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Review Article

Trend of studies on carbon sequestration dynamics in the Himalaya hotspot region: A review

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Abstract
The present communication deals with the carbon dynamics in the Himalaya hotspot region. The Himalaya, a mountain range shared by Pakistan, India, Nepal, Bhutan and Myanmar, is one of the biologically richest regions in the world that play an important role as source and sink in global carbon cycle. The purpose of this paper was to review and provide available studies related to carbon sequestration in the Himalayas. The carbon in forest is stored in five different pools *viz.* above-ground biomass, below-ground biomass, litter, deadwood and soil organic carbon. Estimates of biomass, carbon stock and soil organic carbon contents by almost all forest types including agroforestry systems and plantations in the Himalaya hotspot have been documented in this communication. The net rate of carbon sequestrated by forest was reported to be 2.4 ±0.4 Pg C yr^{-1} on a global scale. The Indian Himalayan Region constitutes about 5.4 billion tonnes of C and sequesters about 65 million tonnes of C yr^{-1}. We analysed more than 135 peer-reviewed journal articles related to biomass and carbon sequestration. The review identifies that the studies estimated 3697.05, 3898.10 and 4235.05 tonnes carbon per hectare for Western, Central and Eastern Himalayan region respectively. The research on the biomass/carbon estimation received attention as early as 1980s, but increased gradually after 2001. These findings would contribute to policy-makers with useful information for mitigation of CO_2 emissions.

Keywords: Biomass, Carbon dioxide, Carbon sequestration, Forests, Himalaya hotspot

BACKGROUND

The United Nations Framework Convention on Climate Change (UNFCCC) in 1992 aims to stabilize Green House Gases emissions in the atmosphere (Pires *et al.,* 2011). The carbon dioxide (CO_2) is the most concerned greenhouse gas (GHG), which is the primary cause for the increasing concentration of atmospheric GHGs, influencing the global environment (Brown, 1993). In recent millennia, global warming has become a very problematic issue (Mishra *et al.,* 2014). The warming of Earth is strongly associated with the sequestration of CO_2 degassed from the inside of Earth (Gaillardet and Galy, 2008). The increase in CO_2 emission since the onset of industrial revolution from 280 parts per million (ppm) is projected to lead to 540 ppm by the year 2100 (Alamgir and Al-Amin, 2007). The main source behind the rising atmospheric CO_2 level is due to fossil fuels combustion and human induced activities (Bolin, 1977; Joshi and Dhyani, 2019). Reduction of CO_2 emission and storage of carbon are the faithful options to mitigate climate change and global warming (Kusmana *et al.,* 2018). During the 20th century, there has been a distinct rise in the sea-level along with the change in ecosystems and the rate of occurrence of forest fire either by human actions or natural events (Lal, 2008).

Carbon (C) is a primary component of all known life on Earth, representing approximately 50% of dry forest biomass (Kebede and Soromessa, 2018). It is the fourth most abundant element in the universe by mass after hydrogen, helium, and oxygen. The exchange of C among three reservoirs *viz*. the atmosphere, terrestrial biosphere and ocean, is known as the carbon cycle (Post *et al.,* 1990). Forests are significant component of the global carbon cycle because they acts as carbon source or as carbon sink (Masera *et al.,* 2003). About 30% of global land area is under permanent forest cover (Whitehead, 2011).

Forest represents a major carbon pool, comprising approximately 60% of terrestrial carbon storage (Sandeep *et al.,* 2014). Tropical, boreal and temperate forests are estimated to store roughly between 378 to 564, 249 to 295, and 113 to 125Pg C, respectively, of the existing carbon (Pan *et al.,* 2011). The Kyoto Protocol, recognizes forestry as a sink measure under the Clean Development Mechanism (CDM) but only in form of afforestation and reforestation (Arora and Chaudhry, 2014). India, being a signatory member to the Kyoto Protocol, carried out numerous studies in the country (Salunkhe *et al.,* 2018).

The Intergovernmental Panel on Climate Change (IPCC) and Reducing Emission from Deforestation and Forest Degradation (REDD) mechanisms provides guidelines for enhancing carbon sequestration and reducing deforestation (Vieilledent *et al.,* 2012). The process of removal or capture of the atmospheric carbon dioxide into other long-lived C pools is called *'Carbon Sequestration'* (Dhanwantri *et al.,* 2014). Carbon sequestration is defined by the UNFCCC as "the process of removing carbon from the atmosphere and depositing it in a reservoir" (Nair, 2012). Carbon Dioxide Removal (CDR) is referred as "a set of techniques that aim to remove CO_2 directly from the atmosphere by either (1) increasing natural sinks for carbon or (2) using chemical engineering to remove the CO_2, with the intent of reducing the atmospheric CO_2 concentration" (IPCC, 2012b). Through sequestration activities, global climate change could be prevented by enhancing carbon stock in trees and soils, by reducing CO_2 and other GHGs emissions, and by preserving existing carbon of trees and soils. Carbon is therefore sequestered biologically in the forest ecosystem (Khurana, 2012).

Globally from 1990 to 2007, the net rate of C sequestrated by forest was 2.4 ±0.4 Pg C yr^{-1} (Zhang *et al.,* 2019). Carbon sequestration by forests has attracted much interest world-wide as a mitigation approach. The emissions of CO_2 have increased continuously during the recent decades. In 2018, the CO_2 emissions from fossil fuels raised to 10.0 ±0.5 Gt C yr^{-1}, those from land use change was assessed as 1.5±0.7 Gt C yr^{-1} and the global average annual concentration of atmospheric CO_2 resulted 407.38 ±0.1 ppm (Friedlingstein *et al.,* 2019). Carbon emissions from India report an estimation of 2,607.49 million tonnes CO_2 equivalent (FSI, 2019). According to the Global Energy and CO_2 Status Report (IEA, 2019). India emitted 2,299 million tonnes of CO_2 equivalent in 2018. India's emissions rose by 4.8% from last year due to a rise in coal consumption. In the terrestrial ecosystem, the carbon is stored in five different pools *viz.* above-ground biomass (AGB), below-ground biomass (BGB), litter, deadwood and soil organic carbon (Yaklaşımlar, 2012). The AGB includes all living biomass above the soil (stem, stump, branches, bark, seeds and foliage) and the BGB includes all live roots (Penman *et al.,* 2003). Estimation of AGB is very important to access carbon stocks changes (Manickam *et al.,* 2014).

BIODIVERSITY HOTSPOTS

The concept of biodiversity hotspots was first introduced by Norman Myers, a biologist, in the year 1988 and identified 10 hotspot areas in tropical forests (Myers, 1988). Two years later, 8 other hotspot areas were recognized, four in tropical forests and four in Mediterranean-type ecosystems (Myers, 1990). Conservation International and MacArthur Foundation adopted Myers concept of hotspots in 1989 (Mittermeier *et al.,* 1998). The number of hotspots increased to 25, covering 1.4% of Earth's land area, containing 44% of world's plant species and 35% of vertebrate species. Presently, there are 36 recognized biodiversity hotspots that covers 2.4% of Earth's land with Forests of East Australia and North American Coastal Plain being identified in 2011 and 2016, respectively (CEPF, 2019). India being one of the Mega-diverse country with diverse biogeographical and climatic conditions, ranging from the cold and high Himalayas in the north to the hot and humid peninsula in the south, and from the wet, green, north-eastern forest to the dry north-western desert harbours four biodiversity hotspots: the Himalaya, the Indo-Burma region, the Western Ghats-Sri Lanka and the Sundaland (Venkataraman and Sivaperuman, 2018).

THE HIMALAYA HOTSPOT

The word "Himalaya" is derived from Sanskrit, meaning the "abode of snow" (*Hima*-snow and *alaya*-abode) (Negi, 2009). The magnificent Himalaya, a geologically young mountains (Singh and Rawat, 1999) is well notable to the South Asia and in addition to the Earth for its diversity of ecosystems (Sharma *et al.,* 2008). The Himalaya biodiversity hotspot extends in a curve 3,000 km of northern Pakistan, Nepal, Bhutan and the north-western and north-eastern parts of India (Fig. 1). With an area approximately 750,000 sq. km, the mountain range of Himalaya has been broadly classified into three provinces: the Western Himalaya (the north-west Kashmir, Himachal Pradesh, Uttarakhand and northern Pakistan); the Central Himalaya (the Garhwal and Kumaun) and the Eastern Himalaya (the parts of Nepal, Bhutan, the north-east Indian states of West Bengal, Sikkim, Assam, Arunachal Pradesh, south-east Tibet and northern Myanmar) (Sharma, 1999). The population of the Himalaya belongs to four distinct ethnic groups i.e., Indie, Tibetan, Afghan–Iranian and Burman or Southeast Asian people (Karan, 1987). In 2011, the Himalaya's population has reached 52,776,118 people. Out of the total population, the Western Himalaya is inhabited by 25,592,222 people, the Central Himalaya by 19,220,834 and the Eastern Himalaya by 7,963,062 people (Apollo, 2017). The protected area network in the Himalaya hotspot comprises of 55 National Parks, 146 Wildlife Sanctuaries, 6 Biosphere Reserves and 7 World Heritage sites (Seeland, 2000; Shrestha *et al.,* 2010; Beffasti and

Galanti, 2011; ENVIS, 2019).

The Himalayas and connected moist regions in the South Asia harbour extra-tropical broadleaved evergreen forest, a type generally ignored in analyses of forest responses to global change (Zobel and Singh, 1997).

The Indian Himalayan Region (27°50' to 37°06' N and 72°30' to 97°25' E) forms the largest part of the Himalaya and stretches over 5.37 lakh sq. km from Jammu & Kashmir in the northwest to Arunachal Pradesh in the northeast, and fully covering ten states *viz.* Jammu & Kashmir, Himachal Pradesh, Uttarakhand, Sikkim, Arunachal Pradesh, Meghalaya, Mizoram, Nagaland, Tripura and Manipur while partially covers only the hill districts of Assam and West Bengal. It contributes about 16.2% of India's total geographical area and more than 41.5% is accounted by a rich forest cover (Kumar *et al.,* 2018). Of the estimated 18,440 species of plants in the Indian Himalayan Region (IHR), about 25.3 % are endemic to the Himalaya that include 1748 medicinal plants, 675 wild edibles, 279 fodder species, 155 sacred plants, 118 essential oil plants with medicinal values (Stephen *et al.,* 2015).

CARBON DYNAMICS IN THE HIMALAYAS

The Himalayas have several influences on the global carbon cycle. To determine whether they are net sources or sinks of atmospheric CO_2 can only be determined by considering the significance of biomass, net primary production and exploitation rates (Singh *et al.,* 1985). The Himalayan forests have become a net source of CO_2 to the atmosphere due to overexploitation. On the basis of forest management activities done in community forests, the Indian Himalayan Region (IHR) constitute about 5.4 billion tonnes of C and sequester about 65 million tonnes of C yr^{-1}.

In India, the sum of annual C sequestered is approximately equal to 15% of the CO_2 emissions from fossil fuels (Singh *et al.,* 2010). Therefore, the Himalayan forests can be considered as a carbon sink. In the forest ecosystems, accumulated biomass is an important feature for assessing sustainable utilization, productivity and the amount of CO_2 sequestered from the atmosphere. The accuracy of biomass estimation is therefore, very important for numerous applications like global carbon cycle, timber extraction and to track carbon stock changes (Vashum and Jayakumar, 2012; Kaushal *et al.,* 2016). The aboveground forest biomass have been estimated by various methods through field measurement, tree inventories data, species-specific biomass estimation, remote sensing and geographical information systems (GIS) methods (Brown *et al.,* 1989, 1999; Lu, 2006; Murali *et al.,* 2005).

Field measurement method is classified into two types, *viz.*, destructive and non-destructive biomass estimation methods. The destructive method also known as harvest method, is the direct method for estimation of aboveground forest biomass and carbon stock (Gibbs *et al.,* 2007) and consists of cutting or harvesting of trees of the given area followed by weighing the different components of the harvested tree like trunk, leaves and branches (Lodhiyal and Lodhiyal, 2003; Xiao and Ceulemans, 2004; Ravindranath and Ost-

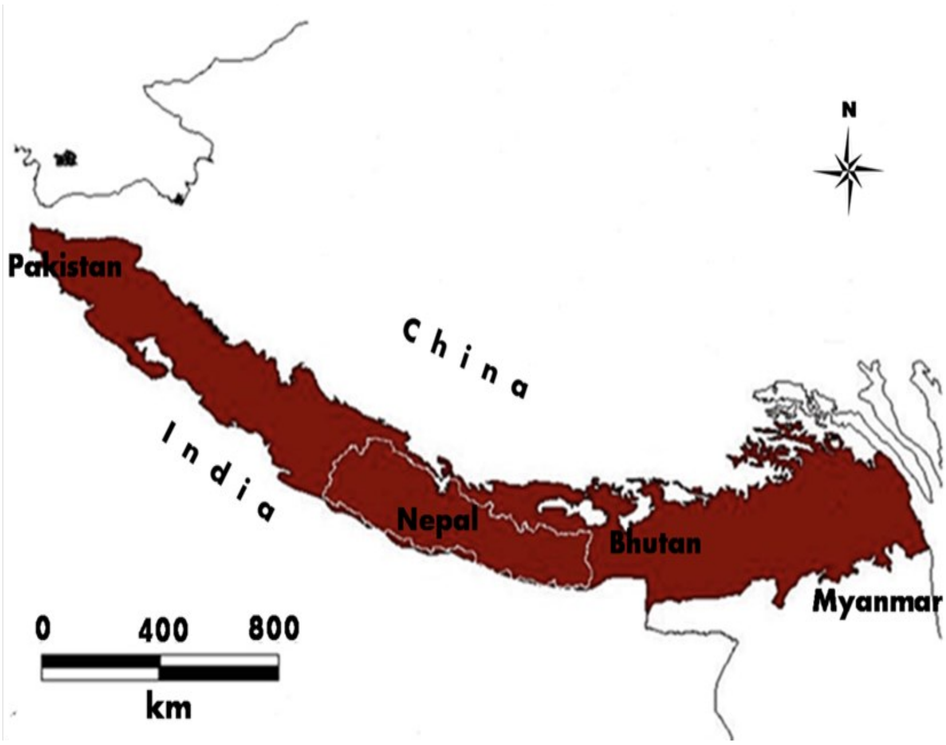

Fig.1. *Map of Himalaya Hotspot region.*

wald, 2008; Devi and Yadava, 2009). This method is expensive, destructive and time-consuming and could be applied to small tree sample sizes and small plots (Ketterings *et al.,* 2001) and also not applicable in degraded forests containing threatened species (Montes *et al.,* 2000). The non-destructive method of biomass estimation is assessed by two-dimensional analytical techniques, on the basis of relationships between biomass and measurable parameters, like girth at breast height (GBH) (Aboal *et al.,* 2005). This method is used to get an estimate of biomass and allometric equation preparation on larger-scale forest (Bhandari and Neupane, 2014). Another method for estimation of biomass is remote sensing and GIS. It is an alternative to traditional methods for biomass estimation and forest's carbon stocks (Ravindranath and Ostwald, 2008). Several studies have been conducted applying remote sensing techniques to estimate the biomass of forest (Nelson *et al.,* 1988; Hame *et al.,* 1997; Drake *et al.,* 2003; Anaya *et al.,* 2009; Hudak *et al.,* 2012; Koppad *et al.,* 2020). However, the data from field is usually essential for authentication.

WESTERN HIMALAYA

The Western Himalaya (Latitude 28°43'N to 37°05'N and Longitude 72°31'E to 81°01'E) extends from Badshahkahan in North Eastern Afghanistan upto Central Nepal. In India, states of Jammu and Kashmir, Himachal Pradesh and Uttarakhand fall in this region (Bhatt *et al.,* 2016). Chisanga *et al.* (2018) studied the carbon stock in Kinnaur district of Himachal Pradesh based on land use and altitudinal ranges. The biomass estimation was species and region specific including form factor for tree volume. The maximum estimation was AGB (84.65 ton ha^{-1}), BGB (19.50 ton ha^{-1}), and total biomass (104.10 ton ha^{-1}). The total ecosystem carbon density of 166.36 ton ha^{-1} and soil carbon density of 155.77 ton ha^{-1} were recorded.

Goswami *et al.* (2014) evaluated biomass and carbon sequestration based on non-destructive method in the different agroforestry land use systems of the Kwalkhad watershed of middle Himalayan region and recorded C stocks as 14.78 Mg C ha^{-1} for agrisilvihorticulture and 14.45 Mg C ha^{-1} for agrihortisilviculture. The greatest number of C credits (1 C credit = 1 ton CO_2) was produced by agrisilvihortivulture (21.49 ha^{-1}), while the lowest by silvipasture (5.46 ha^{-1}). Palchowdhuri *et al.* (2016) estimated the change in the AGB and carbon stock for three major forest types in Shimla as a consequence to landuse dynamics using NDVI-based approach. It was found that the correlation between carbon stock and NDVI values was significant (*r* = 84% for 2003 and 80% for 2013). In the sub-tropical forests of Himachal Pradesh, comparable study was carried out by (Bhardwaj *et al.,* 2016).

Aziz *et al.* (2019) assessed the biomass and soil carbon stocks in the alpine and subalpine regions of Kashmir where the average carbon stocks of 372.5 ton ha^{-1}, biomass carbon of 2.27 ton ha^{-1} and the soil organic carbon stocks of 370.6 ton ha^{-1} were recorded. Dad (2019) conducted a study to estimate soil organic carbon (SOC) stocks in 20 grasslands of Kashmir Himalaya and showed high variable results in SOC stocks ranging between 28.85 and 94.76 Mg C ha^{-1}, with mean value of 54.52 Mg C ha^{-1}.

As per Shaheen *et al.* (2016), carbon stocks in living trees of different subtropical forest types in Kashmir ranged from 326 ton ha^{-1} on *Pinus roxburghii* to 75.86 ton ha^{-1} on mixed forest, with total carbon stock of 186.27 ton ha^{-1}. The estimated average biomass carbon was 151.38 ton ha^{-1} with calculated soil carbon stocks as 34.89 ton ha^{-1} and agricultural soil carbon of 27.18 ton ha^{-1}. Dar *et al.* (2017) studied the temperate forests of Kashmir Himalaya and estimated an average dry biomass of 234.2 ton ha^{-1}, AGB and BGB of 223 ton ha^{-1}, understorey vegetation of 1.3 ton ha^{-1} and detritus of 9.9 ton ha^{-1}. Similar type of study was conducted by (Dar and Sahu, 2018) in temperate forests of northern Kashmir Himalaya. Rashid *et al.* (2017) assessed the changes in the AGB and carbon stocks of Lidder valley, Kashmir Himalaya, using satellite data, phytosociological data and allometric equation for 33 years and found a strong correlation between land use land cover (LULC) and C dynamics of forest with NDVI and biomass. Also about 1.018 Mg of aboveground biomass and 0.5 Mg of aboveground carbon was lost from the area. For estimation of biomass across a chronosequence of Chir Pine forest in Murree Hill of Pakistan, Amir *et al.* (2018) used field inventory data based on basal area, height and form factor and reported overall mean carbon values from 90.3 ton ha^{-1} to 309.5 ton ha^{-1}.

Uddin *et al.* (2019) analysed the soil, species composition and carbon stock in the *Abies pindrow* dominant community in Dir Kohistan, Pakistan and found that the stem density ranged between 3 ha^{-1} in *Acer caesium* to 273 ha^{-1} in *Abies pindrow*, with 350 trees ha^{-1} as a total stand density. The total biomass carbon and the total average carbon stock were 967 ton ha^{-1} and 568.63 ton ha^{-1}, respectively.

Rajput *et al.* (2015) conducted a study to estimate the biomass, carbon density and CO_2 mitigation potential of 7 different land use systems along an altitudinal gradient in north-western Himalayas with results showing highest AGB and BGB estimates at orchard + cereal-cereal system as 75.64 Mg ha^{-1} and 23.60 Mg ha^{-1}, respectively; highest CO_2 mitigation potential at altitudinal range of 1,900-2,200m as 7.81 Mg ha^{-1} $yr^{-1}$and highest carbon density of both soil + plant at altitudinal range of 1,300-1,600m as 90.88 Mg ha^{-1}.Rai *et al.* (2020) assessed the dry matter dynamics of forests along treeline ecotone in Kedarnath Wildlife Sanctuary, Western Himalaya by adopting regional specific allometric equations for the biomass and net primary productivity (NPP). The average forest biomass of 33.27 ±16.97 Mg/0.1 ha, ranging from 8.87 Mg/0.1 ha to 44.98 Mg/0.1 ha and NPP range from 1.49 to 2.11 Mg/0.1 ha year^{-1} was estimated.

For the estimation of aboveground and belowground biomass, Toky and Bisht (1993) used harvest method and reported AGB (kg/tree) from 11.6 to 37.5, BGB (kg/tree) from 2.2 to 8.7 and NPP ranging from 0.98 to 9.33 kg/tree/year in important fuel wood trees from arid north-western India. Mandal and Joshi (2015) calculated aboveground biomass and carbon stocks of an invasive woody shrubs applying allometric equation in the subtropical deciduous forests of Doon Valley, western Himalaya, India. Results indicated the maximum coverage (58.57% ha^{-1}), highest biomass (13,559.60 kg ha^{-1}) and carbon density (6373.01 kg ha^{-1}) of *Lantana camara*. Vaidya *et al.* (2017) developed allometric equations to estimate biomass and soil carbon stock in subtropical-subtemperate regions of Western Himalaya. The mean biomass and soil carbon stock ranged from 150.50 to 544.94 ton ha^{-1} for different farm plantations. In the plantation forests of north western Himalaya, Devi *et al.* (2012) estimated biomass and carbon sequestration of 185.57 ±48.99 and 42.47 ±10.38 ton ha^{-1} in *Ulmus villosa* with highest vegetation carbon density of 118.37 ± 1.49 ton ha^{-1} in *Albizia procera* and lowest in *Acacia catechu* (36.50 ±9.87 ton ha^{-1}). The highest soil carbon density was 219.86 ±10.34 ton ha^{-1} in *Alnus nitida*, and lowest in *Pinus roxburghii* (170.83 ±20.60 ton ha^{-1}). The highest CO_2 mitigation potential (29.09 ±12.78 ton ha^{-1}) and carbon sequestration (7.91 ± 3.4 ton ha^{-1}) was in *Ulmus villosa*. Shahid and Joshi (2015) conducted a study to estimate biomass and carbon stock in the three forest ranges of Doon valley, Western Himalaya using volumetric equations where biomass varied from 338.40 to 438.17 Mg ha^{-1} and carbon stocks from 169.20 to 219.08 Mg C ha^{-1}(Table 1). Giri *et al.* (2014), developed Biomass Expansion Factor (BEF) and estimated carbon pool in *Ailanthus excela* with total biomass of 126.07 ton ha^{-1}, AGB of 102.96 ton ha^{-1}, BGB of 23.11 ton ha^{-1} and BEF value of 1.23.

CENTRAL HIMALAYA

The Indian Central Himalaya is located in the centre of the Himalayan Mountain Range. Out of total geographic area of 51,125 sq. km (Latitude 28°44'N to 31° 25'N and Longitude 77°45'E to 81°01'E), 92.6% is mountainous, which is called mainland. It comprises of two distinct divisions- Garhwal and Kumaun Himalayas, and is demarcated by Himachal Pradesh in the northwest, Haryana in the west, Uttar Pradesh in the south, Nepal in the east, and Tibet in the north (Sharma, 1999).

Sharma *et al.* (2011) assessed carbon stock on different slope aspects in seven major forest types of temperate region of Garhwal Himalaya, India. Results showed that minimum value of total tree C density of 77.3 Mg Cha^{-1} on South-East (SE) aspect and maximum value of 291.6 Mg C ha^{-1} on North-East (NE) aspect and soil organic carbon ranged from 40.3 Mg C ha^{-1}on SW aspect and 177.5 Mg C ha^{-1} on NE aspect. In moist temperate forest of Garhwal Himalaya, the total live tree biomass density (TBD) ranged from 215.5 to 486.2 Mg ha^{-1} and total live carbon density (TCD) ranged from 107.8 to 234.1 Mg C ha^{-1}. For the study area, the average values of TBD and TCD were 356.8 ±83.0 Mg ha^{-1} and 178.4 ±41.5 Mg C ha^{-1}, respectively (Gairola *et al.,* 2011). In Balganga Reserved Forest (BRF) in Garhwal, Uttarakhand, estimation of forest carbon (C) stock was carried out by (Kumar and Sharma, 2015), where results showed the maximum total biomass density (TBD) and total carbon density (TCD) estimates at site III in the altitudinal range (1800 –2600 m) as 108.26 and 53.45 Mg ha^{-1} followed by site II in the range (1600–1800 m) as 83.92 and 41.96 Mg ha^{-1}, and minimum at site I in the altitudinal range (1000–1400 m) as 57.22 and 28.61 Mg ha^{-1} with an average of 83.13 and 41.56 Mg ha^{-1}, respectively.

Pala *et al.* (2016) conducted a study in four community based religious conserved forests areas of Garhwal Himalaya and estimated total carbon density of 782 trees ha^{-1} to 1352 trees ha^{-1} and total basal cover (TBC) from 31.67 m^{2}ha^{-1} to 84.34 m^2 ha^{-1}. As per Mahato *et al.* (2016), total biomass density and total carbon density were 132.74 Mg ha^{-1} and 66.36 Mg ha^{-1} in community-managed forests of Garhwal Himalaya. Studies from various pure Conifer forest types of Garhwal Himalaya, showed maximum growing stock of 988.3 m^3 ha^{-1} in *Abies pindrow* forest, followed by 922.3 m^3 ha^{-1} for *Cupressus torulosa* (Dimri *et al.,*

Table 1. Carbon estimation in extensions of Western Himalaya.

Region	AGB (tha^{-1})	BGB (tha^{-1})	Deadwood (tha^{-1})	Litter (tha^{-1})	SOC (tha^{-1})	Total (tha^{-1})	Source
Doon Valley	951.59	247.42	-	-	-	1199.01	Shahid and Joshi (2015)
Himachal Pradesh	71.3	19.92	1.66	1.76	68.87	163.51	FSI (2019)
Uttarakhand	62.77	16.86	1.21	2	69.76	152.62	FSI (2019)
Punjab	19.09	7.4	0.14	0.67	44.89	72.18	FSI (2019)
Kashmir Himalaya	1261.4	252.3	-	-	174.47	1688.17	Shaheen *et al.* (2016)
Haryana	15.32	5.8	0.11	0.86	43.23	65.31	FSI (2019)
Pakistan	33.97	6.63	-	-	315.65	356.25	Aziz *et al.*(2019)

Abbreviations: AGB-Above Ground Biomass; BGB-Below Ground Biomass; SOC-Soil Organic Carbon; tha^{-1}- Tonnes per hectare

2014). Similarly, the total carbon density and CO_2 mitigation potential in Oak and Pine forests of Garhwal, central Himalaya were 2420.54 Mg C ha^{-1} and 8,713.94 Mg C ha^{-1} (Oak) and 986.93 Mg C ha^{-1} and 3552.95 Mg C ha^{-1} (Pine), respectively (Nautiyal and Singh, 2013).

Pant and Tiwari (2014), estimated tree biomass and carbon sequestration in Chir-Pine forests under various disturbance levels in Kumaun Central Himalaya where total biomass was 14.7 ton ha^{-1} at highly disturbed site, followed by 94.46 ton ha^{-1} in moderately disturbed forest, and 112.0 ton ha^{-1} in protected forest. The carbon sequestration rate ranged from 0.60 (ton/ha) per annum to 4.3 (ton/ha) per annum. Similarly, Jina *et al.* (2008) estimated rates of carbon sequestration and total carbon stock in degraded and non-degraded sites of Pine and Oak forests in Kumaun Central Himalaya and found variation in carbon stock from 242.56 to 290.62 ton ha^{-1} and 16.73 to 18.54 ton ha^{-1}, respectively, and in non-degraded and degraded Chir Pine sites it varied from 81.31 to 115.40 ton ha^{-1} and 17.59 to 33.42 ton ha^{-1}, respectively. Similar studies on biomass and carbon sequestration in Oak and Pine forests of Kumaun Himalaya, were conducted by (Joshi *et al.,* 2013; Gosain *et al.,* 2015).

Kanime *et al.* (2013) carried out study for estimation of tree biomass and carbon sequestration in different tree-based systems of Central Himalayan Tarai region and found the highest total biomass of 94.8 Mg ha^{-1} and carbon stocks ranging from 4.51 Mg C ha^{-1} to 43.39 Mg C ha^{-1}. Arora *et al.* (2014) assessed growth, biomass carbon storage and sequestration along an age series of *Populus deltoides* plantations at Tarai region of central Himalaya. Results showed that the total carbon stock increased from 64.4 Mg C ha^{-1}at 1 year to 173.9 Mg C ha^{-1} at 11 years. Sheikh *et al.* (2020) studied biomass and carbon stocks in temperate *Cedrus deodara* forests along the altitudinal gradients in the Central Himalaya and estimated carbon stock of 395.4 ton ha^{-1} for lower altitude, followed by 321.6 ton ha^{-1} and 282.5 ton ha^{-1} for middle and upper altitude respectively. At Banj Oak forests of Central Himalaya, total biomass stock ranged from 225.82 ±26.46 ton ha^{-1} to 595.50 ±5.64 ton ha^{-1}and total tree density showed a range from 920 ind ha^{-1} to 402.5 ind ha^{-1} (Pandey *et al.,* 2020).

Yadav *et al.* (2017), estimate biomass and carbon allocation in different production systems in the mid hills of Indian Himalaya, and found the highest biomass of 56.5 ton ha^{-1} and carbon stocks of 25.3 ton ha^{-1} in wheat + pecan nut system followed by 53.2 and 23.9 ton ha^{-1}in lentil + pecan nut system with the lowest of 2.75 and 1.17 ton ha^{-1} in pure lentil production system. The carbon stock and rate of carbon sequestration in pecan nut were 22.8 ton ha^{-1}and 1.67 ton ha^{-1}year^{-1}, respectively. Rana *et al.* (2015) made an assessment in the Cypress forest of Central Himalaya, and estimated the total biomass ranging between 178 and 431 ton ha^{-1} while carbon stock varied between 89.07 and 206 ton ha^{-1}. Similarly, Verma *et al.* (2012) studied the carbon storage capacity of *Quercus semecarpifolia*, forests of Central Himalayan region and observed the difference in the carbon biomass between 210.26 and 258.02 ton ha^{-1} and mean carbon stock between 3.7 and 4.8 ton ha^{-1}yr^{-1}, respectively. Yadava (2011), carried out study under six different agroforestry systems, in Tarai region of Central, Himalaya. The biomass, carbon storage, CO_2 mitigation potential and total carbon sequestration of trees were estimated. Adhikari *et al.* (2020) made an assessment of crop composition, yield, biomass, net primary productivity (NPP), carbon stock and carbon sequestration in agri-silviculture (AS) and agri-horticulture (AH) agroforestry systems of Central Himalaya and showed the biomass and net primary productivity of trees as 128.3 ton ha^{-1} and 16.24 ton ha^{-1} yr^{-1} in AS system while 171.95 ton ha^{-1} and 14.4 ton ha^{-1} yr^{-1} in AH system (Table 2). The carbon sequestration of tree were 7.7 ton ha^{-1} yr^{-1} for AS and 6.8 ton ha^{-1} yr^{-1} for AH systems.

EASTERN HIMALAYA

The Eastern Himalaya,with total geographic coverage of 524,190 sq. km (Latitude 21°57'N to 29°27'N and Longitude 82°42'E to 100°18'E) starts from the Kaligandaki Valley in central Nepal up to northwest Yunnan in China. The region includes Bhutan, parts of India (North East Indian states, and the Darjeeling hills of West Bengal), northern Myanmar, and southeast Tibet and parts of Yunnan in China (Tse-ring *et al.,* 2010). Rai *et al.* (2018) estimated biomass and carbon stock across the timberline of Khangchendzonga National Park, eastern Himalaya and revealed that the total AGB ranged between 279.25 ±3.04 and 15.35 ±7.38 Mg ha^{-1} while the total BGB ranged between 144.76 ±8.10 and 9.85 ±4.82 Mg ha^{-1}, with the total

Table 2. Carbon estimation in extensions of Central Himalaya.

Region	AGB (tha^{-1})	BGB (tha^{-1})	Deadwood (tha^{-1})	Litter (tha^{-1})	SOC (tha^{-1})	Total (tha^{-1})	Source
Kumaun	639.8	160.4	-	-	-	800.2	Rana *et al.* (2015)
Garhwal	890.97	245.95	-	20.5	1646.2	2797.62	Sheikh *et al.* (2020)
Tarai	239.36	60.92	-	-	-	300.28	Adhikari *et al.* (2020)

Abbreviations: AGB-Above Ground Biomass; BGB-Below Ground Biomass; SOC-Soil Organic Carbon; tha^{-1}- Tonnes per hectare carbon content ranging between 195.03 ±2.32 and 11.59 ± 5.61 Mg C ha^{-1}. Oo *et al.* (2006) assessed the biomass of the planted forests of 2 main species and biotic climax of shrub and grass communities in Myanmar. The biomass of the *Eucalyptus camaldulensis* forests ranged from 3.80 to 27.68 Mg ha^{-1} and that of the planted *Acacia catechu* forests was 10.62 Mg ha^{-1} whereas the biomass + litter weight of biotic climax of shrub and grass communities varied between 2.36 and 23.14 Mg ha^{-1}.

For estimation of carbon sequestration, Thant *et al.* (2012) carried out study in mangrove plantations and a natural regeneration stand in the Ayeyarwady Delta, Myanmar and reported the total carbon stock of 73 Mg, 43 Mg, 21 Mg and 18 Mg C ha^{-1} in NR (*Ceriops decandra, Bruguiera sexangula* and *Aegicerus corniculatum*), *Sonneratia apetala, Avicenia marina* and *Avicenia officinalis*, respectively. Similarly, Aye *et al.* (2011) conducted a study in Myanmar and estimated the biomass and total carbon stock of *Xylia xylocarpa* (80.4 ton ha^{-1} and 120.5 ton ha^{-1}) and of *Pterocarpus macrocarpus* (77.2 ton ha^{-1} and 130.8 ton ha^{-1}). The total biomass carbon pool production in north-eastern India was 460.5 Mg ha^{-1}, of which AGB and BGB contributed 91.20% and 8.8%, respectively. Results indicate that, out of total biomass, 77% contribution was by *Pinus kesiya*, 13.5% broad-leaved tree species, 0.12% shrub, 0.03% herb and 0.5% litter. The annual NPP assessed was 17.5 Mg ha^{-1} yr^{-1} (Baishya and Barik, 2011).

Baral *et al.* (2009) assessed the above-ground carbon stock in the five major forest types of Nepal using allometric equations and estimated the above-ground carbon stock per hectare and carbon sequestration rate ranging between 34.30-97.86 dry wt. ton ha^{-1} and 1.30-3.21 ton ha^{-1} yr^{-1}, respectively. Similarly, Mandal *et al.* (2013) established allometric equations for *Eucalyptus camaldulensis* to estimate biomass of Sagarnath Forest, Nepal. Bhatta *et al.* (2018) studied carbon stock variation among trees of planted forest of Kathmandu, Central Nepal. The biomass of 418.2 Mg ha^{-1} and C-stock of 196.4 Mg C ha^{-1} were estimated. Using Sentinel 2 data, Pandit *et al.* (2018) made an assessment of AGB in sub-tropical buffer zone community forest in Parsa National Park, Nepal and estimated the average AGB of 153.04 ton ha^{-1}. Poudel *et al.* (2011) estimated AGB of *Cinnamomum tamala* grown in the western hill regions of Nepal using destructive technique. The maximum AGB was in stem (47.24 % tree^{-1}) followed by leaves (22.75 % tree^{-1}), branch (19.69 % tree^{-1}) and bark (10.31 % tree^{-1}). Gurung *et al.* (2015) estimated carbon stock under different management regimes of tropical Sal forest in the Terai Nepal. The total C stock ranged from 291.55 ±42.51 Mg C ha^{-1} at protected areas, followed by 237.15 ±32.54 Mg C ha^{-1} for community forests, 189.16 ±26.46 Mg C ha^{-1} for government-managed forests and 126.76 ±56.36 Mg C ha^{-1} in other forests. Similar study was assessed by (Banik *et al.,* 2018) in Sal forests under two management regimes in Tripura. Majumdar *et al.* (2016) estimated biomass of selected tropical forest patches of Tripura, with the help of allometric equations where biomass ranged between 37.85 to 85.58 Mg ha^{-1}. Mishra and Sarkar (2019) studied the relationship between total organic carbon and soil carbon pools under different land management systems of Garo hills, Meghalaya, where maximum total organic carbon (TOC) were shown by tea gardens (62.75 ±1.47 ton ha^{-1}) and the minimum by jhum lands (33.34 ±5.04 ton ha^{-1}).

Rabha (2014), reported the average aboveground biomass of 239.45 ±12.8 Mg ha^{-1} and carbon stocks of 119.73 ± 6.4 Mg C ha^{-1} in an undisturbed regenerating Sal forest of Goalpara Assam. Kalita *et al.* (2017), estimated carbon stock applying species specific volume equations, wood-specific gravity, and biomass expansion factor at Tea agroforestry system of Barak valley, Assam. The carbon stock estimates in 6, 14, and 22 years old plantation were 44.8 ±1.3, 50.2 ±4.6, and 56.7 ±4.9 Mg C ha^{-1}, respectively. Similarly, towards the North-East India, Gogoi *et al.* (2017) estimated biomass and carbon stock of rain forest under the Dibrugarh Forest Division, using suitable regression equations.

Sharma *et al.* (2018) studied the diversity of trees and carbon stock of Hmuifang forest, Mizoram, using allometric equations. The results showed the total carbon stock and total CO_2 sequestration of 468.26 ton ha^{-1} and 1718.5 ton ha^{-1}, respectively. At Muli Bamboo forest of Mizoram, Devi and Singh (2019) estimated the rate of carbon stock as 50.25 Mg C ha^{-1} in Lengpui and 56.37 Mg C ha^{-1} in Kelsih. Devi and Yavada (2015) carried out study for estimation of carbon stock and carbon sequestration rate in a tropical deciduous forest of Manipur, the AGB ranged between 18.27-21.922 ton ha^{-1}, the carbon stock from 9.13-10.96 ton C ha^{-1} and the carbon sequestration rate differed from 1.4722 to 4.64136 ton ha^{-1} year^{-1}. Thokchom and Yadava (2017) assessed biomass and carbon stock in ten forest stands along an altitudinal gradient in the forest of Manipur where AGB ranged between 124.56 and 254.99 ton ha^{-1} and carbon stock ranged from 60.09 to 121.43 ton ha^{-1}. Niirou and Gupta (2017) analysed carbon stocks in different form of land uses in Senapati district of Manipur. The results indicated the carbon stocks ranging from 25.51-164.81 ton ha^{-1}.

Tshering (2019) made an assessment of C stocks in Western Bhutan Himalaya and recorded highest biomass and carbon stock from Thimpu forest with 62.306 Mg ha^{-1} and 31.153 Mg C ha^{-1}, followed by 55.503 Mg ha^{-1} and 27.752 Mg C ha^{-1} for Khasadrapchu forest, 41.556 Mg ha^{-1} and 20.778 Mg C ha^{-1}for Chamgang forest and 32.133 Mg ha^{-1} and 16.066 Mg C ha^{-1} for Gidakom forest, respectively (Table 3). Tashi *et al.* (2017) based on harvest method estimated biomass and carbon stocks of forests along altitudinal gradient in the eastern Himalayas and found the aboveground C stocks increased with altitude from 57

Table 3. Carbon estimation in extensions of Eastern Himalaya.

Region	AGB (tha^{-1})	BGB (tha^{-1})	Deadwood (tha^{-1})	Litter (tha^{-1})	SOC (tha^{-1})	Total (tha^{-1})	Source
Myanmar	66.14	12.75	-	5.01	131.46	215.36	Aye *et al.* (2011)
China	1235.6	-	-	-	1095.6	2331.20	Zhang *et al.* (2013)
Nepal	634.56	-	-	-	-	634.56	Baral *et al.* (2009)
Bhutan	211.09	-	-	-	-	211.09	Tshering (2019)
Sikkim	53	16.07	1.51	1.99	98.69	171.04	FSI (2019)
Meghalaya	30.55	8.74	0.43	2.53	63.46	105.72	FSI (2019)
Tripura	32.44	7.14	0.38	2.81	55.68	98.44	FSI (2019)
Assam	30.3	7.47	0.39	2.55	55.66	95.37	FSI (2019)
Manipur	26.55	7.9	0.3	2.33	69	106.08	FSI (2019)
Arunachal Pradesh	49.61	15.05	1.17	2.31	89.5	157.65	FSI (2019)
Mizoram	24.98	5.51	0.25	2.51	53.7	108.54	FSI (2019)

Abbreviations: AGB-Above Ground Biomass; BGB-Below Ground Biomass; SOC-Soil Organic Carbon; tha^{-1}- Tonnes per hectare

to 207 Mg C ha^{-1} using the best-fit models.

GEOGRAPHICAL DISTRIBUTION OF PUBLICATIONS

The geographical distribution of publications as an indicator of the research productivity has become a field of interest. The trend of publications was analysed for four decades from the year 1980 to 2020. The majority of publications on biomass/carbon estimation in the Himalaya hotspot are from Eastern Himalaya (51 %), while 27% are from Central Himalaya and 22% from Western Himalaya (Fig. 2). In the Western Himalaya, there is no evidence of papers being published in journals during 1980-1990 and the number of publications accessed for 1991-2000 was only three. However, the decade between 2011 and 2020 was particularly significant, with a total of 38 articles. Out of 41 publications, the majority of the studies were carried out in Himachal Pradesh (32%), followed by Kashmir Himalaya and Pakistan (20%) and Uttarakhand (17%). Doon Valley comprised only 7% of the publications, whereas only one publication are from Punjab and Haryana. Similarly, towards the Central Himalaya, the number of publications during 1980-1990 and 1991-2000 was 11 and 4, respectively, while the number of research studies increased during 2001-2010 and 2011-2020 as 11 and 24, respectively. Among 50 publications, 29 publications (58%) are from Kumaun,

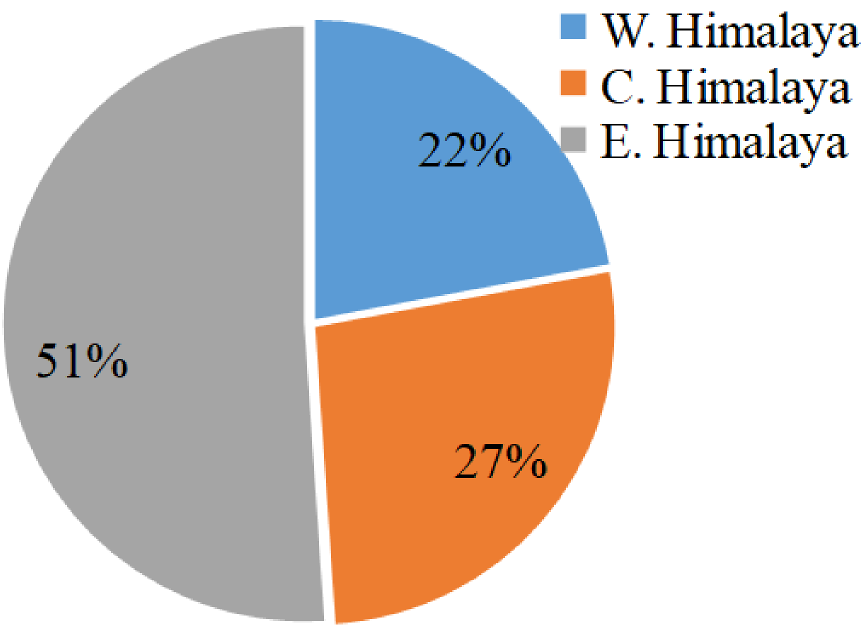

Fig. 2. *Percentage record of carbon related publications in the Himalayan region.*

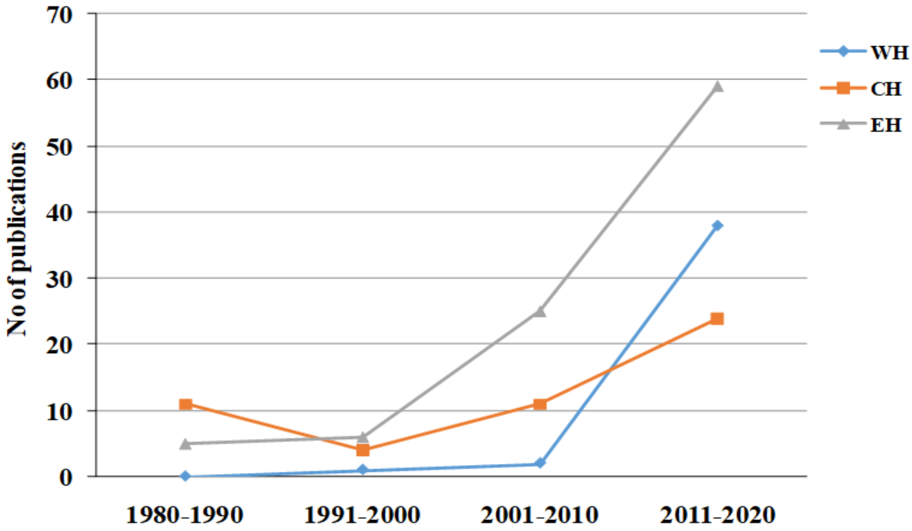

Fig. 3. *Pattern of carbon related publications from the Himalaya hotspot.*

32% from Garhwal and 10% from Tarai region. Our review shows that a huge number of papers were published from the Eastern Himalaya (Fig.3). Between 1980 and present, 95 publications were documented. Nepal and north-east region of India are the most studied area, comprising 62% of the total. China (25%) is the second most studied area, followed by Myanmar (9%), whereas Bhutan (3%) and Sikkim (1%) are comparatively less studied in the Eastern Himalaya. It is to be noted that the concept 'biomass/carbon estimation' exhibits a sudden and marked increase in publications after 2001. The pattern of the research interest indicates that there is a requirement for prioritizing future research in the Himalaya.

Conclusion

The Himalayan forests have the potential to mitigate climate change and global warming. The present communication has highlighted different aspects of estimation of forest's biomass to assess the carbon loss and gain in the Himalaya hotspot. Although, there have been several scientific studies conducted from the western to eastern extensions of the Himalaya hotspot forests related to biomass and carbon stocks, there is a need to develop methods for precise estimation rather than the conventional laborious approach. From policy standpoint, there is a need to recognize the essence of the pristine Himalayan region for their carbon sequestration and ecosystem services.

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Conflict of interests

The authors declare that they have no conflict of interests.

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