_2 absorption.

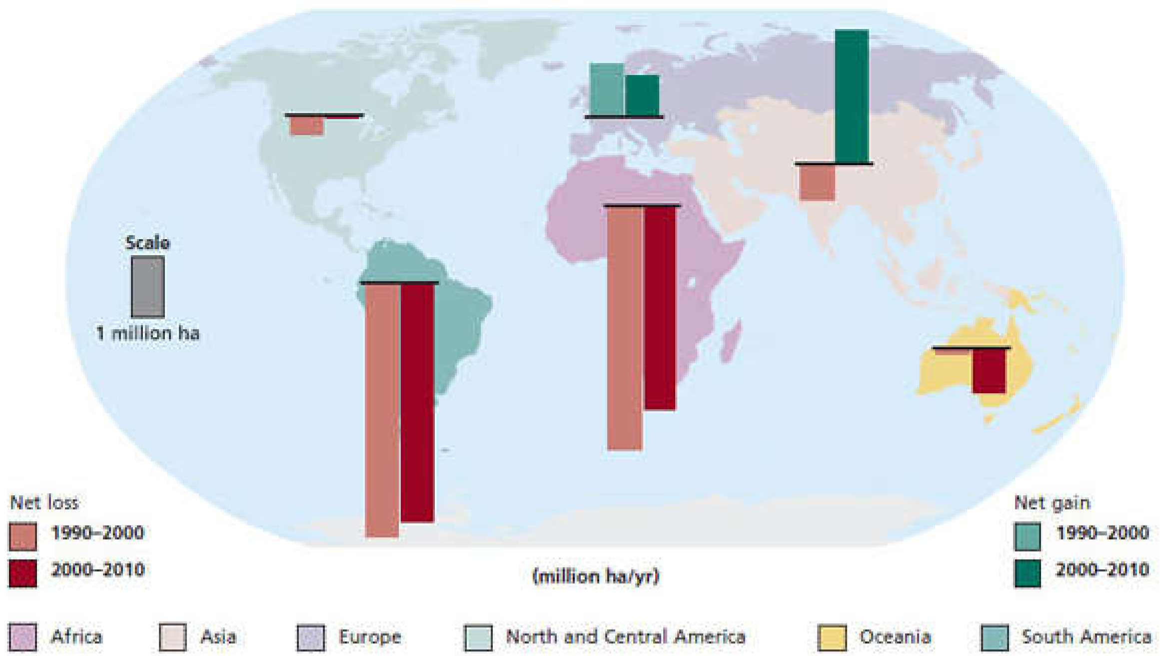

Figure 15: Afforestation Drive by China *Source: United Nation & Global Engagement Data Bank*

A massive drive of afforestation is adopted by China in which has transformed the Asia green belt to a greater extent. The figure below depicts the above statement.

Similar drive should be adopted by countries across world to make world more clean green and sustainable.

With all these literature study and analysing the inputs from rewilding scheme, a numerical illustration is proposed which is represented below:

$$\text{Carbon Sink} = \text{Carbon Source} - [\int_0^n (f(Af)dAf + Ksds)]$$

Where A_f, afforestation factor, K_{sds} various sustainable development schemes towards carbon absorption.

Conclusion: The idea behind the study is to formulate an eco-friendly measure to restrict world's average temperature below 2ºC. With all the literature review and schematic calculation towards environmental sustainability with afforestation, it is evident that the true benefits of trees and healthy forests go far beyond carbon storage. Their value for biodiversity, social impact, and the stability of the global climate for better future sustainability are well illustrated. This may also be a challenge to measure the actual balance and deficit findings for future resilient model, but at the end of the day the need to protect and restore our earth temperature, balance in carbon cycle by planting trees is essential and needs to be adopted with regulation by all countries.

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