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Carbon and Biodiversity Co-benefits in Tropical Forest and Agroforestry Ecosystems: A review

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Abstract

Global efforts to mitigate climate change are focused on the protection and restoration of forest carbon. These efforts do not only hold promise for climate protection but also other benefits including conservation of biodiversity, the majority of which is sheltered in the forest. These include actions to combat climate change and land degradation and actions to halt biodiversity loss through sustainable forest management. However, the challenge remains as to what extent forest conservation that optimizes carbon storage will conserve biodiversity. Understanding synergies between climate change mitigation and biodiversity conservation could be the basis for attaining sustainable development goals. Library catalogues and public database for studies that included carbon stock and biodiversity co-benefits/relationships in tropical forests were searched and included in a review. This review reveals that forest conservation for carbon is showing promising results for biodiversity in undisturbed/relatively disturbed tropical forest ecosystems. However, some areas with high biodiversity but low carbon may not benefit from carbon-based conservation. Given the tropical ecosystem dynamics, it is important to generate more data based on a specific ecosystem to ascertain the level of this co-benefit. This review forms the basis for considering biodiversity conservation in carbon-based conservation planning.

Keywords: Carbon storage; Carbon stock; Co-benefit; Correlation; Conservation

Background

Carbon sequestration and biodiversity conservation are among the crucial environmental benefit of the forests. Additionally, they are also at the forefront of scientific policy and discussion (Grassi et al. 2017). Worldwide forest stores 80% of the above-ground carbon (Dixon 1994, Goodale et al. 2002, Santoro et al. 2021, IPCC 2018), but also provide habitat for vertebrate and invertebrate animals (Lindermayer and Franklin 2002, FAO 2018). As a result, thoughtful efforts are ongoing to protect forests and restore degraded forests, particularly in the tropics. This is supported by the fact that tropical ecosystems are well known for their ability to provide ecosystem services such as carbon sequestration, but also, they are among the most biodiverse terrestrial habitats in the world (Lewis 2009). Therefore, the importance of understanding relationships between carbon stock and biodiversity in the tropical forest ecosystems is being addressed. These efforts are not only to reduce carbon dioxide accumulation in the atmosphere but also to conserve biodiversity, the majority of which is harbored in tropical forests (Lewis 2006, Anderson-Teixeira, 2018).

Reducing Emissions from Deforestation and Forest Degradation plus (REDD+) is among the efforts where billions of dollars have been invested in the United Nation's programme (Grassi et al. 2017). The "plus" denotes extra climate-protecting forest-related actions, such as sustainable forest management and the preservation and enhancement of forest carbon stores. Developing nations that reduce deforestation are eligible to earn results-based payments for their emission reductions under the framework of these REDD+ programmes. In addition, programme consists of five sets of activities namely: reducing emissions from deforestation, reducing emissions from forest degradation, conserving (existing) forest carbon stocks, managing forests sustainably, and increasing forest carbon stocks (for example by planting and regeneration on formerly forested land) (UNFCCC 2010). With this set of activities, the initiative offers developing nations incentives to reduce their emissions while preserving carbon stocks and other co-benefits like biodiversity preservation and promote development (Ghazoul et al. 2010; Strassburg et al. 2012). Even though this is good news for tropical forest conservation, it is not certain if forest conservation that enhances carbon storage will support the conservation and protection of biological diversity. The discovery of such synergies between climate change mitigation and biodiversity conservation could be basic for attaining sustainable development goals 13 and 15. These goals encampus actions to combat climate change and land degradation and actions to halt biodiversity loss through sustainable forest management (UNFCCC 2015; SDG 2015).

Correspondingly, an understanding of the extent to which efforts based on carbon conservation may support biodiversity may provide useful insight that may guide further research management and recommendations. This may also inform policy makers on proper objective formulation for climate mitigation and biodiversity conservation. Furthermore, given the limited funds available, multi-objective planning of considering carbon and biodiversity in a single framework of analysis is the best way to increase the efficiency of such limited resources for both climate mitigation and biodiversity conservation (Venter et al. 2009; Thomas et al. 2013).

Several studies from tropical forest ecosystems, have used different taxa to evaluate the extent to which biodiversity may benefit from carbon conservation efforts. Taxa used in these studies are taxonomically well known and are good indicators of environmental changes. These taxa include small mammals, birds, beetles, amphibians, plants, butterfly, ants, wasp and their parasitoids (for example Basham et al. 2016, De Beenouwer et al. 2016, Mandal et al 2013, Cavanaugh et al. 2014, Kessler et al. 2012, Martin et al 2017). Relationships between the diversity of different taxa and carbon stock have been analysed at the landscape, continental and global levels. This is emanating partly from the ecological theory by Wright (1983), which demonstrated that there is a positive relationship between carbon and abundance of animals. Based on Wright's ecological theory, a positive correlation between carbon and the abundance and diversity of animals may exist, as both could be related to primary productivity (Wright 1983). Among the suggested mechanism is that primary producers are directly linked to carbon stocking and carbon fluxes. This is evident because plants utilize atmospheric carbon dioxide during the process of photosynthesis and enhancing carbon cycle components. As a result, increased primary productivity may encourage the abundance of consumers, which could account for higher species richness since species abundance can achieve a sizeable viable population and community tenacity (Srivastava and Lawton, 1998). Numerous experimental research have provided evidence in favour of the theory (Cardinale et al. 2012, Vilà et al. 2013, Ruiz-Benito et al. 2014, Liang et al. 2016, Manhaes et al. 2016). These experimental studies have reported that, higher plant diversity can promote productivity and hence biomass. This is attained through the mechanism of niche partitioning and species interaction which further allows diverse communities to exploit resources more efficiently.

This review focuses on potential of tropical forest ecosystems for both carbon stocking and biodiversity conservation. Also, it aimed at understanding when and where carbon optimization effectively protects biodiversity, but also to guide maximization of carbon storage alongside biodiversity conservation. The available patterns of the relationship between carbon stocks and biodiversity were also scrutinized on the level of congruency and carbon conservation benefit on biodiversity. The knowledge gaps on the linkage between carbon stock and biodiversity are also highlighted.

Methodology

A systematic review of previous tropical forest studies which met inclusion criteria was carried out. Google scholar search engine was the main scientific database used to identify relevant publications on carbon stock and biodiversity co-benefit which were previously conducted in tropical forests. The search was conducted and studies were filtered to studies from tropical forest ecosystems. Therefore, studies from other tropical ecosystems which are not forest as well as other forest ecosystems which are not tropical were excluded. The review process considered works that were published from 1997 to august 2023. The work published since 1997 were considered because, it was the year when REDD style project was initiated by Noel Kempff Mercado climate action project. It was in the same year when the seeds for REDD were planted under Land Use Land Use Change and Forestry (LULUCF) and removed in 2003. Later in 2005, REDD was back into the agenda until in 2008 when the concept to broaden REDD to REDD+ so that it includes conservation, sustainable management of forest and enhancement of forest carbon stock was made (Holloway and Giandomenico 2009). Despite the fact that REDD+ was launched in 2013, several studies (including Saha et al. 2009; Egoh et al. 2009; Strassburg et al. 2010; Sharma et al 2010; Hooper et al. 2012) were reported before REDD+ was launched, hence played great role in advocacy of REDD+. It should also be noted that, this review was not limited to studies reported under REDD+ activities, rather it included all studies reporting about carbon stock and biodiversity which met inclusion criteria.

Peer-reviewed articles, international reports, books, proceeding documents and letters were searched using the keywords “carbon stock”, “biodiversity”, “soil organic carbon”, “above ground carbon”, “carbon biodiversity co-benefit”, carbon stock and biodiversity relationship, “carbon and species diversity/abundance/richness”. The search was limited by restricting retrieval to ecosystem services mentioning carbon stock. Articles that report species diversity, abundance and richness in relation to carbon stock were also retrieved. Publications written in English language were considered in this review. After a thorough screening of the abstract using the titles, 180 articles were selected for review. From the read abstract it yielded 54 publications for full review. The inclusion criteria included all publications reporting about carbon biodiversity co-benefit, the relationship or correlation between carbon stock and biodiversity in terms of species richness, abundance and diversity which are based in tropical forest ecosystems.

Results

Positive relationship between carbon and biodiversity in tropical forests

Tropical forests are well known for their ability to host a high level of biological diversity and their crucial role in balancing greenhouse gases through carbon storage (Myers et al. 2000, Houghton 2005, Gardener et al. 2012). Studies at the global and continental level are suggesting that conservation of tropical forests may curb greenhouse gases and at the same time safeguard biodiversity. A study involving tropical forest in America, Africa and Asia reported that, the above ground carbon correlated positively with both taxonomic diversity and functional dominance ($r = 0.62$. $p = 0.001$; Cavanaugh et al. 2014) and between species richness and carbon stock ($r = 0.82$, $p = 0.001$; Strassburg et al. 2010). Both studies differed significantly on the methods used in data collection. Strassburg et al. 2010 ultilised available dataset of the distribution of mammals, birds and amphibia in tropical forests. The carbon dataset was obtained from IPCC (Intergovernmental Panel for Climate Change) good governance and practice guidance (Eggleston et al. 2006) On the other hand, Cavanaugh et al. 2014 obtained data from TEAM network. The methodologies and course of analysis might have masked fine scale variations in congruency between carbon and biodiversity. Other tropical studies by Hooper et al. (2012) and Grassi et al. (2017) have revealed a positive relationship between plant species richness, plant productivity and carbon cycle components. Similarly, studies by Poorter et al. (2016) and Liang et al. (2016) have reported that higher tree species richness support higher productivity as a result of accumulating higher tree carbon. Poorter et al. (2016) and Liang et al. (2016) regarded tree diversity as a factor influencing productivity and carbon storage. Studies at global and continental level are challenged in the sense that they can only provide limited insight to carbon biodiversity co-benefit. In order to understand the implications of such heterogeneity on the relationship between carbon and biodiversity, studies at national and subnational level are more relevant.

At subnational level, it was revealed that there was a positive relationship between plant species diversity and carbon stock in southern eastern Tanzania (McNicol et al. 2018). However lower biomass areas were also diverse, implying that carbon-based conservation would fail to include important areas for conservation (McNicol et al. 2018). In Colombia, Armenteras et al. (2015) reported a positive relationship between carbon storage and biodiversity (amphibians, birds and mammals) at the national level, with the highest congruency between amphibian's species richness and carbon storage ($r = 0.67$, $p = 0.001$), but relatively lower congruency between bird species richness and carbon stock ($r = 0.43$, $p = 0.001$). In the subtropical forest of Gutianshan National Reserve in Southeast China, Liu et al. (2018) reported that plant species-rich stands had higher below and above carbon stock when compared to stands with low species richness. Liu and the team further insisted that afforestation policies elsewhere should focus on multispecies plantations to increase carbon stock. This was supported by the niche complementarity hypothesis coined by Tilman et al. 1997, accordingly species richness promotes resource use and nutrient retention as a result permitting larger carbon stocks in an area (Williams et al. 2017). Amara et al. 2019, reported a moderate positive relationship between above-ground carbon and tree species richness ($r = 0.475$, $p < 0.001$) and Shannon diversity index ($r = 0.375$, $p < 0.05$) in humid savanna landscapes in northern Sierra Leone. Furthermore, Amara et al. (2019) observed that there was a weak relationship between above-ground carbon and soil organic carbon ($r = 0.17$, $p < 0.05$), moderate relationship was reported between tree species richness and above ground carbon ($r = 0.475$, $p = 0.001$) and Shannon diversity index and above ground carbon ($r = 0.375$, $p < 0.05$). Likewise, a review by van der Sande et al. 2017 aimed at integration of approaches to enhance insight into the role of biodiversity in climate change mitigation, suggested that, higher tree species richness support higher productivity as a result of accumulating higher tree carbon. van der Sande et al. (2017) considered tree diversity as a factor influencing productivity and carbon storage. Likewise, a study by Dayamba et al. (2016) in Burkina Faso, reported a weak positive relationship but significant between tree species diversity and above and below-ground carbon pools ($r = 0.469$ $p < 0.0001$ and $r= 0.575$ $p< 0.0001$ respectively. Similarly, Shannon diversity was positively correlated to above ground and below ground biomass $r=0.283$, $p = 0.027$ and $r = 0.583$, $p = 0.0001$ respectively (Dayamba et al. 2016). In a community forest in Nepal, Aryal et al. 2018, revealed a positive relationship between soil carbon and diversity and density of trees ($r = 0.344$, $p=0.062$ and $r = 0.205$, $p=0.000$ respectively). Likewise, a positive significant relationship between mean soil carbon and density of species, endemic and threatened taxa of plants was reported in the Virunga landscape and Federal District of Brazil (Sheil et al. 2016). This implies that conserving soil carbon-rich habitats can conserve biodiversity as well. In a study to reconcile biodiversity and carbon stock conservation in Afrotropical Forest landscape, positive relationship for leaf lichens and tree species richness was revealed (Van de Perre et al. 2018). Likewise, a positive relationship between carbon stock and plant species diversity was reported in a regenerating preserved tropical landscape in southern Brazil (Capellesso et al. 2021). This supports the importance of considering regeneration as an alternative to increase carbon stocks and biodiversity in carbon-based conservation plans (Capellesso et al. 2021)

The impact of disturbance on carbon and biodiversity in tropical forest ecosystems are evident. However, some disturbed areas such as those affected by selective logging can have high tree carbon stock, this is due to the fact that, selective logging tend to leave trees which are unpreferred for timber to grow to large diameter at breast height (DBH) (Mwambala et al. 2023). It is expected that, trees with large DBH values stock high amount of carbon (Chave et al. 2003, Bastin et al 2015). Yet the effects of such disturbances on biodiversity are alarming (Hegerl et al 2017, Mwambala et al. 2019). A study by Mwambala et al. (2019) reported that abundance of carabid beetles was positively correlated with soil organic carbon stock in control sites in Uzungwa Scarp Nature Forest Reserve (USNFR), Tanzania. This suggests that the relatively undisturbed forest can support both biodiversity and carbon stocks. In another study by Mwambala et al. (2023) it was revealed that tree carbon stock had a weak positive relationship with carabid beetle’s species diversity in USNFR. Similarly, Egoh, et al. (2009) reported a positive but low correlation between carbon storage and plant species richness in South Africa. They concluded that efforts to conserve ecosystem services such as carbon may also strengthen biodiversity occasionally. This calls for multi-objectives to protect both carbon and biodiversity.

A study by Ferreira et al. (2018) reported that in anthropogenically disturbed areas, low-biomass forests, carbon is a good proxy for biodiversity (i.e. birds, dung beetles, small mammals and plants). However, the relationship becomes weak when biomass reaches approximately 100 MgC ha^{-1} equivalent to 60% of the typical biomass of an intact forest. This suggests that carbon projects targeting the restoration of highly disturbed landscapes would deliver commensurable biodiversity co-benefit, although both would be low when compared to intact forests (Ferreira et al. 2018).

In disturbed and regenerating ecosystems studies have reported contrasting results on the relationship between carbon and biodiversity, thus providing different conclusions regarding carbon biodiversity co-benefits. A study by Basham et al. (2016) found a positive relationship between vegetation carbon stock and amphibian species richness and abundance in disturbed regenerating forests; however, the authors mentioned that regenerating forests and the relatively undisturbed natural forest were in a very close proximity of which they might have led to the observed positive relationship. Through their study they suggested that carbon-based funding which support regrowth of forest can also conserve biodiversity of amphibians. Like-wise, Edwards et al. (2014) reported a positive relationship between vegetation carbon stock and dung beetles and birds in a disturbed regenerating natural forest in Borneo. Similarly, in Indian western Ghats dominated by human habitat, Osuri et al. (2020) reported a positive relationship between tree diversity and above ground carbon. This is due to the fact that, anthropogenic activities that influenced species loss consistently reduced carbon storage capacity of the landscape.

Negative relationship between carbon and biodiversity in tropical forest

The negative relationships between carbon and biodiversity have been reported by several studies using different taxa. Majority of which are emanating from anthropogenically disturbed habitat or areas with history of disturbance or least cost areas. For example, Siikamäki and Newbold (2012) have reported limited geographical overlap between carbon retention and biodiversity conservation in least cost areas. Furthermore, studies on carbon-biodiversity relationship are reported at global and continental level (Strassburg et al. 2010: Cavanaugh et al. 2014: Beaudrot et al 2016). However, given the heterogeneity level of the scale at which conclusions are made, and the fact that many tropical forests face local disturbances such as fire, logging and hunting, for instance in USNFR and Brazilian state of Para forest (Beaudrot et al. 2016, Barlow et al. 2016, Ferreira et al. 2018). Since some of the disturbances reported could be source of such variations, it is important to focus on specific ecosystems and its own disturbances (Gibson et al. 2011, Lewis et al. 2015). Siikamaki and Newbold (2012) considered carbon and biodiversity relationship at continental level, the results could be reported at finer scale and provide insightful information if could be done at national or subnational level (Ferreira et al 2018, Mwambala et al 2019).

A study by Anderson-Teixeira, (2018) suggested that carbon conservation project targeting the high carbon forest would fail to safeguard the most diverse forests. Likewise, in human inhabited areas studies by (Filqisthi and Kaswanto, 2017) and (Zimudzi and Chapano, 2016) reported lack of relationships between tree species diversity and carbon stocks for Pekarangan home gardens in West Java, Indonesia and Ngomakurira Mountain, Zimbabwe, respectively. Correspondingly, in a community forest in Nepal, Aryal et al. (2018), revealed a negative relationship between total carbon and both tree diversity and density ($r = -0.6$, $p=0.000$ and $r = -0.318$, $p = 0.086$ respectively). Similar observation was revealed in a village landscape of Cisadane watershade in west Java, Indonesia which was affected by human activities, where plant species richness and diversity index were negatively correlated to carbon stock ($r = -0.81$, $p = 0.3$ and $r = -0.16$, $p = 0.1$ respectively) (Sunardi et al. 2020). Likewise, a negative relationship was observed between carabid beetles' abundance and tree carbon stock in USNFR ($r = 0.61$, $p = 0.2$) (Mwambala et al. 2023). Similarly, Grainger et al. (2009) reported that, conservation for biomass does not entail conservation for biodiversity, due to the fact that forests are dynamic. This demand for the need to understand where and when carbon optimisation protects biodiversity, also to develop guidance for protection of biodiversity and carbon storage in parallel (Phelps et al. 2012, Gardner et al. 2012).

In naturally regenerating subtropical forests with native trees it was observed that tree species diversity was negatively correlated to carbon ($r = -0.25$, $p = 0.05$), implying that forests with higher tree species diversity had relatively lower carbon stock (Sharma et al. 2010). The situation might be attributed by the fact that, regenerating natural forest might have high tree species diversity but low carbon stock due to the low DBH size of many tree stems during regeneration process. A study by Mwambala et al. (2019) reported that abundance of ground beetles and soil organic carbon stock were negatively correlated in areas affected by anthropogenic activities such as selective logging in the USNFR. Likewise, the above ground carbon was negatively related to slime molds in Afrotropical Forest in Congo (Van de Perre et al. 2018).

Lack of relationship between carbon and biodiversity in tropical forests

Studies by Sullivan et al. (2017) and Morandi et al. (2020) reported a lack of relationship between carbon stock and tree diversity in tropical forests of South America and Africa, suggesting that, carbon centered conservation plans will certainly miss many highly diverse ecosystems. Similarly, Beaudrot et al. (2016) in a study on limited carbon and biodiversity co-benefits for tropical forest mammals and birds, found out that carbon storage was not a potential predictor for any of the diversity measures. Data on mammals and birds were collected during dry season only using camera traps which did not cover the entire study site (Beaudrot et al. 2016). This is due to the fact that, the camera traps were set at a density of one camera trap per 2 square kilometers, which might have effect on the species richness. The authors further insisted that prioritizing for carbon will not necessarily meet biodiversity conservation for ground dwelling endotherms (Beaudrot et al. 2016). The same author further argued that, conservation planning that will take into account both endotherm diversity and carbon will benefit both.

In a characteristic human modified landscape in Southeast Asia, Deere et al. (2018), reported lack of association between carbon and species richness of medium-large mammals. Likewise, lack of relationship was reported between the above ground carbon and species richness of fungi, bark lichens, flies, ants, rodents and shrews in Afrotropical Forest in Congo (Van de Perre et al. 2018). The lack of relationship between carbon stock and biodiversity have been noted in many studies which involved consumers and decomposer. The consumers and decomposers are less related to primary productivity compared to plants. Nevertheless, their diversity is a result of plant consumption and distribution of resources (Groner and Novoplansky 2013: Sobral et al 2017). Moreover, a lack of relationship between carbon and biodiversity in disturbed sites can suggest that disturbance leads to blurred or lack of association. Disturbance can affect both biodiversity and carbon in tandem. However, the manner in which biodiversity is affected is dependent on the taxon and nature of disturbances (Mwambala et al. 2023). Therefore, in order to maximise carbon stock alongside biodiversity conservation, tropical forest must be protected from disturbance.

Carbon and biodiversity relationship in tropical agroforestry ecosystems

Agroforestry ecosystems are considered as a typical land sharing strategy where biodiversity and agriculture co-occur (Phalan et al. 2011, Fischer et al. 2014). Agroforest practices have been adapted as the way to reconcile biodiversity and food security and deliver other ecosystem services in many tropical landscape, due increased demand for food as a result of human population growth (Gardner et al. 2009, Perfecto et al 2014). Nevertheless, agroforestry ecosystems are expected to conserve less number of species compared to natural forests, therefore, the number of ecosystem services are expected to be lower (Cardinale et al., 2012; Naeem et al, 2012, Gascon et al. 2015). This is due to the fact that, natural forests are exceptional with regard to biodiversity conservation Gibson et al 2011. Despite the lower ecosystem services and a smaller number of species in agroforestry ecosystems, the relationship between carbon stock and biodiversity have been reported to be positive and, in some ecosystems, it was wanting.

Positive relationship between carbon stock and biodiversity in agroforestry ecosystems

In coffee farming in Ethiopian moist montane forest, a co-benefits in terms of carbon storage and wood plant species conservation was reported ($r = 0.69$, $p = 0.001$) in a study by De Beenhouwer et al. (2016). The study further demonstrated that widespread coffee farming in Ethiopian moist afromontane forest can provide crucial co-benefit in terms of wood plant species diversity and carbon. Likewise, in parkland agroforestry system in northern Ethiopia (Gebrewahid and Meressa 2020) reported a weak linear weak correlation between tree species evenness and above ground carbon. In Kalabakan Forest reserve which was under conversion to oil palm in Malaysia, Deer et al. (2018) reported a positive relationship between carbon and threatened and disturbance sensitive mammal species. This informed that REDD+ activities in kalabakan forest could be valuable to most species which are vulnerable to land use change

In agroforestry ecosystems involving four practices such as woodlots, parkland, boundary plantation and home gardens it was reported that tree abundance was significantly correlated to total biomass carbon stock. Likewise soil organic carbon (SOC) at a depth from 0-60 cm was significantly positively correlated to tree diversity (Manaye et al. 2021). Similarly, Saha et al. (2009) reported that in agroforestry ecosystems involving home gardens soil organic carbon stock at a depth from 0-100 cm was directly related to plant diversity, implying that home gardens with higher plant species diversity had higher soil organic carbon. In cacao agroforestry ecosystem of Sulawesi Indonesia, it was reported that carbon stocks had a strong positive relationship with tree diversity ($r = 0.82$, $p < 0.05$) (Sari et al. 2020).

Lack of relationship between carbon stock and biodiversity in tropical agroforestry ecosystems

In Ethiopian highlands agroforestry ecosystems, it was reported that, ground beetles were not correlating with carbon stock (De Beenhouwer et al. 2016). Despite the fact that agroforestry ecosystems were reported to stock a reasonable amount of carbon, management intensity have negatively affected both carbon stock and wood plant diversity and abundance of beetles (De Beenhouwer et al. 2016). Likewise, in cacao agroforest that has replaced the former natural forest in Sulawesi India, Kessler et al. (2012) found that, there was no significant link between carbon stock and diversity of four groups of plants and eight animals species. Consequently, the author reported a significant loss of plant and animal species related to forest which depend much on the presence of natural forest. In agroforestry and pasture in Panama, it was reported that there was no direct relationship between tree diversity and carbon storage (Kirby and Potvin 2007).

In northern Ethiopian parkland agroforestry, it was revealed that tree species evenness, Simpson index and Shannon wiener index had no significant relationship to total tree carbon (Gebrewahid and Meressa, 2020). Similar observations were reported in Pekarangan complex agroforestry ecosystem in watershed in Indonesia (Choliq and Kaswanto, 2017; Filqisth and Kaswanto 2017). Likewise in agroforestry ecosystems involving four practices i.e. woodlots, parkland, boundary plantation and home gardens, biomass components were not significantly correlated with tree diversity (Manaye et al. 2021). In this review, positive correlation between carbon and biodiversity constituted high number of reported studies. However, lack of correlation results were also reported. This can be attributed to by different factors such as the context of the landscape, nature of the forest and anthropogenic disturbances which may create heterogeneity of the landscape (Cavanaugh et al. 2014, Poorter et al. 2016)

In agroforestry systems which are based in the tropics, majority of the reviewed results show lack of potential relationship between carbon and biodiversity. However, the results also reveal that agroforestry ecosystems can stock a reasonable amount of carbon but cannot support biodiversity of specialist species which requires certain specific habitat conditions. This had led to lack of relationship between carbon stocks and biodiversity. This was evident in agroforestry ecosystems with intensified management practices when compared to least managed agroforestry ecosystems. The latter, stock a reasonable amount of carbon and supported biodiversity of generalist species which do not require specific habitat. This implies that, for agroforestry ecosystems to support both carbon and biodiversity, management intensity should be kept as minimal as possible.

Conclusion and Recommendations

For the vast majority of tropical ecosystems, this review has shown a positive link between carbon and biodiversity. Roughly half of the assessed publications reported a positive correlation between biodiversity and carbon. 40.7% of the 51% came from forests, while almost 11% came from agroforestry. This lends credence to the idea that carbon and biodiversity coexist in most tropical ecosystems. Some exceptions have been noted where some ecosystems stock low carbon yet are rich in biodiversity, leading to lack and negative relationships (25% and 22.2% respectively) between carbon and biodiversity. This imply that carbon-based conservation efforts should include the ecosystems with low carbon stock in order to safeguard biodiversity. Furthermore, regenerating tropical forests are potential for carbon and biodiversity co-benefit if the temporal scale is considered, thus carbon-based conservation efforts can pursue biodiversity in these ecosystems. In most disturbed areas, carbon and biodiversity were negatively/not correlated when compared to relatively undisturbed forests.

Therefore, maximizing carbon stock alongside biodiversity can only be feasible if disturbance is kept minimal or totally restricted in tropical forests. Long term studies on carbon and biodiversity co-benefit are scarce in most of the reported research especially on animal taxa are based on single season of data collection. Given ecosystems dynamic and seasonal variations of majority of animal taxa it is important to have long term studies covering both seasons to understand when and where the co-benefit exist. There is also a need to carryout carbon inventory studies on both above ground and below ground including soil organic carbon which is less studied in most tropical ecosystems. Since the reviewed studies varied in methodologies on carbon and biodiversity measurement, there is need to design effective and standardised methods for carbon and biodiversity assessments. This will help to come up with reliable results to inform policymakers and other stakeholders. The relationship between biodiversity and carbon stocks varies in natural, planted, disturbed, managed forests and agroforests. This variation can also be attributed by scale of analysis, taxa in consideration and the measure of biodiversity used. Also, given the fact that considerable portion of carbon is found in soil and plant roots, further research should focus on the relationship between soil carbon and biodiversity, specifically the ground dwelling taxa.

References

Amara E, Heiskanen J, Aynekulu E and Pellikka PK 2019. Relationship between carbon stocks and tree species diversity in a humid Guinean savanna landscape in northern Sierra Leone. Southern Forests. *J. For. Sci*. 81(3):235-45.

Anderson-Teixeira, KJ 2018 Prioritizing biodiversity and carbon. *Nature Climate Change* 8(8):667–668.

Armenteras D, Rodríguez N and Retana J 2015 National and regional relationships of carbon storage and tropical biodiversity. *Biol. Conserv*.192:378-386.

Aryal S, Shrestha S, Maraseni T, Wagle PC and Gaire NP 2018 Carbon stock and its relationships with tree diversity and density in community forests in Nepal. *Int. For. Rev*. 20(3):263-73

Barlow J, Lennox GD, Ferreira J, Berenguer E, Lees AC, Nally RM, Thomson JR, Ferraz SF, Louzada J, Oliveira VH, Parry L 2016 Anthropogenic disturbance in tropical forests can double biodiversity loss from deforestation. *Nature* 535(7610):144-147.

Basham EW, Medina-Uribe CA, González del Pliego P, Acosta Galvis AR, Woodcoc P, Haugaasen T, Gilroy JJ and Edwards DP 2016 Quantifying carbon and amphibian co-benefits from secondary forest regeneration in the Tropical Andes. *Anim. Conserv.* 19(6):548–560.

Bastin JF, Barbier N, Réjou-Méchain M, Fayolle A, Gourlet-Fleury S, Maniatis D, De Haulleville T, Baya F, Beeckman H, Beina D and Couteron P 2015 Seeing Central African forests through their largest trees. *Sci. Rep.* 5(1):1–8

Beaudrot L, Kroetz K, Alvarez-Loayza P, Amaral I, Breuer T, Fletcher C, Jansen PA, Kenfack D, Lima MG, Marshall AR and Martin EH 2016 Limited carbon and biodiversity co-benefits for tropical forest mammals and birds. *Ecol. Appl.* 26(4):1098-111.

Capellesso ES, Cequinel A, Marques R, Sausen TL, Bayer C and Marques MC 2021 Co-benefits in biodiversity conservation and carbon stock during forest regeneration in a preserved tropical landscape. *For. Ecol. Manag*. 492:119222.

Cardinale BJ, Duffy JE, Gonzalez A, Hooper DU, Perrings C, Venail P, Narwani A, Mace GM, Tilman D, Wardle DA and Kinzig AP 2012 Biodiversity loss and its impact on humanity. *Nat*ure 486(7401):59-67

Cavanaugh KC, Gosnell JS, Davis SL, Ahumada J, Boundja P, Clark DB, Mugerwa B, Jansen PA, O'Brien TG, Rovero F and Sheil D 2014 Carbon storage in tropical forests correlates with taxonomic diversity and functional dominance on a global scale. *Glob. Ecol. Biogeogr.* 23(5):563-73.

Choliq, MBS and Kaswanto, R L 2017 Correlation of carbon stock and biodiversity index at the small-scale agroforestry

Landscape in Ciliwung Watershed. *Environ. Earth Sci*. 91(1).

Chave J, Condit R, Lao S, Caspersen JP, Foster RB, Hubbell SP 2003 Spatial and temporal variation of biomass in a tropical forest: results from a large census plot in Panama. *J. Ecol*. 91(2):240–252.

Dayamba SD, Djoudi H, Zida M, Sawadogo L and Verchot L 2016 Biodiversity and carbon stocks in different land use types in the Sudanian Zone of Burkina Faso, West Africa. *Agric. Ecosyst. Environ* 216:61-72.

De Beenhouwer M, Geeraert L, Mertens J, Van Geel M, Aerts R, Vanderhaegen K and Honnay O 2016 Biodiversity and carbon storage co-benefits of coffee agroforestry across a gradient of increasing management intensity in the SW Ethiopian highlands. *Agric. Ecosyst.Environ*. 15:222:193-9.

Deere NJ, Guillera-Arroita G, Baking EL, Bernard H, Pfeifer M, Reynolds G, Wearn OR, Davies ZG and Struebig MJ 2018 High carbon stock forests provide co-benefits for tropical biodiversity. *J. Appl. Ecol.* 55(2):997-1008

Dixon, RK 1994 Carbon pools and flux of global forest ecosystems. *Sci.* 263(5144):185–190.

Edwards FA, Wheeler C, Medina Uribe CA, Haugaasen T, Edwards DP, Woodcock P and Girloy JJ 2014 Optimizing carbon storage and biodiversity protection in tropical agricultural landscapes. *Glob. Change Biol.* 20(7):2162-2172

Eggleston HS, Buendia L, Miwa K, Ngara T and Tanabe K 2006 IPCC guidelines for national greenhouse gas inventories.

Egoh B, Reyers B, Rouget M, Bode M and Richardson DM 2009 Spatial congruence between biodiversity and ecosystem services in South Africa. *Biol. Conserv.* 142(3):553-62.

FAO (2018). Food and Agriculture Organization of the United Nations. Rome, URL: http://faostat. fao. org. 25:403.

Ferreira J, Lennox GD, Gardner TA, Thomson JR, Berenguer E, Lees AC, Mac Nally R, Aragão LE, Ferraz SF, Louzada J and Moura NG 2018 Carbon-focused conservation may fail to protect the most biodiverse tropical forests. *Nat. Clim. Change*. 8(8):744-9.

Filqisthi TA and Kaswanto RL 2017 Carbon stock and plants biodiversity of pekarangan in Cisadane watershed West Java. *Environ. Earth Sc.* 54(1):012024. IOP Publishing.

Fischer J, Abson DJ, Butsic V, Chappell MJ, Ekroos J, Hanspach J, Kuemmerle T, Smith HG and von Wehrden H 2014 Land sparing versus land sharing: moving forward. *Conserv. Lett.* 7(3):149-57.

Gardner TA, Barlow J, Chazdon R, Ewers RM, Harvey CA, Peres CA and Sodhi NS 2009 Prospects for tropical forest biodiversity in a human-modified world. *Ecol. Lett.* 12(6):561-82.

Gardner TA, Burgess ND, Aguilar-Amuchastegui N, Barlow J, Berenguer E, Clements T, Danielsen F, Ferreira J, Foden W, Kapos V and Khan SM 2012 A framework for integrating biodiversity concerns into national REDD+ programmes. *Biol. Conserv.*154:61-71.

Gascon C, Brooks TM, Contreras-MacBeath T, Heard N, Konstant W, Lamoreux J, Launay F, Maunder M, Mittermeier RA, Molur S and Al Mubarak RK 2015 The importance and benefits of species. *Curr. Biol.* 25(10):431-438.

Gebrewahid Y and Meressa E 2020 Tree species diversity and its relationship with carbon stock in the parkland agroforestry of Northern Ethiopia. *Cogent. Biol.* 6(1):1728945.

Ghazoul J, Butler RA, Mateo-Vega J and Koh LP 2010 REDD: a reckoning of environment and development implications. *Tree* 25(7):396-402

Gibson L, Lee TM, Koh LP, Brook BW, Gardner TA, Barlow J, Peres CA, Bradshaw CJ, Laurance WF, Lovejoy TE and Sodhi NS 2011 Primary forests are irreplaceable for sustaining tropical biodiversity. *Nature* 478(7369):378-381.

Goodale CL, Apps MJ, Birdsey RA, Field CB, Heath LS, Houghton RA, Jenkins JC, Kohlmaier GH, Kurz W, Liu S and Nabuurs GJ 2002 Forest carbon sinks in the Northern Hemisphere. *Ecol. Appl.* 12(3):891-9.

Grainger A, Boucher DH, Frumhoff PC, Laurance WF, Lovejoy T, McNeely J, Niekisch M, Raven P, Sodhi NS, Venter O and Pimm SL 2009 Biodiversity and REDD at Copenhagen. *Curr. Biol*. 19(21):974-976.

Grassi G, House J, Dentener F, Federici S, den Elzen M and Penman J 2017 The key role of forests in meeting climate targets requires science for credible mitigation. *Nat. Clim. Change*. 7(3):220-6.

Groner E and Novoplansky A 2003 Reconsidering diversity–productivity relationships: directness of productivity estimates matters. *Ecol. Lett*. 6(8):695-699.

Hegerl C, Burgess ND, Nielsen MR, Martin E, Ciolli M and Rovero F 2017 Using camera trap data to assess the impact of bushmeat hunting on forest mammals in Tanzania. *Oryx*. 51(1):87-97.

Holloway V and Giandomenico E 2009 Carbon planet white paper: The History of REDD poly. Adelaide SA

Hooper DU, Adair EC, Cardinale BJ, Byrnes JE, Hungate BA, Matulich KL, Gonzalez A, Duffy JE, Gamfeldt L and O'Connor MI 2012 A global synthesis reveals biodiversity loss as a major driver of ecosystem change. *Nat*. 486(7401):105-8.

Houghton RA 2005 Above ground forest biomass and the global carbon balance. *Glob. Change Biol*. 11(6):945-58

IPCC (Intergovernmental Panel on Climate Change), 2018. *Global Warming of 1.5° C. An IPCC Special Report on the impacts of global warming of 1.5° C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*. Geneva: ipcc.

Kessler M, Hertel D, Jungkunst HF, Kluge J, Abrahamczyk S, Bos M, Buchori D, Gerold G, Gradstein SR, Köhler S and Leuschner C 2012 Can joint carbon and biodiversity management in tropical agroforestry landscapes be optimized?. *PLoS ONE*. 7(10):1–7.

Kirby KR and Potvin C 2007 Variation in carbon storage among tree species: Implications for the management of a small-scale carbon sink project. *For. Ecol. Manag*. 246(2-3):208-221

Lewis OT 2009 Biodiversity change and ecosystem function in tropical forests. *Basic Appl. Ecol.* 10(2):97-102.

Lewis SL 2006 Tropical forests and the changing earth system. *Philos. Trans. R. Soc*. 361(1465):195-210.

Lewis SL, Edwards DP and Galbraith D 2015 Increasing human dominance of tropical forests. *Sci*. 349(6250):827-832.

Liang J, Crowther TW, Picard N, Wiser S, Zhou M, Alberti G, Schulze ED, McGuire AD, Bozzato F, Pretzsch H and De-Miguel S 2016 Positive biodiversity-productivity relationship predominant in global forests. *Sci.* 354(6309).

Lindenmayer DB and Franklin JF 2013 Conserving forest biodiversity: a comprehensive multiscaled approach. Island press, London.

Liu X, Trogisch S, He JS, Niklaus PA, Bruelheide H, Tang Z, Erfmeier A, Scherer-Lorenzen M, Pietsch KA, Yang B and Kühn P 2018 Tree species richness increases ecosystem carbon storage in subtropical forests. *Proc. R. Soc. B.* 285(1885):20181240.

Manaye A, Tesfamariam B, Tesfaye M, Worku A and Gufi Y 2021 Tree diversity and carbon stocks in agroforestry systems in northern Ethiopia. *Carbon Balance Manag*. 16(1):14.

Mandal RA, Dutta IC, Jha PK and Karmacharya S 2013 Relationship between carbon stock and plant biodiversity in collaborative forests in Terai, Nepal. *Int. Sch. Res. Notices.* 2013(1):625767.

Manhães AP, Mazzochini GG, Oliveira-Filho AT, Ganade G and Carvalho AR 2016 Spatial associations of ecosystem services and biodiversity as a baseline for systematic conservation planning. Divers. Distrib. 22(9):932-943.

Martin JP, Simon L, Oliver L, Serge K, Steege T, Lee JT, Cristo E, Almeida E, Davila A, Luiz EO, Aymard C 2017 Diversity and Carbon Storage Across The

Tropical Forest Biome. *Sci. Rep.*1–12.

McNicol IM, Ryan CM, Dexter KG, Ball SM and Williams M 2018 Aboveground carbon storage and its links to stand structure, tree diversity and floristic composition in south-eastern Tanzania. *Ecosyst*. 21:740-754.

Morandi PS, Marimon BS, Marimon-Junior BH, Ratter JA, Feldpausch TR, Colli GR, Munhoz CB, da Silva Junior MC, de Souza Lima E, Haidar RF and Arroyo L 2020 Tree diversity and above-ground biomass in the South America Cerrado biome and their conservation implications. *Biodivers. Conserv*. 29:1519-1536.

Mwambala, AN, Bruno, AN and Elikana, K 2019 Interface of biodiversity and ecosystem services: Does soil organic carbon correlate with the diversity of carabid beetles (Coleoptera: Carabidae) in the Uzungwa Scarp Nature Reserve, Tanzania? *Int. J. Biodivers. Conserv.* 11(4): 114–124.

Mwambala AN, Nyundo BA and Kalumanga E 2023 Tree biomass, carbon stock characteristics and ground beetles (Coleoptera: Carabidae) diversity in the Uzungwa Scarp Forest Nature Reserve, Tanzania. *Environ. Manag.* 71(1):190-200

Myers N, Mittermeier RA, Mittermeier CG, Da Fonseca GA and Kent J 2000 Biodiversity hotspots for conservation priorities. *Nat*. 403(6772):853-8.

Naeem S, Duffy JE and Zavaleta E 2012 The functions of biological diversity in an age of extinction. *Sci.* 336(6087):1401-6.

Osuri AM, Machado S, Ratnam J, Sankaran M, Ayyappan N, Muthuramkumar S, Parthasarathy N, Pélissier R, Ramesh BR, DeFries R and Naeem S 2020 Tree diversity and carbon storage cobenefits in tropical human-dominated landscapes. *Conserv. Lett.* 13(2):12699.

Perfecto I, Vandermeer J and Philpott SM 2014 Complex ecological interactions in the coffee agroecosystem. *Ann. Rev. Ecol. Evol. Syst.* 45(1):137-58.

Phalan B, Onial M, Balmford A and Green RE 2011 Reconciling food production and biodiversity conservation: land sharing and land sparing compared. *Sci*. 333(6047):1289-91.

Phelps J, Webb EL and Adams WM 2012 Biodiversity co-benefits of policies to reduce forest-carbon emissions. *Nat. Clim. Change*. 497-503.

Poorter L, Bongers F, Aide TM, Almeyda Zambrano AM, Balvanera P, Becknell JM, Boukili V, Brancalion PH, Broadbent EN, Chazdon RL and Craven D 2016 Biomass resilience of Neotropical secondary forests. *Nat.* 530(7589):211-4.

Ruiz-Benito P, Gómez-Aparicio L, Paquette A, Messier C, Kattge J and Zavala MA 2014 Diversity increases carbon storage and tree productivity in S panish forests. *Glob. Ecol. Biogeogr*. (3):311-22.

Saha SK, Nair PK, Nair VD and Kumar BM 2009 Soil carbon stock in relation to plant diversity of homegardens in Kerala, India. *Agrofor. Syst*. 1:53-65.

Santoro M, Cartus O, Carvalhais N, Rozendaal DM, Avitabile V, Araza A, De Bruin S, Herold M, Quegan S, Rodríguez-Veiga P and Balzter H 2021 The global forest above-ground biomass pool for 2010 estimated from high-resolution satellite observations. *Earth Syst. Sci. Data*. 13(8): 3927-3950.

Sari RR, Saputra DD, Hairiah K, Rozendaal DM, Roshetko JM and Van Noordwijk M 2020 Gendered species preferences link tree diversity and carbon stocks in cacao agroforest in Southeast Sulawesi, Indonesia. *Land*.9(4):108.

SGD 2015 United Nations Sustainable Development Goals. Available online: https: //sustainabledevelopment.un.org/sdg15.

Sharma CM, Baduni NP, Gairola S, Ghildiyal SK and Suyal S 2010 Tree diversity and carbon stocks of some major forest types of Garhwal Himalaya, India. *For. Ecol. Manag*. 260(12):2170-9.

Sheil D, Ladd B, Silva LCR, Laffan SW and Van Heist M 2016 How are soil carbon and tropical biodiversity related? *Environ. Conserv.* 43(3):231-241.

Siikamäki J and Newbold SC 2012 Potential biodiversity benefits from international programs to reduce carbon emissions from deforestation. *Ambio* 41:78-89.

Sobral M, Silvius KM, Overman H, Oliveira LFB, Raab TK and Fragoso JMV 2017 Mammal diversity influences the carbon cycle through trophic interactions in the Amazon. Nat Ecol Evol. 1(11):1670-1676.

Srivastava DS and Lawton JH 1998 Why more productive sites have more species: an experimental test of theory using tree-hole communities. *Am. Nat.* 152(4):510-29.

Strassburg BB, Rodrigues AS, Gusti M, Balmford A, Fritz S, Obersteiner M, Kerry Turner R and Brooks TM 2012 Impacts of incentives to reduce emissions from deforestation on global species extinctions. *Nat. Clim. Change* 2(5):350-5.

Strassburg BB, Kelly A, Balmford A, Davies RG, Gibbs HK, Lovett A, Miles L, Orme CD, Price J, Turner RK and Rodrigues AS 2010 Global congruence of carbon storage and biodiversity in terrestrial ecosystems. *Conserv. Lett.* 3(2):98-105.

Sullivan MJ, Talbot J, Lewis SL, Phillips OL, Qie L, Begne SK, Chave J, Cuni-Sanchez A, Hubau W, Lopez-Gonzalez G and Miles L 2017 Diversity and carbon storage across the tropical forest biome. *Sci. Rep*. 7(1):39102.

Sunardi S, Kaswanto RL and Sjaf S 2020 Relationship between Plant Biodiversity and Carbon Stock in Rural Area of Cisadane Watershed. *J. Env.Sc.*18(3):610-6.

Thomas CD, Anderson BJ, Moilanen A, Eigenbrod F, Heinemeyer A, Quaife T, Roy DB, Gillings S, Armsworth PR and Gaston KJ 2013 Reconciling biodiversity and carbon conservation. *Ecol. Lett.* 16:39-47.

Tilman D, Knops J, Wedin D, Reich P, Ritchie M and Siemann E 1997 The influence of functional diversity and composition on ecosystem processes. *Science* 277(5330):1300-2.

UNFCCC 2015 Historic Paris Agreement on Climate Change: 195 Nations Set Path to Keep Temperature Rise Well Below 2 Degrees Celsius. Retrieved from United Nations Climate Change: https:// unfccc.int/news/finale-cop21.

UNFCCC 2010 The Cancun agreements: Outcome of the work of the Ad Hoc Working Group on Long-Term Cooperative Action under the convention. Decision 1/CP16, Cancun, Mexico. Retrieved from http://unfccc.int/resource/docs/2010/cop16/ eng/07a01.pdf

Van de Perre F, Willig MR, Presley SJ, Bapeamoni Andemwana F, Beeckman H, Boeckx P, Cooleman S, de Haan M, De Kesel A, Dessein S and Grootaert P 2018 Reconciling biodiversity and carbon stock conservation in an Afrotropical forest landscape. *Sci. Adv.* 4(3):eaar6603.

van der Sande MT, Poorter L, Kooistra L, Balvanera P, Thonicke K, Thompson J, Arets EJ, Garcia Alaniz N, Jones L, Mora and Mwampamba TH 2017 Biodiversity in species, traits, and structure determines carbon stocks and uptake in tropical forests. *Biotropica* 49(5):593-603.

Venter O, Laurance WF, Iwamura T, Wilson KA, Fuller RA and Possingham HP 2009 Harnessing carbon payments to protect biodiversity. *Sci.* 326(5958):1368

Vilà M, Carrillo-Gavilán A, Vayreda J, Bugmann H, Fridman J, Grodzki W, Haase J, Kunstler G, Schelhaas M and Trasobares A 2013 Disentangling biodiversity and climatic determinants of wood production. *PloS One*. 8(2):53530.

Williams DR, Alvarado F, Green RE, Manica A, Phalan B and Balmford A 2017 Land-use strategies to balance livestock production, biodiversity conservation and carbon storage in Yucatán, Mexico. *Glob. Change Biol*. 23(12):5260-72.

Wright DH 1983 Species-energy theory: an extension of species-area theory. *Oikos*. 1:496-506.

Zimudzi C and Chapano C 2016 Diversity, population structure, and above ground biomass in woody species on Ngomakurira Mountain, Domboshawa, Zimbabwe. *Int. J. Biodivers.* 2016(1):4909158.