Carbon sequestration potential of disturbed and non-disturbed forest ecosystem: A tool for mitigating climate change

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Received 14 September, 2020; Accepted 6 November, 2020

Climate change is the severest environmental threat of the 21st century. The main factor responsible for the current pace of climate change is attributed to anthropogenic emission of greenhouse gases (GHGs), mainly carbon-dioxide (CO₂). So, the aim of reducing carbon sources and increasing the carbon sink can be achieved by protecting the carbon pools. Forests are the largest carbon pool on earth as they hold more than 80% of all terrestrial above ground carbon (AGC) and more than 70% of all soil organic carbon (SOC). Therefore, forests are found to play a key role in the emission mitigation by sequestrating the atmospheric carbon into biomass and soil, and it plays an important role in the global carbon cycle. This article is focused on to understand the carbon sequestration potential of disturbed and undisturbed/managed forest ecosystems due to community interventions which could have a significant contribution against global climate change. It concludes that managed/undisturbed forests are the most effective and consistent sinks of GHGs compared to unmanaged forests. Besides the forest biomass, forests soils also have the potential to slow down the rate of atmospheric CO₂ enrichment through the process of carbon sequestration. Therefore, proper and systematic management of forests can store a huge amount of carbon, contribute to mitigate climate change, and help to achieve the required goal of emission reduction as per Kyoto Protocol. Hence, further research is needed to develop a better understanding on the impacts of disturbances on carbon sequestration of the forests ecosystem.

Key words: Biomass, carbon pools, carbon sequestration, climate change, forests, greenhouse gases.

INTRODUCTION

Climate change is the most serious threat of the 21st century. It has been considered as one of the debatable burning issues among scientists as well as political communities globally (Ferrarini, 2012). Climate change is

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Carbon sequestration is the process of net removal of carbon from the atmosphere and depositing it into long-lived pools/reservoirs of carbon principally through changes in land use (Mandal and Van Laake, 2005). Forests are capable of effective sequestration and storage of atmospheric carbon in above-ground and below-ground biomass by way of processes of photosynthesis and tree growth (Liu et al., 2016). These terrestrial ecosystems are productive and susceptible to environmental fluctuation, which varies with seasonal carbon fluxes and other functions occurring in the forests (Baldocchi, 2008; Stoy et al., 2008; Smith et al., 2015). To sequester the carbon in terrestrial ecosystems, there are mainly 3 basic mechanisms which are as follows (Jina et al., 2008).

(i) By increasing the amount of carbon inputs to an ecosystem
(ii) By segregating the total amount of carbon to longer-lived pools, and
(iii) By increasing the reliability of possible existing carbon pools. The general objective of carbon sequestration activities is to uphold the ecosystem in the sink phase. Although, if the system is disturbed from the activities such as forest fire, timber logging or land cultivation, a large quantity of previously accumulated carbon may be released into the atmosphere through combustion or decomposition (Scharlemann et al., 2010; Joshi et al., 2020).

Similarly, soil also plays a vital role in carbon sequestration by increasing soil organic carbon. The carbon pool in the soil is more advanced than the vegetation carbon pool (IPCC, 2006). Out of the total global terrestrial carbon pools, 60% of the carbon has been found shared by forests and soil only (Winjum et al., 1992) and a single forest ecosystem comprises more than 90% of the land sequestration capacity (EPA, 2016). Thus, forests play a vital role in the regional and global carbon cycle because they sequester a large fraction of carbon in vegetation and soil as well as exchange the sequestered carbon with the atmosphere through the process of photosynthesis and respiration when they get disturbed by natural or human causes. Hence, the forests and soil can be well managed to sequester or safeguard substantial amounts of carbon on the land (Brown et al., 1996; Sharma et al., 2011). Carbon emission from deforestation accounts for an estimated 20% of global carbon emission (IPCC, 2007), second only to that produces by fossil fuel combustion (Campbell et al., 2008). The emergent trees and other vegetation absorb CO₂ from the atmosphere and combine it with water to produce sugars and carbohydrates which is the result of the removal of 3.67 ton of carbon dioxide from the atmosphere (Hunt, 2009). This global importance of forest ecosystem emphasizes the need to accurately determine the amount of carbon stored in different forest ecosystem (Nizami, 2010).

defined as “alteration in the climate which is directly or indirectly attributed to an anthropogenic activity that modifies the global composition of atmosphere” (UNFCCC, 2001). The global climate is changing more drastically in the present than in the past period. The anthropogenic activities that contribute GHGs are the major causes of recent climate change and the concentration of GHGs has been found to increase over the past centuries. Carbon has been existing in the earth's atmosphere for vast periods of geological history primarily in the form of carbon dioxide gas that constitutes a very small percentage of the atmosphere that is about 0.04% approximately (Halmann and Steinberg, 1998).

According to the Intergovernmental Panel on Climate Change (IPCC)’s fifth assessment report, climate change is already adversely affecting the ecosystem and is expected to continue (IPCC, 2014). IPCC synthesis report (2014), mentions that the last three decades have been experienced as warmer decades than any foregoing decade since 1850. On the other hand, globally averaged combined data as calculated by a linear trend on land and ocean surface temperature shows a warming of 0.85°C (0.65 to 1.06°C) from 1880 to 2012. Moreover, the period from 1983 to 2012 was the warmest in 30 years since 1400, specifically in the Northern Hemisphere where such assessment is feasible (IPCC, 2014). IPCC (2014) has predicted 3.7 to 4.8°C warming if the business as usual continues. The continuous increase in greenhouse gas emission due to anthropogenic pressure would further amplify the rate of increase in temperature and intensify the frequency of extreme weather events including floods, droughts, changing rainfall patterns, water resources depletion, and severe heat/cold waves.

Nepal also has experienced direct impacts of climate change, and it is recognized as one of the most vulnerable countries to climate change globally. The data trend from 1975 to 2005 shows that the mean annual temperature has been increased by 0.06°C, while the mean rainfall has decreased by 3.7 mm (-3.2%) per month, per decade (MoPE, 2016). Similarly, mean annual temperature is expected to increase between 1.3 to 3.8°C by the 2060’s and 1.8 to 5.8°C by the 2090’s; while annual precipitation can diminish by the range of 10 to 20% across the country (MoPE, 2010). To control global warming and rapid climate change, there are many options such as the mitigative option which comprise sequestration of CO₂ and reduction of emission; the adoptive option which consist of adjustment in ways that reduce the negative impacts of the environment in temperature; and indirect policies like controlling population growth or changing technologies. Among the options, increasing the consistency of carbon sequestration potential in forested areas is the best and cost-effective mitigative option (IPCC, 1995). The importance of forested areas in carbon sequestration has already been well recognized and documented (Sohel et al., 2009; Tiwari and Singh, 1987).
Deforestation and forest degradation are the main drivers that have a direct impact on the lives of 1.6 billion people whose livelihoods depend on forests; among them, one billion are the world’s poor (Madhurima and Banerjee, 2013). In every two seconds, an area of forest equivalent to football ground is being destroyed by illegal loggers around the globe; as a result, consequences are the release of $\text{CO}_2$ emission (IPCC, 2014). Similarly, more than 50% of the tropical forests have been devastated globally since the 1960s, and in every second, more than one hectare of tropical forests is being destroyed or significantly degraded. Halting deforestation and forest degradation can support to stop 18% of $\text{CO}_2$ emission (IPCC, 2014) and one of the important purposes of REDD (Reducing Emissions from Deforestation and Forest Degradation) is to enhance the forests (Araya and Hofstad, 2016). REDD has been therefore evolved into REDD+ integrating the degree of conservation, sustainable management of forests, and enhancement of forest carbon stocks. For combatting the impact of climate change, REDD+ is considered as an effective and efficient mitigation mechanism in tropical countries (Skutsch and Laake, 2008). In this review paper, we report to understand the current status of carbon sequestration potential of disturbed and non-disturbed forest ecosystem along with mechanisms and factors affecting carbon dynamics with a limited focus on climate change mitigation strategies through all literature and secondary information.

**FOREST ECOSYSTEMS: AS CARBON SINK**

The forest is a reservoir, a component of the climate system where greenhouse gas is captured, as well as a sink, a process that removes GHG from the atmosphere (IPCC, 2000; Herzog et al., 2000). Forest ecosystem shows dual characters in balancing the global carbon cycle. Its strong mitigation potential makes carbon management as a main component of proposed future natural climate solutions (Griscom et al., 2017; Fargione et al., 2018).

In one aspect, it plays the role of the sink by sequestering the atmospheric $\text{CO}_2$ through the process of photosynthesis, while in others it plays the role of source by releasing carbon through land-use change. The role of forests in carbon sequestration is probably best understood and appears to offer the greatest near-term potential for human management as a carbon sink. Carbon content in soil of the biosphere is potentially feasible sink for atmospheric carbon (Lal, 2004). The sink capacity of forest increases when tree density and area expand. It stores more $\text{CO}_2$ (4500 Gt $\text{CO}_2$) than the atmosphere (3000 Gt $\text{CO}_2$) (Prentice et al., 2001). In average, 50% dry weight of the biomass is a carbon (MacDicken, 1997). Forest soil and vegetation contributes nearly 60% of the global terrestrial carbon (Winjum et al., 1992). Therefore, forests are very critical in the emission of carbon into the atmosphere. When trees are cut down, carbon stored in above and below-ground biomass and the soil is liberated back into the atmosphere. In the global carbon pool, forests share 17-20% of the greenhouse gas emission (CO$_2$) (IPCC, 2007). This is higher than the emission by the whole transport system. The total contribution of Nepal to the global annual GHG emission is about 0.025% (MoPE, 2004). The very simple and least cost-effective solution to abate global climate change is afforestation, reforestation, conservation and management of forests (Brown et al., 1996). Since, forest functions as emission sources as well as viable sinks of atmospheric carbon, prudent sustainable community forest management will be the milestone steps in trade-off of the carbon concentration in global mitigation of climate change (Banskota et al., 2007).

Carbon stored in a forest ecosystem is classified into 5 major carbon pools by Good Practice Guidelines developed by IPCC (2006). The living portion of biomass is divided into two pools: aboveground biomass and belowground biomass. Dead organic matter is also classified into two pools: deadwood and litter. The fifth pool is soil organic matter, which consists of a substantial amount of organic carbon. The different carbon pools of the forest ecosystem are shown in Figure 1.

**CLIMATE CHANGE AND REDD+**

$\text{CO}_2$ is simply sequestered by the plants through photosynthesis and respiration when they get disturbed by natural and human causes (Brown et al., 1996). This sequestered carbon is now stored as plant biomass (IPCC, 2006). This process is an important strategy to minimize the risks of climate change. Reducing Emission from Deforestation and Forest Degradation (REDD) is the proposed mechanism which is developed at the United Nation Framework Convention on Climate Change (UNFCCC) in Bali, Indonesia in December 2007. This is such a mechanism in which those who help to reduce carbon dioxide emission through reducing deforestation and forest degradation, in turn, would be paid. Here, the developing countries conserve their forest in their way, and in return they were compensated through the carbon credit they have accumulated. The concept of REDD is not a new idea. Compensating tropical forest conservation was proposed by environmental scientists in the 1980’s and 1990’s, but it gained popularity at the international level, when it was discussed in UNFCCC forums, especially at COP-3 in Kyoto in 1997. Kyoto Protocol established a policy to reduce GHG emission through reforestation and afforestation (Corbera et al., 2010).

The Coalition for Rainforest Nations (CfRN), a group of tropical countries lobbying for the inclusion of forest
conservation, put forward the REDD policy in consecutive UNFCCC that received attention in Bali Action Plan, 2007. Now, this has proliferated as REDD+ that includes reducing emission from sustainable management and forest enhancement in excess. The participation in the Reducing Emissions from Deforestation and Forest Degradation plus (REDD+) mechanism has a brighter prospect for Nepal as it has opened the door for Nepal's forest to participate in carbon trading, to generate carbon revenues as well as non-carbon benefits for the nation and the people where preliminary estimates show that REDD+ may bring between $20-86 million per year to Nepal (UN-REDD, 2014). By enhancing the carbon sequestration rate of the community forest, Community Forest User Groups (CFUGs) could gain monetary benefits through carbon credits, and dependent indigenous peoples could get the benefits and maintain a sustainable livelihood. In context to climate change, community-based forest management can be a potential contributor to REDD+ schemes/programs in the near future which may also help to achieve the binding target of Kyoto protocol to offset emissions.

**FORESTRY AS MITIGATION OPPORTUNITIES**

Forest ecosystems offers several ecosystem services such as provisioning, regulatory, supporting, and cultural services that are important to the lives and livelihoods of humans, and they also play a significant role in sustaining environment and habitats that support global biodiversity (Raich et al., 2014; Escobedo et al., 2011). Compared to other terrestrial ecosystems, forests store the most carbon (Pan et al., 2011), with the majority of sequestered carbon held in woody biomass (Scott et al., 2004). Due to this, forests can also play a vital role in global climate change mitigation (Millar et al., 2007) (Figure 2). Carbon sequestration by forest was a subject matter of the Kyoto protocol, 1997, and was looked like a potential climate change mitigation options. Mitigation opportunities by using the forest as a potential instrument are:

(i) Increasing the standing phytomass and soil biomass, either through expanding the area of forest, increasing the growth rate of existing forests, or reducing the rate of forest loss and/or conversion to other land uses.
(ii) Increasing the storage of carbon in long-lived forest products.
(iii) Substituting wood products for other materials whose manufacture and usage causes more carbon to be emitted to the atmosphere.
(iv) Utilizing biomass energy as a replacement for fossil fuels.

The above mitigation opportunities would come to an effect on multiple regimes. One of the regimes is by providing economic incentives to encourage additional tree planting and conservation efforts that bring positive CO₂ balances and to offset the CO₂ emission (Sampson and Sedjo, 1997). However sometimes, carbon stored in the forest ecosystem may return to the atmosphere by disturbances such as fire and insect outbreaks, exacerbated by climate extremes and climate change. As a result, it may cause a high risk for climate change mitigation through forest ecosystem. Hence, it is concluded that proper management of natural forests has greater potential to store more amount of carbon which can be a cost-effective tool to mitigate climate change (Figure 3).

**DISCUSSION**

Recent decades shows the escalating trend of climate change which directly or indirectly impacts on ecological
systems and livelihoods worldwide, and the vulnerability of forest-dependent communities raise concerns about the consequences of ecosystem changes for human well-being. The various shreds of evidence collected from local climate stations of the Himalayas overwhelmingly show a global warming trend at different rates and in different periods depending on specific regional and seasonal circumstances (Gautam et al., 2013). Several studies evaluating the impact of climate changes in forest ecosystems in India has been published recently by Gopalakrishnan et al. (2011). However, most of these studies are lacking the assessment of predicted development at the local level (Upgupta et al., 2015). According to Levy et al. (2004), the forest ecosystem acts as a major biological scrubber of atmospheric CO₂ which can significantly increase its efficiency when careful management and conservation is done. Hence, the managed forests are known for its effective and reliable sinks of GHGs accumulating more carbon stock than disturbed forests. However, Klooster and Masera (2000) found that among the different practices of sustainable forest management prevailing in the world, community-managed forestry programs are the most desirable options of carbon sequestration, primarily in emerging
countries. The community-based forestry programs are supporting to impound a higher amount of carbon stock into biomass as well as in soil through two approaches. Primarily, there is a substantial increase in carbon pool due to active reforestation or afforestation in a waste/barren land, and secondly, reduced emissions due to the control of deforestation. Carbon sequestration in forest soil has huge potential to lessen the rate of enrichment of atmospheric concentration of CO₂ (Joshi et al., 2020). The carbon stock of the forest soils can be enhanced through sustainable forest management including various management activities such as site preparation, afforestation, selection of the species, species management, use of fertilizers, and fire management (Banik et al., 2018). However, as per the study conducted by Lal (2004), the efficiency of carbon stock and its productivity in any forest ecosystem depends on the age of its vegetation. It is well-known that tree plantation in the forest ecosystem generally have higher carbon sequestration capability beyond maturity which would vary from 25 to 75 years depending upon the type of forests (Lal and Singh, 2000). Thus, plantation of trees on disturbed/degraded forest ecosystem can be a better option for long term carbon storage that ultimately acts as a tool for combating climate change.

However, natural/undisturbed forest ecosystem resulted in lower above-ground biomass (AGB) due to the wide variation in stand structure and tree growth. Different stages of forest growth cycle, varying tree density, species variability, and its habitat are the other factors liable for lower AGB (Terakunpisut et al., 2007) In natural forest ecosystem, many researchers have stated that there is a net addition to standing biomass leading to carbon storages only until maturity of trees which may arise due to various erratic and contemporary disturbance events (Baishya et al., 2009). The total amount of gross primary productivity in a mature forest ecosystem is either consumed in respiration or reverted to the soil as litter with no net addition to the standing biomass (Jassal et al., 2007). Hence, these matured natural/undisturbed forest ecosystems do not contribute significantly towards carbon accumulation, though helps to promote regeneration and biodiversity in a sustainable manner.

In a study conducted by Brown et al. (1996), it was found that the progressive carbon dynamics distinguished by long phases of steady build-up of biomass (sink), substituted with short periods of huge biomass loss (source). Thus, the forests ecosystem alters between being a source or a sink for existed carbon pool (Dixon et al., 1994). It is well-understood that the binding target of declining carbon sources and increasing the carbon sink can be attained well by managing and conserving the carbon pools in existing forest ecosystems (Binkley et al., 2002). However, based on the disequilibrium theory, given by Luo and Weng (2011), the depletion of C due to disturbance drives the C cycle towards a disequilibrium stage. At the disequilibrium stage when the C pool size is smaller than the equilibrium size, respiratory CO₂ release is less than the photosynthetic influx, leading to C sequestration and an increase in the C pool size over time. With the gradual increase of C accumulation, the ecosystem will get to a new equilibrium state. In a study, conducted by FAO (2006), it was found that the total carbon content in the world’s forest ecosystem was 638 Gt of carbon, in which biomass accounts for 44%, soil carbon up to 30 cm depth includes 46%, dead-wood 6% and litter 4% of total forest ecosystem carbon. According to the FAO total carbon stock of the whole world is 161.1 ton per ha. FAO (2010) global forest resource assessment report indicates that the world’s forests store more than 650 billion tons of carbon, 44% in the biomass, 11% in dead wood and litter, and 45% in the soil, estimating total carbon stock of the world more than 289 Gt. FAO (2010) assessed the global average of regional distribution of carbon stock to be 161.8 ton per hectare (Table 1).

In recent years, there has been made a substantial progress towards a deeper understanding of the process of controlling carbon storage that ultimately helps in improving and deploying predictive models of C dynamics that can guide policy and decision-makers. However, it is equally true that many new (and some old) gaps in our knowledge have been identified and the need for further research has been assessed. The sustainable management and conservation of forest ecosystem effectively augments biomass and carbon that might be used to offset emissions globally (Binkley et al., 2002). Similarly, SOC forms a major portion of the overall carbon content of many forest ecosystems, and if the ecosystem is cleared then the accumulation and disintegration rates of SOC may have a direct influence on comprehensive carbon stability of forest ecosystem (Banik et al., 2018). More specifically, accepting the contribution and distribution of SOC in forest ecosystems is significant for improving its soil quality and production sustainably (Liu et al., 2016). The total amount of biomass captured in the forest ecosystem under community-based forest management (CBFM) depends upon its different practices of forest management and awareness level among the local users (De Stefano and Jacobson, 2018). The concept of forest management was progressed after the late 1970s when massive deforestation started to occur in state-controlled forests (Gautam et al., 2008). According to Thoms (2008), after accepting the dependence and contribution of local users on the forest ecosystem and their significant role in the conservation aspect, the concept of the consumption of these forest products sustainably must arise within the management. To overcome these challenges it may require a drastic change among the forest policy-makers for comprehensive decision making. Local forest users groups should be engaged in this sort of forest management practices to promote them towards the conservation and protection of the forest ecosystem.
Climate change is the most severe environmental threat of this century. It is concluded that increasing carbon emission in the atmosphere is one of today’s major concerns that can be overcome by managing and increasing forest cover. Forests are found to be the largest carbon pool on earth surface that acts as a major source and sink of carbon in nature. As the importance of forested areas in carbon sequestration has been already well recognized and documented, it has the potential to form a principal constituent in the mitigation of global warming and adaptation to climate change. Thus, the selection and plantation of species that store more carbon are highly recommended for all forest types. Similarly, soil also plays a vital role in carbon sequestration by increasing soil organic carbon. The carbon pool in the soil is higher than the vegetation carbon pool. Though the forest is the most imperative land use for mitigation of GHGs, agro-forestry intervention in the farming sector seems to be the most appropriate land use strategy for carbon sequestration. It is well-known that the assessment of carbon stocks in forest ecosystems will enable us to estimate the amount of carbon loss during deforestation or the amount of carbon that a forest can capture when such forests are regenerated. The carbon sequestration trend in afforested forests or reforested forests is generally found to be higher in comparison to the old forest. Thus, it is highly recommended for the plantation in barren and wasteland to regulate the climatic condition and to get benefit from carbon trading. Hence, properly managed forests are seen to be the most consistent and effective sinks of GHGs capturing more amount of carbon than unmanaged/disturbed forests. It also shows the huge potential of storing and sequestering carbon in the community forest as well. Similarly, carbon sequestration in forest soils also has a great potential to lessen the rate of enrichment of atmospheric concentration of CO2 too. Therefore, it is proven that proper management of natural forests has the potential to store more amount of carbon which can be a cost-effective tool to mitigate climate change.

### RECOMMENDATIONS

The increasing phenomenon of climate change and its effects on human lives have been a worldwide issue of discussion and debate in recent years. Forests are a large pool of both the carbon sink and sources. Inadequate information about the status of biomass and carbon stock in the forest has been a major problem to estimate the total contribution of forest carbon sequestration. Hence, to increase the viable sinks of atmospheric carbon and for climate change mitigation, following recommendations should be practiced:

(i) It is recommended to conduct sufficient research in different forest types, different agro-climatic zones, different soil types, and different forest management systems to collect enough data on carbon stock and sequestration.

(ii) The allometric equation for the different tree species of different ages are recommended for precise and accurate calculation of biomass of tree species of the forest ecosystem at local and regional levels.

(iii) It is recommended to use remote sensing techniques with limited field data that can help to get forest resource assessment over a large area in a cost-effective manner within a short period.

(iv) The selection and plantation of species that store more carbon is highly recommended for all forest types. Based on the research and study, the tree species like Shorea robusta, Tectona grandis, etc. are recommended for Terai region and the species like Pinus roxburghii,
Cedrus deodara, etc. are recommended for hilly regions. (v) Carbon content varies with species to species; therefore, species-specific assessment of carbon stock should be prioritized. (vi) It is recommended to manage the forest effectively as it has enormous potential to sequester more carbon, which could be useful to different forest user groups if the forest is included under the clean development mechanism. (vii) The carbon sequestration efficiency in younger forests is generally found higher compared to old forests. So, it is strongly recommended for the plantation in a barren land and wasteland to regulate the climatic condition and to get benefit from carbon trading. (viii) The economic valuation of forest carbon sequestered must be carried out and public awareness would be raised about the benefit of carbon sequestration.

**CONFLICT OF INTERESTS**

The authors have not declared any conflict of interests.

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