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Carbon sequestration in Tropical Montane Cloud Forests

The determination of carbon storage in tropical forests is among mitigation measures for climate change. There are numerous studies worldwide about this topic. Nevertheless, few are the studies of carbon storage in Tropical Montane Cloud Forests (TMCFs). TMCFs play an important role in hydrological balance and carbon sequestration. Studies of carbon sequestration are scarce in TMCFs due to their difficult access and the assumption of low carbon sequestration. In this review article, the methods of carbon sequestration estimation in TMCFs and their results were analysed. We classified them depending the source of carbon storage. Thus, three class were established: vegetation carbon storage, soil carbon storage and litter carbon storage. Results showed that the most used method to determine carbon storage is field method for carbon storage in vegetation and the remote sensing method is the less used. In addition, it was found that the majority of research is concentrated in America, specifically in Mexico and Peru. According to Pearson's correlation coefficient, it was found that the frequency of investigations by country is directly related to the forest area of the country ($p < 0.08$). Few studies on TMCFs carbon storages have been carried out in the world and they showed differences in the estimation of the carbon content in data and methodologies. It is needed to increase the efforts in the research of TMCFs carbon storage to reach a better stage and accumulate data that could help to provide policies and actions to mitigate climate change through the conservation of these carbon sinks.

Key words: tropical forest, tropical montane cloud forest, carbon storage, carbon sequestration biomass, soil organic carbon

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Секвестрационная способность тропических горных туманных лесов

Оценка объема запасов углерода в тропических лесах является одной из задач в рамках принятия мер по смягчению последствий изменения климата. По всему миру было проведено множество исследований по данному направлению. Тем не менее, количество исследований по оценке запасов углерода в тропических горных туманных лесах (TMCF) не велико. TMCF играют важную роль в гидрологическом балансе и связывании углерода. Исследования по изучению способности TMCF хранить углерод немногочисленны ввиду труднодоступности самих лесов, а также по причине результатов некоторых исследований, фиксирующих низкую секвестрационную способность данных экосистем. В данной обзорной статье проанализированы методы оценки запасов углерода в TMCF и их результаты. Классификация исследований проводилась в зависимости от объекта изучения и включала исследования накопленного углерода в растительности, почве и в подстилке. Результаты исследований демонстрируют наибольшую результативность полевого метода определения накопления углерода, в то время как метод дистанционного зондирования применяется реже. Кроме того, обнаружено, что большая часть исследований сосредоточена в Северной и Южной Америке, в частности, в Мексике и Перу. Использование коэффициента корреляции Пирсона позволило установить прямую связь частоты исследований накопления углерода TMCF странами и площади лесов данного типа на их территории ($p < 0,08$). В мире выполнено несколько крупных исследований углеродных запасов TMCF, которые были проведены с использованием разных входных данных, методик и демонстрируют неоднозначные результаты. Таким образом, необходимо усилить методологическую базу исследования хранения углерода тропическими горными туманными лесами, с целью накопления знаний и достижения единства результатов для последующей разработки мероприятий и действий по смягчению последствий изменения климата за счет сохранения лесов данного типа.

Ключевые слова: тропический горный туманный лес, запас углерода, биомасса, подстилка, почва

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Introduction

Forests (vegetation, soil and litter) play a fundamental role in carbon dynamics [Pan et al., 2011]. Photosynthesis and plant respiration are the fluxes through plants take up and return back carbon; Then, plants fix carbon in the soil and it is stored as soil organic carbon [Van Den Meerssche, 2020]. The conservation of those carbon sinks lets to mitigate the climate change through emissions reduction. Worldwide, the total carbon storage in soils and terrestrial vegetation (2000 PgC) is more than in the atmosphere (800 PgC) [Bauters, 2013].

Tropical forests are the biggest of the world (45%), thus they are the greatest carbon sinks (55% of C) of all the forests ecosystems [Pan et al., 2011]. In spite of their importance as carbon sink, tropical forests are deforested every year. Deforestation represent 20% of emissions from total anthropogenic greenhouse gas emissions [Mapstone, 2017].

Based on forest structure, rain forest is classified as tropical forests and its area in the world and in South America occupies the first place, 668 of 1468 million km^2 respectively. Approximately, 10% of tropical rain forest corresponds to Tropical Montane Cloud Forest (TMCF). This ecosystem has some important services like hydric balance and carbon storage; Also, they possess high biodiversity [Stadtmüller, 1987]. TMCFs have been quite affected by global warming because they have specific climate and altitudinal features [Gibbon et al., 2010]. Hence, all the ecosystems services have also been affected. However, vegetation functioning aspects, including carbon storage, are little studied. This makes it difficult to know the degree of vulnerability of the TMCF to climate change. The importance to promote studies in TMCFs is because they can be used as early warning alerts of climate change due to their sensitivity to climate [Martin, Bellingham, 2016].

TMCF are found in South and Central America, Caribbean, Asia, Oceania and Africa with an estimated area of 214630 km^2 (1.4% of tropical forests). TMCFs are located between 1,500–2,500 m.a.s.l, and 2,400–3,300 m.a.s.l., depending of their latitude [Stadtmüller, 1987]. The main characteristic of TMCFs is the cloud coverage, high humidity and horizontal precipitation. These forests are recognized by their hydrological balance role and high biodiversity. Despite of their ecosystem importance, TMCFs have been heavily deforested and are highly threatened. Carbon cycle and storage role of TMCFs is not well known due to its difficult access and the assumption that productivity and carbon stocks are low. Also, the scarce carbon dynamics studies are divergent in terms of results [Girardin et al., 2010, 2013].

Over time, studies connected with estimation of carbon storage in TMCFs have increased because it is a major issue in the field of global climate change. American countries lead the estimation of carbon in TMCFs [Van Dunne, Kappelle, 1988; Nadkarni et al., 2004; Köhler et al., 2007; Schawe et al., 2007; Schembre, 2009; Campos, 2010; Gibbon et al., 2010; Gradstein, Gehrig-downie, 2011; Román et al., 2011; Alvarez et al., 2012; Nottingham et al., 2012; Bauters, 2013; Girardin et al., 2013, 2014; Tanner et al., 2014; Taylor et al., 2014; Cavelier et al., 2015; Ahlstrand, 2016; Anaya et al., 2016; Bruneel, 2016; Zimmermann et al., 2016; Gómez et al., 2017; Mapstone, 2017; Oliveras et al., 2018; Avendaño et al., 2019; Horwath et al., 2019; Berry et al., 2020; Van Den Meerssche, 2020; Leija et al., 2021; Markham, Fernández, 2021], follow by Asia countries such as China, India and Malaysia [Schawe et al., 2007; Chen et al., 2010; Zhang, 2012; Jeyanny et al., 2013, 2014; Vijayan et al., 2018; Hu, Huang, 2019; Cheng et al., 2020; Lai, Liu, Chung et al., 2020; Lai, Liu, Kuo et al., 2020a, 2020b], and finally Africa and Oceania countries [Itkonen, 2012; Mitchard et al., 2012; Venter, 2015;

Dries Van Der, 2016]. However, different methodologies, carbon sources and scales led differences in the carbon estimation of TMCFs. This review provide information about carbon estimation methodologies in TMCFs and the development status in different countries. This information could be technical support to establish adequate management and conservation strategies for these forests to combat climate change.

The objective of the study is to review and analyze of carbon estimation methods in TMCFs around the world and in recent years.

Materials and research methods

In Publons database (connected with Web of Science), google academics and Scielo (latin database) we filtered search with keywords: Tropical montane Cloud forest or TMCF, carbon, and biomass stocks. Then, the results were reviewed in order to validate whether the study effectively determines carbon storage. We classified into three categories of carbon estimation source (vegetation, soil and litter carbon) in order to establish the research status and trends.

Results and discussion

In total, 53 studies related to forest carbon storage in TMCF, between 1996 and 2021, were found in the search. Despite being few investigations related to the estimation of carbon stored in TMCF, it is evident that the number of investigations have been increasing over time (Fig. 1). In 2012, the number of investigations carried out is the maximum, which is explained by the increase in attention to the issue of climate change.

Three interval scales for the frequency of research by country were developed by using RStudio software. Mexico ranked first with 13 studies, followed by Peru with 10 studies (Fig. 2). In addition, the frequencies of research were correlated with land area, forest area and Gross domestic product (GDP) of each country (data from World Bank). The correlation analysis (Table 1), by using Statistica software, showed that frequencies research are positive and moderate correlate with all the factors but are no significant ($p < 0.08$).

Forest carbon storage determination applies different methods like vegetation, soil and litter carbon storage estimation methods. Main methods applied in vegetation carbon storage estimation are: (1) field estimation and (2) geospatial technologies-based estimation. Field carbon storage estimation method calculates carbon storage based on inventory data from the forests like: density, volume, height and diameter at breast height (DBH). For instance, regressions and conversions with the forests variables, from inventories, are used in order to determine biomass [Alvarez et al., 2012; Gibbon et al., 2010; Girardin et al., 2014; Berry et al., 2020; Cheng et al., 2020; Lai, Liu, Kuo, et al., 2020a]. Geospatial technologies-based estimation includes remote sensing, geographic information systems (GIS) and global positioning system (GPS). The data is taken from satellites through the platform of data distribution and is processed and analyzed using GIS software (ArcGIS, ERDAS Imagine, QGIS, GRASS, etc.) or cloud platforms (e.g. Google Earth Engine). Between the advantages are the minimum cost and the rapid assessment of large areas [Itkonen, 2012; Mitchard et al., 2012; Lai, Liu, Chung et al., 2020; Leija et al., 2021].

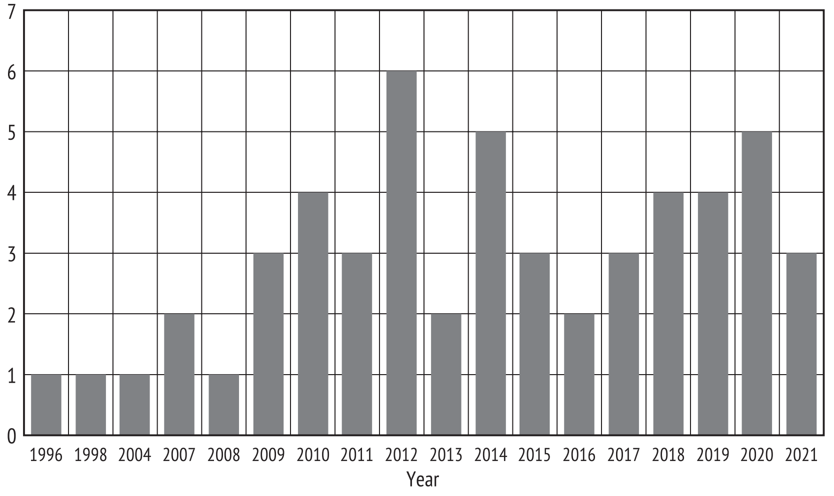

Fig. 1. Number of related research publications of carbon storage in TMCF per year

Table 1

Correlations between research frequency and influencing factors (number of countries = 15)

	Research frequency	Land area, sq. km	Forest area, sq. km	GDP, US$
Research frequency	1.00			
Land area, sq. km	0.39	1.00		
Forest area, sq. km	0.47	0.96*	1.00	
GDP, US$	0.33	0.98*	0.91*	1

* $p < 0.01$.

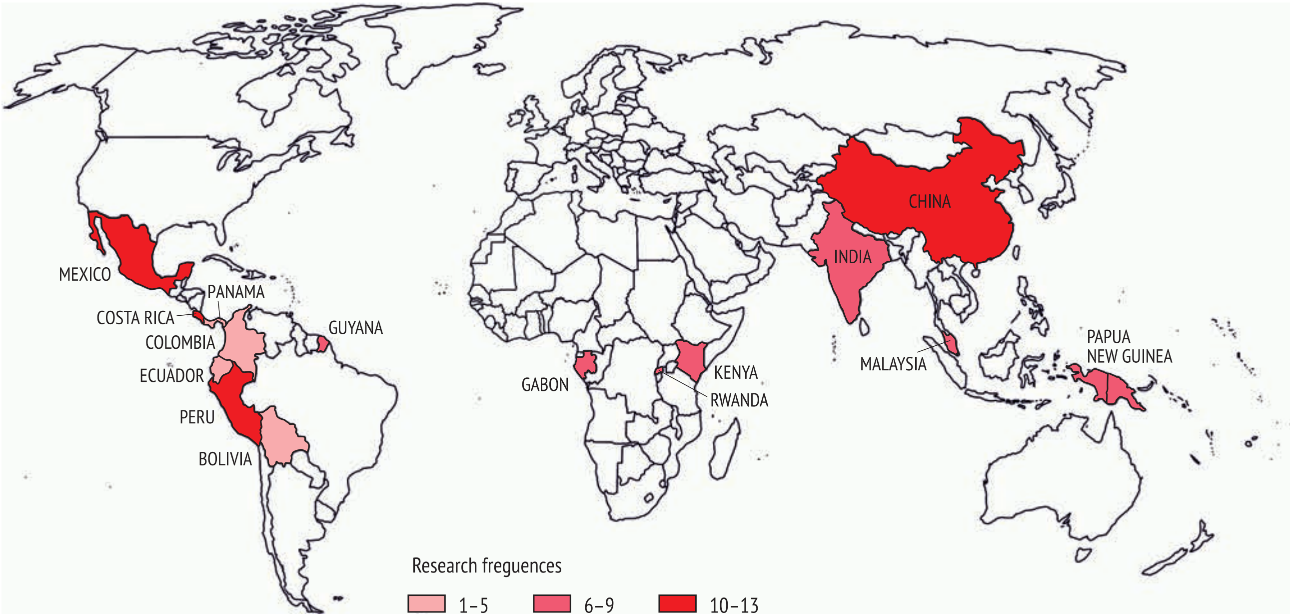

Fig. 2. Distribution pattern of research frequencies in TMCFs around the world

In TMCF, the most widely used source to determine carbon storage in TMCF is vegetation (Fig. 3). Field methodology is widely used to determine carbon storage in vegetation. One of the characteristics of TMCF is to have epiphytes and bryophytes in abundance, so a representative number of investigations were focused on determining the carbon stored in those plants [Van Dunne, Kappelle, 1988; Köhler et al., 2007; Chen et al., 2010; Gradstein, Gehrig-downie, 2011; Ahlstrand, 2016; Gómez et al., 2017; Horwath et al., 2019; Lv et al., 2019; Lai, Liu, Kuo, et al., 2020a, 2020b; Markham, Fernández, 2021]. The geospatial methodology was found in only four research [Itkonen, 2012; Mitchard et al., 2012; Lai, Liu, Chung et al., 2020; Leija et al., 2021]. The low number of investigations that apply this method is due to the fact that the TMCF is covered most of the time by clouds. Clouds coverage difficult the access to optimal satellite images or their processing and corrections for later analysis.

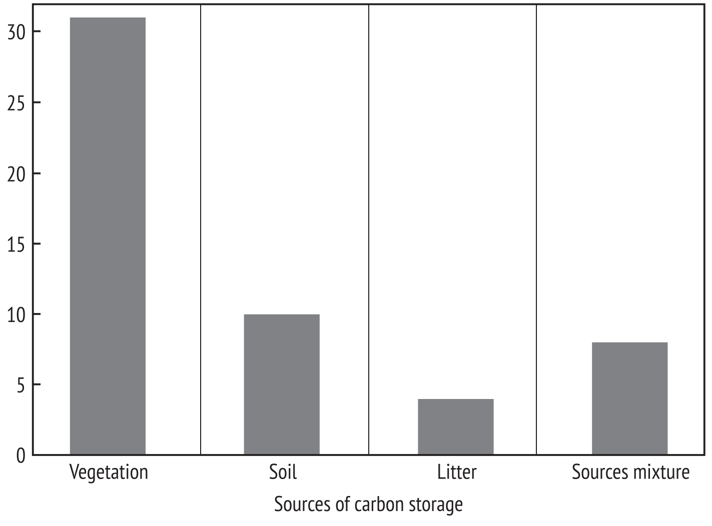

Fig. 3. Number of related research publications of carbon storage in TMCF by source of carbon storage

Soil carbon estimation methods applied in TMCFs were classified in: physical method by loss ignition and physicochemical method. For instance, in Colombia the collected soil samples (without roots) were dried at 70 °C and grounded in a mortar. To quantify organic matter content (OMC) the samples were placed in oven at 550 °C and the differences of weight determined the OMC [Campos, 2010; Ramírez et al., 2017]. In the physicochemical method, soil samples need also to be dried and sieve. Then, the soil organic carbon (SOC) is measured by a chemical method like Walkley and Black method or in a specific device like Leco CHN-Analyzer [Schawe et al., 2007; Gibbon et al., 2010; Jeyanny et al., 2013; Tanner et al., 2014; Anaya et al., 2016]. From the total investigations found worldwide about soil carbon estimation (Fig. 3), the majority corresponds to physicochemical methodology (70%).

Five percent of total carbon storage in forests belongs to carbon litter. Nevertheless, litter plays an important role in carbon cycle linking vegetation and soil carbon storage sources [Pan et al., 2011]. The applied methods of carbon determination in litter is divided in two: (1) Field method, when litter samples are collected, then stored in a 70 °C and to remove water are placed in the oven, and finally are weighed [Hu, Huang, 2019] and (2) Litter decomposition method. The decomposition is estimated from litterbags with a respirometer and thermometer to determine CO_2 emission and atmospheric temperature [Vijayan et al., 2018]. In TMCF the carbon storage in litter is the least studied. This variable is taken as complementary in mixed studies were the aboveground and belowground biomass are estimated. Those mixed studies were in total eight (Fig. 3).

The determination of carbon in TMCFs has been carried out more frequently in certain countries (Fig. 2). These studies are diverse most of which have determined the above ground biomass (AGB). Carbon stored can be calculated by applying the concept that 50% of the AGB corresponds to carbon. A comparative table of carbon stored by hectare in different sources (AGB, root, soil and litter) was elaborated (Table 2). Some studies determined AGB by vegetative species and/or by its components. Therefore, those units cannot be compared with the content of carbon estimated in TMCFs that considered all species. This is the case of specific carbon determination of bryophyte, epiphytic component and roots. In the case of soil as a carbon source, the SOC determined in different countries is also shown in Table 2. Studies where the soil organic matter was estimated in percentage were not included because they cannot be compared with SOC. Finally, carbon storage in litter is include in Table 2.

It was found that the amount of carbon stored in the vegetation is homogeneous regardless of the country in which TMCF is located. The range of carbon stored goes between 112.14 to 227 Mg/ha^{-1} according to studies carried out in Rwanda, Mexico, Ecuador, Bolivia and Peru (table 2). It is important to mention that this range of carbon stocks belongs to undisturbed old growth forest and natural forest with patches in recovering process from past agriculture pressure. Also, species diversity is similar

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Table 2

Carbon storage (Mg/ha) in aboveground biomass, soil and litter of TMCFs

Country	Type of forest (Description)	System state	Carbon Source	Carbon storage, Mg/ha	Reference
Rwanda	Tropical montane forest with dense canopy and quite open structure, with large patches of open terrain dominated by a native but invasive liana (*Sericostachys scandens*)	Undisturbed old-growth forest	AGB	121.91	[Dries Van Der, 2016]
Ecuador	Tropical Montane Cloud Forest	Undisturbed natural forest and patches in recovering from agriculture pressure	AGB	113.41	[Van Den Meersscheche, 2020]
				126.30	[Bauters, 2013]
	Tropical Montane Cloud Forest (lowland to hilly evergreen rainforest and lower montane evergreen rainforest)			112.14	[Bruneel, 2016]
Ecuador, Peru, Bolivia	Tropical Montane Forest	Undisturbed	AGB	123.50	[Girardin et al., 2013]
Mexico	Tropical Montane Forest	Natural and managed vegetation (pasture, row-crop sugar maize, potato)	AGB	166.00	[Berry et al., 2020]
Mexico	Tropical Montane Cloud forest (low forest with lichens and epiphytes; high forest floristic affinity with Genus *Quercus*)	Undisturbed	AGB and Soil	384.16	[Alvarez et al., 2012]

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Peru	TMCF with dominant trees of families Clusiaceae, Cunoniaceae, Myrsinaceae, Rosaceae and Clethraceae TMCF. Predominant species are herbaceous, shrub and trees of Baccharis, Berberis, Brachyotum, Chuquiraga,Clethra, Escallonia, Gynoxys, Miconia, Myrsine, Weinmannia, Alnus and Polylepsis	Undisturbed Disturbed by agriculture and fire	AGB	227.00	[Zimmermann et al., 2009]
				92.00	[Román et al., 2011]
	TMCF with three land cover classes: puna where grasses dominate, transition zone with mixture of shrubs and grasses and upper TMCF with closed cannopy trees with ephiphytes maily briophytes, ferns and bamboo	Forest with primary successions and some areas suffered impacts of fire		63.40	[Gibbon et al., 2010]
China	Bryophyte of TMCF with conifer plantation and old-growth forests dominated by hinoki cypress (*Chamaecyparis obtusa*) and Japanese cedar (*Cryptomeria japonica*)	Undisturbed	AGB	0.14	[Lai, Liu, Kuo et al., 2020b]
	Bryophyte of TMCF with conifer forest, dominated by hinoki cypress (*Chamaecyparis obtusa*) and Japanese cedar (*Cryptomeria japonica*)			0.136	[Lai, Liu, Chung et al., 2020]
	Bryophyte of TMCF with conifer plantation and old-growth forests dominated by hinoki cypress (*Chamaecyparis obtusa*) and Japanese cedar (*Cryptomeria japonica*)			0.1359	[Lai, Liu, Kuo et al., 2020a]
Peru	Bryophytes (liverwort spp. and moss spp) of TMCF	Undisturbed old growth forest	AGB	0.5	[Horwath et al., 2019]
China	Bryophyte of TMCF with predominant species of *Lithocarpus crassifolius, Rhododendron irroratum* and bamboo (*Sinarundi naria*)	Disturbed by antrophogenic pressures	AGB	0.001028	[Chen et al., 2010]

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Table 2 (continuation)

Country	**Type of forest (Description)**	**System state**	**Carbon Source**	**Carbon storage, Mg/ha**	**Reference**
Costa Rica	Epiphytic of TMCF with trees and shrubs that include mainly *Oreomunnea Mexicana*, *Quercus* sp. and from families Rubiaceae, Malvaceae, Melastomataceae, Myrtaceae, and Meliaceae	Disturbed by land-pressure	AGB	0.00811	[Köhler et al., 2007]
Panama	Epiphytic of TMCF with common tree species of *Ficus crassiuscula*, *Elaeagia auriculata*, *Weinmannia werclei* and ferns and palms	Disturbed	AGB	0.00821	[Gómez et al., 2017]
Rwanda	Tropical montane forest dense cannopy and quite open structure, with large patches of open terrain dominated by a native but invasive liana, Sericostachys scandens	Undisturbed old-growth forest	Root	3.8	[Dries Van Der, 2016]
Peru	TMCF with three land cover classes: puna where grasses dominate, transition zone with mixture of shrubs and grasses and upper TMCF with closed cannopy trees with ephiphytes mainly briophytes, ferns and bamboo	Forest with primary successions and some areas suffered impacts of fire	Root	13.9	[Gibbon et al., 2010]
	TMCF near to the forest-grassland treeline	Undisturbed and disturbed forest exposed to fire		19.6	[Oliveras et al., 2018]
Colombia	Three areas in TMCF: 10-year-old successional forest dominated by *Tibouchina lepidota* and *Vismia cf. ferruginea*; 20-year-old forest dominated by *Vismia cf. ferruginea* and *Miconia theaezens* and mature forest with *Prestoea* aff. *purpurea*, *Clusia garci-barrigae*, *Alchornea* spp., *Inga* spp., and *Myrcia* sp.	Disturbed by land pressure for grazing, wood extraction and undisturbed	Root	1.86	[Cavelier et al., 2015]

Bolivia	Tropical Montane Rainforest with vegetation formations from lower montane forest, upper montane cloud forest and subalpine cloud forest	Undisturbed	Soil	220	[Schawe et al., 2007]
Costa Rica	Cloud forests with primary forest characterized by upper cannopy with dominant spacies like *Ocotea tonduzii* and *Cecropia polyphlebia*, Secondary forest characterized by *Ochroma pyramidale* and a denser shrub layer	Undisturbed and disturbed	Soil	252.8	[Tanner et al., 2014]
Ecuador	Tropical Montane Cloud Forest	Undisturbed and patches in recovering from agriculture pressure	Soil	136.48	[Bauters, 2013]
Mexico	TMCF with predominant tree species of *Alnus acuminata*, *Clethra mexicana*, *Quercus laurina*, *Quercus rugosa*, and *Styrax argenteus*	Little disturbance related to illegal selective logging and the extraction of resin	Soil	152	[Anaya et al., 2016]
	TMCF (low forest with lichens and epiphytes; high forest floristic affinity with Genus *Quercus*)	Undisturbed		227	[Alvarez et al., 2012]
	TMCF with predominant tree species of *Liquidambar styraciflua*, *Meliosma alba*, *Persea* spp., *Solanum muricatum Aiton*, *Chamaedorea tepejilote*, orchids and ferns.			229.33	[Cristóbal et al., 2019]
Peru	TMCF witn dominat trees of Clusiaceae, Cunoniaceae, Myrsinaceae, Rosaceae and Clethraceae	Undisturbed	Soil	118	[Zimmermann et al., 2016]
	TMCF near to the forest-grassland treeline	Undisturbed and disturbed forest exposed to fire		158.2	[Oliveras et al., 2018]

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End of Table 2

Country	Type of forest (Description)	System state	Carbon Source	Carbon storage, Mg/ha	Reference
Rwanda	Tropical montane forest with dense canopy and quite open structure, with large patches of open terrain dominated by a native but invasive liana (*Sericostachys scandens*)	Undisturbed old-growth forest	Soil	159.1	[Dries Van Der, 2016]
Malaysia	Montane forest and lowland forest common tree families: Myrtaceae, Polygalaceae, Lauraceae, Phyllanthaceae, Dipterocarpaceae, Euphorbiaceae	Undisturbed forest	Soil + Litter	120.0	[Jeyanny et al., 2014]
Peru	TMCF with families of Clusiaceae, Bixaceae, Urticaceae, Moraceae and Fabaceae, Sapotaceae, Moraceae, Clusiaceae, Urticaceae, Euphorbiaceae and Anacardiaceae, Clusiaceae, Cunoniaceae, Sabiaceae, Rosaceae and Lauraceae	Undisturbed forest	Litter	0.29	[Girardin et al., 2014]
Ecuador	TMCF with lowland to hilly evergreen rainforest, lower montane evergreen rainforest	Undisturbed natural forest and patches in recovering from agriculture pressure	Litter	0.36	[Bruneel, 2016]
China	TMCF dominated by *Chamaecyparis obtus*a	Undisturbed	Litter	0.29	[Hu, Huang, 2019]
	TMCF with predominant species of *Chamaecyparis obtusa* and *Chamaecyparis formosensis*	Disturbed with regeneration		4.3	[Chang et al., 2008]
Rwanda	Tropical montane forest with dense canopy and quite open structure, with large patches of open terrain dominated by a native but invasive liana (*Sericostachys scandens*)	Undisturbed old-growth forest	Litter	3.59	[Dries Van Der, 2016]

because all the study sites were TMCF. The low amounts of carbon (92 and 64 Mg/ha^{-1}) is related to the disturbed forest state due to agriculture or fire incidents [Gibbon et al., 2010; Román et al., 2011]. Finally, the highest value of carbon in Mexico is because the SOC amount is added to the carbon in AGB [Alvarez et al., 2012].

The data about carbon storage in epiphytic, bryophytes and roots (specific studies) vary according the system state. Thus, in undisturbed forests of bryophytes the carbon amount was between 0.13 to 0.5 Mg/ha^{-1} and in disturbed forest by anthropogenic pressure decreased to 0.008 and 0.001028 Mg/ha^{-1}. It should be noted that for the estimation of carbon in epiphytes, the effect of the host tree is negligible [Chen et al., 2010], which is why it is feasible to make the comparison between ephyfites of TMCFs from different countries. In the case of carbon amount of roots, it is lower (1.86 Mg/ha^{-1}) in disturbed forest than in undisturbed old growth forest. However, in undisturbed forest the values vary from 3.8 to 19.6 Mg/ha^{-1} and it is because of the predominant species type. When the carbon quantity was low, a native but invasive liana predominated while for upper value of carbon the type of forest was Puna with a dominance of grasses.

The carbon content in soils of different countries was located in a narrow range with an average of 158.65 Mg/ha^{-1} (SD 50.003). All SOC estimations were determined in undisturbed forests or in forests with little disturbance. In addition, the comparison of SOC storage shows that the type of predominant species in TMCF does not affect the SOC stocks.

Finally, in relation to carbon storage in litter (table 2) there is a lower amount in undisturbed forest (0.29–0.36 Mg/ha^{-1}) than in disturbed forest in regeneration (4.3 Mg/ha^{-1}). The reason of this behavior is thanks to the secondary succession characteristic. It points the forest stage in development trying to stabilize and with organic matter in constant production. In the case of Rwanda the carbon storage in litter is out of the common range for undisturbed forests because study site was Nyunywe National park that possess a high species richness and density which increases the litter content.

Conclusion

The state of carbon storage research in TMCFs around the world is in a basic stage due to the low number of publications collected. In 2012, the number of research increased, however, the data accumulation of carbon stocks in these forests is not enough to have global and detailed inventory of carbon storage in TMCFs. Nevertheless, the current data could be used as a basis for future research work.

From all the researches reviewed in this study, the method widely used for carbon estimation was the regression method based on forest inventory data. Depending of the author not the same allometric equations were applied. In the majority of the studies of AGB estimation Chave allometric equation (2005) for moist or wet tropical forest was applied, which includes the parameters of wood density and height [Mitchard et al., 2012; Girardin et al., 2013; Taylor et al., 2014; Venter, 2015; Mapstone, 2017; Oliveras et al., 2018; Hou et al., 2019; Berry et al., 2020; Vizcaíno et al., 2020]. An updated version of Chave equation (2014) was also used in a few studies, this equation has the same parameters but the constant factors change [Dries Van Der, 2016; Van Den Meerssche, 2020]. In comparison to Chavez equation, the Brown´s or its updated equation are less applied in carbon estimation research, but they are also suitable for moist tropical forest, the difference is the exclusion of density [Jeyanny et al., 2013]. Other studies used more than one allometric equation, which also estimate AGB from live and dead trees [Román et al., 2011]. For example, Tanner equation for montane cloud forest in Jamaica where the total dry-weight tree biomass depends of the basal area, Nenninger equation based on typical cloud montane tree species from southern Ecuador that applies DHB multiplied by a factor (0.07) [Román et al., 2011]. In other investigations, the determination of AGB was more specific because they included not only allometric equations of Chave and Brown, but also specific equations for predominant trees [Itkonen, 2012; Bauters, 2013; Bruneel, 2016]. As evidenced in the results, the presence of different factors or the parameters absence in the allometric equations does not abruptly influence the AGB results. Several studies apply the allometric equation of Chave, hence, we recommended its use in future investigations of AGB detection. In the rest of the components (soil, roots and litter) there are not enough studies that use a similar methodology, as in the case of AGB, that allow to recommend a methodology.

To increase carbon storage studies in TMCF it is imperative to use a standardized model such as the example of the Amazon rainforests and Atlantic Forest. Through the RAINFOR project, whose objective is an inventory of these forests, a standardized methodology for carbon determination has been developed. This allows to get information on forests in different parts of the world, which can be compared and thus contribute to their conservation.

Although remote sensing is currently used to estimate biomass in tropical forests, this is not the case, since its use was only evidenced in four studies. This is mainly due to the cloud cover that TMCF maintains almost most of the time. Despite being developing countries, South American countries are the ones that have most promoted the determination of carbon in the TMCFs. It is mainly attributed to environmental care policies that they manage as in the case of Ecuador and Costa Rica. Countries from Asia, Africa and Oceania must increase their investigations in carbon determination owing the large area of TMCFs that they have. Carbon inventories provide valuable information that promotes the conservation of forests. This contributes to the mitigation of climate change by preventing greenhouse gas emissions from forests and also they can be an early warming alert of climate change due to the climate sensitivity of TMCFs.

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