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Research Paper

Indian Forest Carbon Stock: A Review of the Current Situation

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ABSTRACT: *Natural disasters are becoming more common each year as a result of global climate change. The increase in the emission of greenhouse gases, especially CO_2 has led to an increase in the global temperature of the atmosphere. According to Intergovernmental Panel on Climate Change, there will be an increase of 2.7-4.3°C in temperature and a 6-8% increase in rainfall in India, which is the tops one among in carbon emission. India, due to its diverse terrain is doing to face the high impact of climate change in the near future. India's carbon emission is increasing at the rate of 4.3% per year and therefore the country has to take several measures to reduce the carbon emission. Forest vegetation is one of the biggest carbon sinks after the oceans and they store about 86% of the above-ground carbon of terrestrial habitat and 73% of soil carbon of the earth. Therefore, it's very important to conserve the forest ecosystem from being getting declined, especially the natural forests. This review focuses on the biomass and carbon sequestration potential of various forest regions of India and also the carbon capture and sequestration technologies in India till now.*

KEYWORDS: *Climate change, natural disasters, natural forests, biomass, carbon capture, sequestration technologies*

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I. INTRODUCTION

Climate change is one of the serious issues that the whole world is facing by experiencing a rise in temperature, frequent droughts, change in rainfall pattern, cyclones, etc. and we have failed in reaching the global agreement in reducing greenhouse gas emissions [1]. The rise in the amount of carbon dioxide in the earth's atmosphere, which has increased by around 15-25 percent in the last 100 years, is responsible for this harmful effect of climate change [21] and [25]. From the pre-industrial period, the average CO_2 concentration in the atmosphere has increased from 280 µmol mol^{-1} to 364 µmol mol^{-1} in 1994. The current rate of CO_2 increase in the atmosphere is 1.5 µmol mol^{-1} year^{-1} [43]. As per the Global Carbon Budget projection, the global CO_2 emission by the fossils is going to increase by 0.6% in the year 2019 and is going to decline in the US and EU28, but incline in China, India and other rest of other countries in the world [36]. According to the Intergovernmental Panel on Climate Change's (IPCC) 2007 report, India's temperature would rise by 2.7-4.3°C by the 2080s, and rainfall would increase by 6-8 percent by 2100, raising the sea level by 88cm [22]. Because of its diversified topography, India will be hit hard by climate change in the foreseeable future in South Asia [32]. Heat waves, cold waves, tropical cyclones, floods, lightning, heavy rains, and other extreme weather events (EWEs) have had a major impact on various regions of the Indian subcontinent in recent decades, resulting in the loss of lives and land, as well as adversely affecting the livelihood of the vulnerable population [40]. According to the Global Climate Risk Index 2020, India is the fifth most impacted country in the world due to climate change, with strong heatwave impacts in 2018 and 2019 [16]. Between 1950 and 2017, 285 floods were reported in India, affecting 850 million people and resulting in 71,000 deaths, according to a report conducted by the Indian Institute of Tropical Meteorology in Pune [31]. Heavy floods in Mumbai in July 2005 and September 2017; Chennai in November 2015; Uttarakhand in June 2013 and Kerala in August 2018 were the worst ones in this century [2].

India had 11 of its warmest years on record since 2000 [16]. According to data from the Indian Meteorological Department, there has been a 138% rise in heatwaves, 193% increase in lightning, 25% increase in cold waves, 28% increase in flooding, and a 19% fall in tropical cyclones in the last twenty years, relative to the previous twenty years [40]. China, India and United States contribute towards half of carbon emissions in the world. India's carbon emission is increasing at the rate of 4.3% per year which is higher than China's and whereas the US's going down. Therefore, India and China will be the major source of emission of global carbon and measures should be taken by these countries to reduce carbon emission [48].

The terrestrial environment and the oceans serve as natural carbon sinks or sponges. The forest ecosystem is the most effective carbon sink in a terrestrial ecosystem, since it lowers CO_2 levels in the atmosphere during photosynthesis [47]. Tree growth is a significant source of atmospheric carbon capture and storage in vegetation, soil, and biomass materials [3]. Forests store about 86% of the above-ground carbon of terrestrial habitat and 73% of soil carbon of earth [47]. In a vegetation system, biomass stock and storage rates are essential in quantifying the system productivity and deciding the carbon sequestration rate for mitigating climate change problems [11]. Based on biomass studies completed since 2000, this paper reviews the biomass and carbon sequestration potential of forests. This review also looks at the carbon capture and sequestration technologies that have been used in India so far.

II. CARBON SEQUESTRATION IN INDIA

According to India State of Forest Report -2019 by Forest Survey of India, the total forest cover of the country is 71.22 M ha and tree cover of 9.5 M ha, thus making 80.72 M ha of total Forest and tree cover which is 24.56% of the geographical area of the country. When compared with the previous report in 2017, there is an increase of 0.56% of forest cover and 1.29% of tree cover in the country. 7,124.6 M tonnes is the total forest carbon stock in India and there is an increase of 42.6 M tonnes as compared with the previous report. Soil Organic Carbon has 56% of the total carbon stock of the forest, which is 4,004 M tonnes. The total Above Ground Biomass (AGB) was recorded to be 2256.53M tonnes and Below Ground Biomass (BGB) was 700. 82M tonnes in the year 2019 [18].

A study in 2017 showed that the AGB of the Indian forest was 2237.55M tonnes and BGB was 698.70M tonnes [17]. In a spatial forest carbon stock estimated in 2010, the forest carbon in Indian forests was found to be 4368.03 Tg C [38]. In 2004, the AGB was 2101M tonnes and BGB was 663 M tonnes. The carbon stock in 2002 was found to be 93.27 tonnes/ha. [26]. In most of the studies, it is observed that there is a significant increase in the biomass and the carbon stock in the forests of India. In a study conducted in Indian forests from 1994-2010, it was found an increase of 5.74 Mha of forest land from 63.34 Mha in 1994 to 69.08 Mha in 2010. The forest carbon was found to be 3911.78 TgC in 1994, among which 2895.28 TgC was contributed by dense forest and 1016.50 TgC by open forest. In 2010, the total carbon was found to be 4368.03 TgC where the dense forest had 3176.48 TgC and open forest had 1191.55 TgC. In 16 years an annual increment of 25.52 TgC/year of carbon content was found in the Indian forests. In state-wise analysis maximum increase of carbon content was found in Uttarakhand state (176.80 TgC) and maximum decrease in Jammu and Kashmir (110.40 TgC). In 2010, Arunachal Pradesh (695.68 TgC), Uttarakhand (373.14 TgC), Madhya Pradesh (321.67 TgC), Chhattisgarh (296.72 TgC) and Jammu and Kashmir (293.86 TgC) had highest carbon content and in 1994, Arunachal Pradesh (613.03 TgC), Jammu and Kashmir (404.26 TgC), Madhya Pradesh (338.47 TgC), Chhattisgarh (297.96 TgC) and Assam (243.39 TgC) [38].

In a study conducted in Radhanagiri WLS, the mixed moist deciduous at high elevation had the maximum biomass per hectare and minimum at a degraded shrub in both the study period (2004 and 2006). The total carbon sequestration done by all the forest types in the sanctuary was 78x 10^3 tons, with the highest in semi-evergreen forest stratum at middle elevation with $35x10^3$ tons and minimum in plantation with $0.8x10^3$ tones [29]. In a study conducted in tropical deciduous forest in Madhya Pradesh, the tree biomass ranged from 4.04±1.4 to 3.43±0.62 t/ha. The greater biomass was recorded in the sites with dry deciduous forests than moist deciduous forests [41]. In a spectral modeling study conducted in the southwestern part of Karnataka by Devagiri et al (2013) at different vegetation types, the field measure of above-ground biomass ranged from 7.25 to 287.047 t dry wt/ha, with the highest in the evergreen forest of Kodagu district and lowest in the mixed plantation in Hassan district. The spectral model estimated the total above-ground biomass of 3 Mt C in the districts of Kodagu, Mysore and Hassan with a carbon pool of 2.1 Mt, 0.4 Mt and 0.5 Mt respectively. The moist deciduous forest's AGB ranged from 61.86 to 143.17 t /ha and for dry deciduous it ranged from m 7.69 to 20.48 t/ha. The study found that combining remote sensing with field sampling yields fast and accurate estimates of above-ground biomass and carbon pools and that such a method could be more easily applied to carbon inventories at the state and national levels [14].

In a study conducted in Uttara Kannada district in Karnataka in 2009, the maximum carbon stock was found in Nagur reserve forest (165.96 t/ha) and minimum in Chandavar reserve forest (90.58 t/ha). As compared with the values in 1984, there is an increase in 77.26% of carbon stock in the Nagur reserve forest [7] . In the Western Ghats region of Kathalekan hamlet in Karnataka, the stream/swamp forest had mean above-ground biomass of 349.52±110.79 t/ha and had carbon storage of 174.76±55.39 t/ha. The mean above-ground biomass non stream/swamp forest was 263.32±42.04 t/ha and carbon storage was 131.66±21.02 t/ha. It evident that stream/swamp forest has the highest potential to sequestrate carbon than non-stream/swamp forest [10].

In a study conducted at Barak Valley in Assam, it was observed that the vegetation carbon stock was higher in natural forests and low in *Imperata* grassland. After the natural forest, pan jhum agroforestry had the highest carbon stock, followed by rubber plantation, areca plantation, degraded forest and *Imperata* grassland. It was observed according to land use pattern, the carbon sequestration potential also changes and degradation or disturbance of the natural ecosystem leads to a decrease in the carbon sequestration potential [9]. Similarly in a study conducted between natural forest and plantation forest in Jorhat district, Assam, the natural forest had the highest biomass stock. The above-ground biomass and below-ground biomass of the natural forest were 280.70Mg/ha and 67.29 Mg/ha respectively and for plantation forest, it was 236.49 Mg/ha and 56.67 Mg/ha respectively. The carbon stock of natural forest was 197 Mg C/ha and plantation forest was 165 Mg C /ha. 56% of the plantation biomass carbon was contributed by the dominant species *Bombax ceiba, Dalbergia sissoo, Samanea saman, Tetrameles nodiflora*, and *Gmelina arborea* [19]. In a study conducted in Nongkhyllem WLS, Meghalaya, the AGB and carbon was found to be higher in plantation (406 Mg/ ha; 203 Mg C/ha) than the natural forest (324 Mg/ha; 161.97Mg C/ha). The carbon stock was found to be higher in the trees with 40-60cm and 60-80cm dbh in both natural and plantation forests [5]. So most of the studies have pointed out that natural forests have more potential in carbon sequestration because of the high basal densities and of the mixed-species diversity.

Sharma et al. (2010) recorded total carbon density ranging from 59.20±6.93-245.31±18.22Mg/ha in the twenty major types of forest in the Garhwal Himalaya. The lowest was in forest type Riverian *Acacia catechu* (L. f.) Willd – *Dalbergia sissoo* Roxb and highest in Moist *Cedrus deodara* Loud. The highest biomass was observed in conifer-dominated forests. The total carbon density of conifer-dominated forest was found to be 73.30-245 C Mg/ha and 59.20-159.38 for broadleaf-dominated forest. In another study conducted by them in seven major forest types of Garhwal Himalaya, the total carbon density was low at south-east aspect of *Quercus leucotrichophora* forest type with 77.3±10.7 C Mg/ha and high at a northeast aspect of *Cedrus deodara* forest type with 291.6±25.4 C Mg/ha. The total carbon density (soil organic carbon and total carbon density) ranged from 118±13.3 C Mg/ha and 469.1±40.8 C Mg/ha in Himalayan *Pinus roxburghii* (south-west aspect) and Moist *Cedrus deodara* (north-east aspect) respectively. the tree biomass and tree carbon stock were found to be higher in northern aspects than the southern aspects due to shift of sun towards the northern hemisphere, due to which less sunlight is been received in the north-facing slopes and south aspects are exposed to harsh climatic conditions and various natural disturbances [43].

In a study conducted in the Balganga Range of the Garhwal Himalaya region, the highest AGB and BGB was found in the site, which has an elevation of 1800-2600m, with 83.80±68.18 Mg/ha and 23.10±19.25 Mg/ha and total carbon was 53.45±43.72. The highest carbon stock was found in Fir trees (*Abies pindrow*) and lowest in Aayar trees (*Lyonia ovalifolia*) at this site. The lowest carbon was found to be 28.61±34.95Mg/ha at an elevation of 1000-1400m. The vegetative biomass and carbon was found to be increasing with the elevation [30]

In a study conducted in temperate forests of Kashmir Himalayas, it was found that a higher number of tree aboveground, belowground carbon stock, and understorey carbon stock was found in the coniferous forest than the broad-leaved forests. The mean carbon pool of aboveground and belowground was 85.7±5.7 Mg C/ha and 21.3±1.3 Mg C/ha respectively. The highest aboveground and belowground carbon were found in *Abies pindrow* (109.0±4.5 Mg C/ha; 26.6±1.0 Mg C/ha) and lowest in *Betula utilis* (35.5±2.4 Mg C/ha; 9.8±0.6 Mg C/ha). The highest soil organic carbon pool was observed in *Betula utilis* forest with 91.4 Mg C/ha. The total ecosystem carbon pool was higher in *Abies pindrow* and lower in *Juglans regia*. To the total carbon of the ecosystem, 61.5% was contributed by vegetation, 36.3% b the soil carbon and 2.2% by detritus [13].

In a study conducted in a tropical dry forest region in five sites of Sonebhadra and Mirzapur districts of UP by Chaturvedi et al. (2011), it was found that more amount of carbon was found in the older trees. The highest aboveground stem carbon density was found at the Hathinala site (151 t C/ha) and lowest at the Kotwa site (15.6 t C/ha), with a mean of 87 t C/ha. There is a huge variation observed in the highest and lowest values indicating that forests are found as patches and there is an immediate need of protecting these forests. 88-97% of the carbon was found to be stored in the trees with more than 19.1cm dbh.

In a study conducted by Kaushal et al (2016) in the male bamboo, *Dendrocalamus strictus* L., in Doon valley, Dehradun, it was found that the total biomass of the young (6 years) and matured (20 years) plantation was found to be 18.91 Mg/ha and 109.30 Mg/ha respectively and carbon storage was about 8.39 Mg/ha and 49.08 Mg/ha for the same. The culm (48.66%) had the highest carbon concentration, followed by the branch (48.09%).

In a study conducted by Baishya and Barik (2011) in (Riat Laban reserved forest and it's adjoining in Meghalaya) *Pinus kesiya* Royle ex. Gordon forest in north-eastern India, it was found that 460.5Mg/ha was the total biomass of the forest, of which the above-ground biomass constituted 91.2%. 77% of the biomass was contributed by *P. kesiya* (above-ground biomass- 354.6 Mg/ha; below-ground biomass- 31.8 Mg/ha), followed by 13.5% broad-leaved tree species, 0.5% litter, 0.12% shrubs and 0.03% herbs. 283.1 Mg C/ha was the total carbon content of the ecosystem, among which 58.7 Mg C/ha was the soil organic carbon.

In a study conducted by Ray et al. (2011) in Sunderban mangrove forests, the total AGB was found to be 93.72 ± 32.98 t dry wt/ ha or the carbon stock was 49.54 ±17.42 t C /ha. The biomass was found to be increasing with the dbh, but the density varied. *Avicennia marina* contributed highest to the AGB followed by *Avicennia alba, Avicennia officinalis, Excoecaria agallocha* and *Ceriops decandra.* Similarly, in a study conducted in mangrove forests at Kachch, Saurashtra, Gulf of Kachch and South Gujarat, the carbon stock was found to be 2.24M tonnes. The Kachch region had the highest sequestration rate with 31 tonnes/ha and the lowest in Saurashtra with 7 tons/ha. The carbon content found in this forest was found to be lower when compared with the other tropical terrestrial forests [35]. (Table I and II)

Table I: Biomass and carbon content in different parts of India since 2000.

Sl. No.	Study Area	Year	Vegetation Component	Biomass	Carbon	References
1	Barak Valley, Assam	2018	AGB	138.01 Mg/ha	167.37 Mg/ha	Brahma et al. 2018 [9]
			BGB	29.36 Mg/ha		
2	Balganga Reserved Forest, Uttarakhand,	2003-2013	AGB	83.13 Mg/ha	41.56 Mg/ha	Kumar and Sharma, 2015 [30]
3	Damoh, Katni, Panna, Raisen, Rewa, Sagar and Satna districts, Madhya Pradesh	2009	AGB(tropical dry deciduous forest)	31.8 t/ha		Salunkhe et al. 2016 [41]
			AGB(tropical mixed deciduous forest)	20.7 t/ha		
4	Jorhat district, Assam	2020	W	358.30 Mg/ha	197 Mg C/ha	Gogoi et al. 2021 [19]
5	Kolli Hills	2009	AGB	170.65 t /ha	4.49 Tg C	Mohanraj et al. 2011 [33]
6	Lankey reserve forest, Dudhnoi, Goalpara, Assam	2014	AGB	239.45 ± 12.8 Mg /ha	119.73 ± 6.4 Mg /ha .	Rabha, 2014 [37]
7	Manipur	2015	AGB	18.27–21.922 t/ha	9.13 to 10.96 t C/ ha	Devi and Yadava 2015 [15]
8	Nongkhyllem wildlife sanctuary, Meghalaya	2009	AGB	324 Mg/ha	161.97 Mg C/ha	Baishya et al. 2009
9	Pauri district, Uttarakhand	2010	AGB	129 to 533 Mg /ha	59 to 245 Mg/ha	Sharma et al. 2010 [42]
10	Radhanagiri Wildlife Sanctuary, Maharashtra	2004	Bole biomass	140.76 t/ha	1.6 x10^6 tons	Kale et al. 2009 [29]
		2006	Bole biomass	149.98 t/ha	1.7x10^6 tons	
11	Sivaganga district, Tamil Nadu	2013	W	67.85 to 117.987 Mg/ha	30.23 to 58.99 Mg C/ha	Sundarapandian et al. 2013 [45]
12	Tamenglong, Chuurachandpur, Imphal East (Jiribam), Bishnupur, and Thoubal of Manipur	2010-2011	AGB	124.56 to 254.99 t /ha	60.09 to 121.43 t C /ha	Thokchom and Yadava 2017 [46]
13	Uttara Kanada district, Karnataka	2009	AGB	249.67 ± 58.10 t/ha	124.84 ± 29.05 t/ha	Bhat and Ravindranath 2011 [7]
		2010	AGB(stream/swamp forest)	349.52 ± 110.79 t/ha	174.76 ± 55.39 t/ha	Chandran et al. 2010 [10]
			AGB(non stream/swamp forest)	263.32 ± 42.04 t/ha	131.66 ± 21.02 t/ha	

Table II: Carbon content of different trees species in different parts of the country

Sl. No.	Study Area	Year	Species Name	Vegetation Component	Carbon content	References
1.	Different parts of the country	2010	*Eucalyptus tereticornis* Sm.	W	6 Mg Cha−1 yr−1	Kaul et al. 2010 [27]
			Populus deltoides Marsh		8 Mg Cha−1 yr−1	
			Shorea robusta Gaertn. f.		1 Mg Cha−1 yr−1	
			Tectona grandis Linn. f.		2 Mg Cha−1 yr−1	
2.	Different parts of the	2008	*Shorea robusta*	AGB	5800.49g	Jana et al. 2009

	country				(5.22 t C/ha)	[23]
			Albizzia lebbek		6961.61g (6.26 t C/ha)	
			Tectona grandis		8857.73g (7.97 t C/ha)	
			Artocarpus integrifolia		8097.69g (7.28 t C/ha)	
3.	South 24 Parganas district, West Bengal	2014	*Acacia auriculiformis*	Leaf Area Index	1.04t ha/ year	Biswas et al. 2014 [8]
			Albizzia lebbek		1.79 ha/ year	
			Dalbergia sisso		0.9 ha/ year	
			Eucalyptus spp		1.19 ha/ year	
			Swietenia mahagoni		0.23 ha/ year	
			Tectona grandis		0.72 ha/ year	
			Terminalia arjuna		0.12 ha/ year	
4.	Almora district, Uttarakhand	2004-2005	Non degraded oak	W	242.56-290.62 t ha-1	Jina et al. 2008 [24]
			Degraded oak		16.73- 18.54 t ha-1	
			Non degraded chir pine		81.31-115.40 t ha-1	
			Degraded chir pine		17.59-33.42 t ha-1	
5.	Nattarasankottai Village, Sivaganga district in Tamil Nadu	2017	*Acacia leucophloea*	W	532.32 kg/ha	Balasubramanian et al. 2017 [6]
			Acacia mellifera		77.99 Kg/ha	
			Azadirachta indica		369.01 Kg/ha	
			Bauhinia racemosa		260.47 Kg./ha	
			Morinda tinctoria		92.93 kg/ha	
6.	Anantnag District, Kashmir Himalaya, Jammu and Kashmir	2012-2013	*Populus deltoids*	AGB+BGB	114.4±12.6Mg C/ha	
			Juglans regia		70.7±6.9 Mg C/ha	
			Betula utilis		45.4±2.9 Mg C/ha	
			Cedrus deodara		130.7±8.1 Mg C/ha	
			Pinus wallichiana		125.2±5.2 Mg C/ha	
			Abies pindrow		135.6±5.5 Mg C/ha	
			Mixed Coniferous		125.2±5.2 Mg C/ha	

III. CARBON CAPTURE AND SEQUESTRATION (CCS) TECHNOLOGY IN INDIA

Carbon capture and sequestration (CCS) technology is a process by which the waste carbon dioxide is captured from the large emission source, compressed, transported to a location where it is stored in a place such as a deep aquifer or deep ocean. The carbon dioxide is usually captured from the large industries such as coal and natural gas power plant, steel mills and cement plants. As per reports in 2018, India's 66% of the electricity is generated from the thermal power plant and 85% of the thermal power is based on coal. In the year 2007-2008, thirty projects were funded by the Department of Science and Technology for the research and development in carbon capture and sequestration technology but after 2013 only three plants are operating commercially. These plants are Aonla urea plant (Indian Farmers Fertiliser Co-Operative), Jagdishpur - India Urea plant (Indo Gulf Cooperation Ltd.) and Phulpur urea plant (Indian Farmers Fertiliser Co-Operative) and have CO2 absorption capacity of 450TPD, 150TPD and 450TPD respectively. Three of the plants have a capture technology which is amine-based post-combustion capture [20] and [44]. In 2006 National Hydrogen Energy Board created the National Hydrogen Energy Road Map which had a vision of one million hydrogen-powered vehicles and 1000 MW of hydrogen-powered power generation capability by 2020, but the goal is yet to be met. From these mentioned projects, it's clearly evident that there were a lot of efforts taken by the different bodies in order to capture carbon or to reduce emissions, but in later years, its implementation has declined due to the improper management of the projects [34].

IV. CONCLUSION

Carbon sequestration is one of the feasible ways to reduce the level of greenhouse gases in the atmosphere and climate change. As per the reports, the total forest cover of India is been increasing year by year. The government has set up various policies to increase the forest cover and there is an increase in plantation forests across the country, but natural forests also have to be protected as well. Most of the researches has pointed out that natural forests have the ability to sequestrate carbon more than the planted forest and therefore these forests have to be protected to reduce carbon emission. The rotation of trees in planted forest and removal of whole tree biomass doesn't help in the long term storage of carbon. The vegetation density has to be maintained in both natural and planted forests. Wastelands can be converted to planted forests and wetlands which is also a good carbon sink also should be protected. Urban forestry is the other way to increase forest cover. Planting more trees in urban regions will not only help to absorb but also reduces the atmospheric temperature in the urban. More policies should be set up to protect the biodiversity hotspot regions in order to reduce the exploitation and disturbances of the forest region. From the various studies conducted in past years, it is evident that even though India ranks top in carbon emission and measures to control the emission are just on paper. There are a lot of advanced technologies so far, but still, India relies on traditional techniques such as the use of the coal-based thermal plant for electricity generation, etc. It's time for the country to switch to alternative methods. Being a tropical country, energy sources like solar and wind can be used in the generation of electricity, which will reduce carbon emission to an extent, and implementation of CCS technology in coal and other fossil fuel-fired plants will also help to reduce carbon emission. Abhishek Gupta et al. (2019) have mentioned challenges of CCS in India and have suggested a roadmap to successful CCS in India, which includes policy and regulatory framework, identification of suitable carbon dioxide storage, improvement and cost reduction of capture technologies and development of carbon dioxide transport infrastructure. The use of electric vehicles should be promoted among the common people and the public should be made aware of CCS technologies. Various policies are still on paper and government bodies should work on them to make all those works happen. More funds should be given for R&D on carbon sequestration works. All projects and policies should give importance to sustainable development.

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