

Review

Forest Management and Climate Change Mitigation: A Review on Carbon Cycle Flow Models for the Sustainability of Resources

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Abstract: With climate change being a certainty, which today is probably the biggest challenge humanity is facing, and also accepting that greenhouse gas emissions are the main cause accelerating climate change, there is an urgent need to find solutions that lead to the mitigation of the already intense, and in some cases, even violent, effects. Forests can most easily work as carbon sinks. However, it is convenient to analyze the residence time of this carbon in forests, as this residence time will depend on the type of forest management used. This paper aims to analyze forest management models from a perspective of carbon residence time in forests, dividing the models into three types: carbon conservation, carbon storage, and carbon substitution. Carbon conservation models are those models in which the amounts of carbon stored only replace the carbon released, mainly by the industrial use of raw materials. Carbon storage models are models that foster the growth of forest areas to ensure that the amount of carbon stored grows, and where the ratio clearly leans towards sequestration and storage. Carbon substitution models are models that move towards the substitution of fossil carbon by renewable carbon, thus contributing to the creation of a neutral flow.

Keywords: climate change; forest management; carbon flow models; carbon storage; carbon conservation; carbon substitution

1. Introduction

The existence of forests is directly related to the health state of communities, the quality of life in rural areas and the environment in general, particularly the biodiversity of fauna and flora [1,2]. Faced with the reality of global climate change, which is also occurring due to the great loss of forest cover all over this planet, caused by the advancement of agricultural borders and livestock, the massive occurrence of rural fires and the overuse of resources, coupled with the emissions of greenhouse gases (GHGs) into the atmosphere from industrial activity, and the transport of people and goods, mankind has a huge challenge to ensure its survival [3–5].

To meet this transcendental challenge, there are only two complementary paths: reducing the emissions of unwanted greenhouse gases into the atmosphere and recapturing some of these gases and storing them [6].

Emission reduction requires multiple and varied measures, the most important of which is a drastic reduction in the use of fossil fuels, such as oil and coal, and the improvement in the processes

that employ these fuels to make them less polluting. In addition, countries urgently need to develop the technology needed to use a variety of available alternative energy sources, such as biomass, wind, solar, geothermal, tidal, and hydraulic power, among others [7–9].

Regarding the recovery of harmful gases, especially carbon dioxide (CO₂), from the atmosphere, there seems to be only one way, which is the conservation, restoration, and sustainable management of existing forests and the creation of new forests in a sustainable forest management regime [10]. Thus, once again, forests are, in the long term, necessary for the maintenance of life on Earth [11].

Regarding the reduction of GHGs from the atmosphere, forests, through photosynthesis, absorb CO₂ and release O₂, with carbon (C) fixed in their biomass [12]. Also, regarding GHG emission reduction, biomass can replace fossil fuels in power generation, being a renewable resource and considered neutral from the point of view of carbon emissions, as carbon released from combustion is considered to be compensated with carbon absorbed during the life of the plant [13–15].

Sustainable forest management, i.e., the application of forestry to obtain the diverse products and services of today's forests without compromising the ability of future generations to do so, is probably one of the most important current challenges facing humanity [16]. This objective represents a major challenge not only for the economy but also for the conservation of the environment and the lives of members of the population [17,18].

This is the guiding principle behind this review article, which addresses forest management from the perspective of carbon flow analysis, and the ability of forests to work as carbon stocks for longer or shorter periods. In this review, carbon flows have been analyzed and framed with well-known examples of forest space utilization and management, allowing to understand how forests can work as carbon sinks. In this way, it is also possible to understand which models should be applied to create long-term carbon sinks, and thereby allowing the interconnection of models in a more efficient way to get the maximum carbon sequestration and storage.

2. Forest Management and Climate Change

Forests fulfill vital ecological functions, such as the hydrological cycle, nutrient cycles and sediment retention, among many others [19,20]. The transformation of an ecosystem function into an environmental service takes place when it generates ecological, social, and economic benefits for a population. If forests offer a multiplicity of goods and services, society has historically focused on the most obvious asset, wood supply, and, on a smaller scale, non-timber forest products, with many other environmental services being forgotten and relegated [21].

Among the most recognized environmental services that forests can provide are watershed conservation, which includes hydrological services and soil conservation, landscape beauty, biodiversity conservation, and carbon capture or sequestration [22]. Worldwide, forests are an important resource and, in this context, territorial planning of this resource should also consider the multiplicity of goods and services provided by the forest. In the current global panorama, a climate change scenario where emissions of greenhouse gases reach very high levels and cause changes in weather could have serious consequences for humanity [23].

Primary and secondary natural forests as well as forest plantations are important carbon sinks, as they fix carbon in their biomass until harvest and store carbon captured in wood for another period of time, and this is now a recognized environmental service [24]. Portugal, as well as the other Mediterranean countries, has important forest resources and has voluntarily committed to reducing greenhouse gas emissions [25]. With this background, the possibility of organizing forest resources, aiming to improve carbon capture, is foreseen [26,27].

It is important to bear in mind that trees have life cycles like any living being and, at different stages of this cycle, the carbon capture rate varies. In the early years of life, growth rates are high and, therefore, the accumulation rates of biomass and carbon are also very high [28,29]. In adulthood, as trees continue to grow, they accumulate carbon at rates higher than respiration emissions. Then, they go

through a ripening stage where there is a balance between capture and emission. Finally, in the tree collapse stage, emission rates are higher than capture rates [30,31].

On the other hand, from the point of view of the United Nations Framework Convention on Climate Change and the Kyoto Protocol, trees and forests are temporal carbon sinks, as part of the stored carbon is released from harvesting trees from forests to the atmosphere [32]. This means that when trees are cut, burnt, or die, some of the contained carbon is released back into the atmosphere [33]. Therefore, forest policies and strategies should aim to extend the capacity of trees and forests to store carbon for as long as possible [34].

In this context, forests can be organized to mitigate change—that is, to contribute to the reduction of atmospheric CO₂ concentrations [35]. Forest organization that considers this aspect can follow three distinct paths according to the planning postulated by several authors, who divided forestry organization as follows: organization for carbon conservation, storage, and substitution [36–38].

3. Forest Management and Carbon Flows

3.1. Forest Management for Carbon Conservation

The economic goals that arise as a result of this objective are mainly the causes of deforestation and forest degradation, which are often associated with the expansion and degradation of agricultural and grazing land, and the demand for subsistence and commodities of timber products [36]. In this case, it is important that deforestation reduction programs take measures to increase agricultural productivity and sustainability [39]. Figure 1 presents the graphic description of this model, where it is possible to understand the main interactions that contribute to a forest management perspective where carbon amount is conserved in the forest. This model does not contribute to the reduction of atmospheric carbon, but also does not contribute to increase its amount. This model can be considered a neutral model concerning carbon amount.

Measures designed to allow the conservation of larger carbon fractions may include increasing the rotation periods of managed forests, reducing damage in the remaining trees, reducing waste by applying soil conservation techniques, and using wood in a more carbon efficient manner [40].

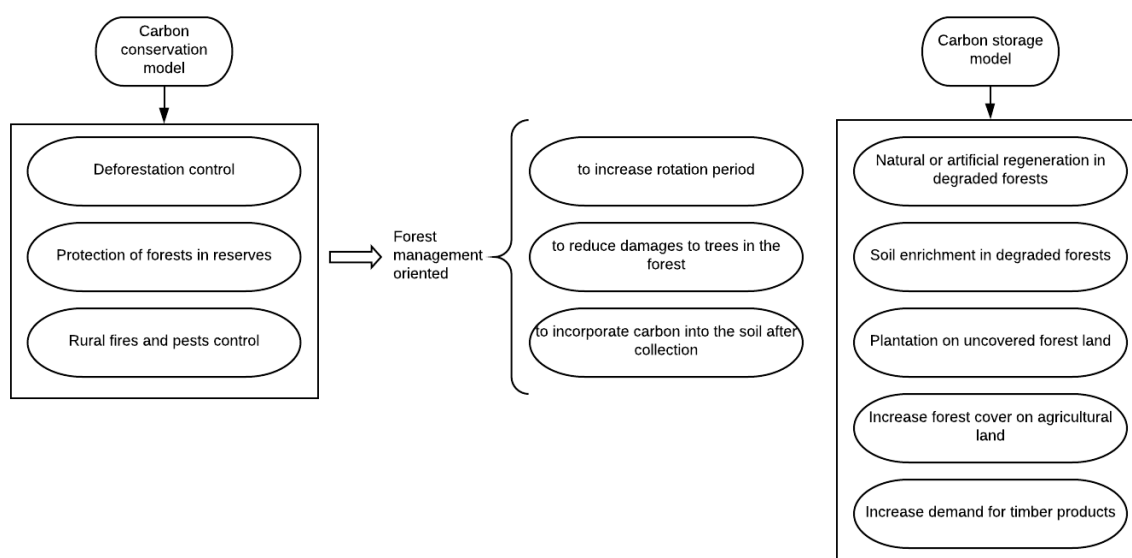


Figure 1. Forest management for carbon conservation (adapted from [41]).

A good example of this type of forest management is what can be found in the *Eucalyptus globulus* planted forests for the supply of raw materials to the pulp industry. These short rotation crops where the plant replacement cycle is short allows the accumulated carbon to be conserved, as in reality this

short rotation system only allows the carbon returned to the cycle to be captured and stored, but does not allow a positive balance towards carbon fixation for long periods.

3.2. Forest Management for Carbon Storage

Figure 2 presents the schematic model of forest management for carbon storage. The objective in this case is to increase the amount of carbon in forest vegetation and soil by increasing the surface and/or carbon content of biomass in natural and planted forests as well as by increasing storage in durable wood products [42].

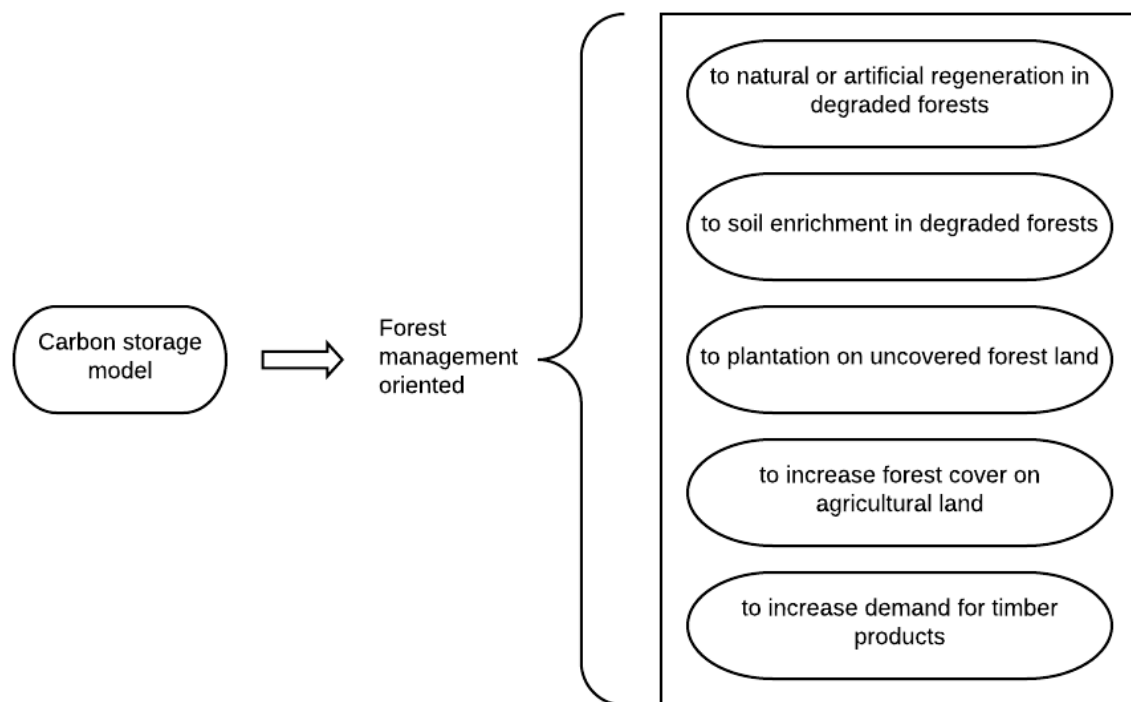


Figure 2. Forest management for carbon storage (adapted from [41]).

To increase carbon reserves in vegetation and soil, this could be achieved by protecting secondary forests and other degraded forest spaces that have carbon values below their maximum value in both biomass and soil by carrying out natural or artificial regeneration and soil enrichment [43].

Plantations on forest land that are without forest cover, together with the promotion of natural or artificial regeneration of secondary forests and increased forest cover on agricultural land or pastures, are measures that contribute to an increased amount of carbon [44].

In the case of timber products, carbon stocks may increase due to the increasing demand for timber products, which is occurring at a faster rate than the rate at which wood deteriorates, and due to the extension of the duration of timber products [45].

A good example of this type of forest management is what can be found in the planted forests of *Quercus suber* for the supply of raw materials for the cork industry. This type of forest with long rotation crops where the plant replacement cycle is very long allows the accumulated carbon to be stored, as in reality this long rotation system allows carbon to be removed from the cycle and stored, allowing a positive balance towards carbon fixation over long periods.

3.3. Forest Management for Carbon Substitution

The goal in this management form, as presented in Figure 3, is to increase carbon transfer from forest biomass to other products such as building materials and/or biofuels, rather than using energy and fossil fuel-based products and cement-based products [41].

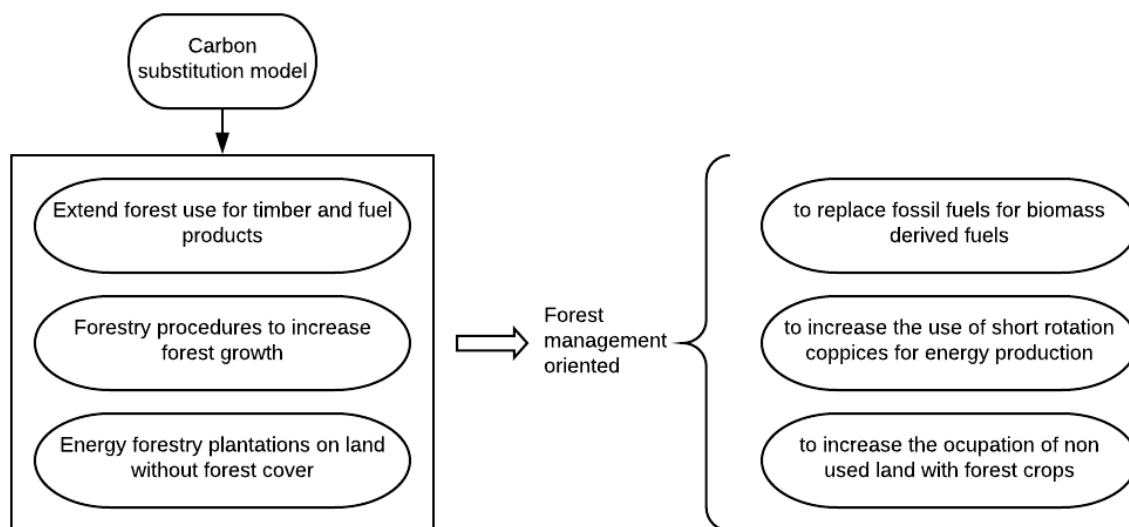


Figure 3. Forest management for carbon substitution (adapted from [36]).

This includes extending the use of forests for timber products and fuels, either by establishing new forests or plantations or by increasing the growth of existing forests through forestry treatments [46].

This type of organization, i.e., situations where biomass energy settle on land without forest cover, produce not only an increase in the amount of carbon stored on that land, but also the biomass that is used as a fuel replaces the use of fossil fuels, creating an effective carbon uptake rate in unburnt fossil fuels, known as offsetting emissions [47].

A good example of this type of forest management is what can be found when management is carried out from a circular economy perspective and where the result of forest clearing and clearing operations is converted into some form of biomass fuel such as biomass pellets or charcoal, which are then used to replace some kind of fossil fuel. This type of exploitation allows for the accumulated carbon to replace carbon of fossil origin.

3.4. Carbon Flow Models Integration

The different types of forest organization described in the previous sections are outlined in Figure 4 and, from here, can be analyzed from the perspectives of the intensity with which different forms of organization can be applied and the tasks leading to the achievement of the proposed objectives.

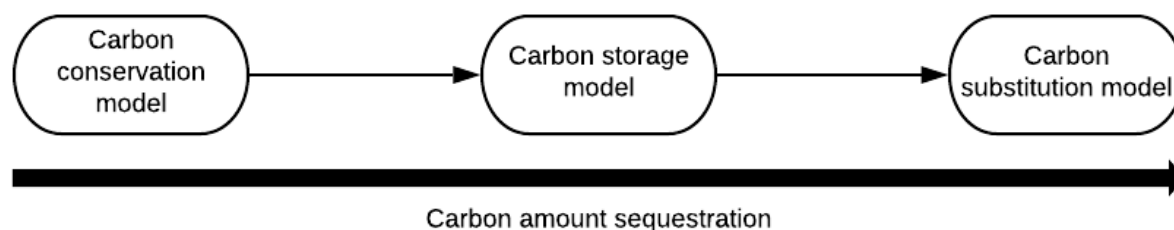


Figure 4. Models of forest organization based on carbon flows (adapted from [36] and [37]).

The model of carbon conservation forest organization is the most basic and simple. The other systems are more complex, as they include more components and more measures that they use to obtain a greater carbon capture rate until, finally, in the last system, measures for offsetting emissions are incorporated [48].

It is very important to understand that these approaches include timber production and environmental goods and services. Therefore, there is an opportunity to broaden the vision of forest resource planning by considering the environmental services of carbon capture, fixation, and storage.

4. Discussion

The ultimate goal of the United Nations Framework Convention on Climate Change is to stabilize greenhouse gas concentrations in the atmosphere at acceptable levels. In principle, this target could be achieved by reducing emissions of these gases by reducing their sources and by removing them using more sinks [49].

Forests play a very important role in carbon balance [50]. Worldwide, a large percentage of terrestrial organic carbon is stored in forest biomass and soil [51]. As a result, any change in the coarse CO₂ balance of forest ecosystems, whether due to changes in use or due to changes in management, has a strong impact on the atmospheric CO₂ concentration [52].

Forest biomass production captures CO₂ from the environment. However, the range of influence of this capture varies greatly depending on the state and composition of the forest. There are even exceptional situations in which the amount of CO₂ released from the system exceeds that which is captured. It is clear that forestry is a key instrument for regulating the carbon storage level of managed natural forests [53].

To achieve the overall objective of the Framework Convention, it is of paramount importance that forest ecosystems around the world are in a state in which their ability to function as greenhouse gas sinks is maintained and enhanced. This requires conservation as well as sustainable management and increased sinks and storage [54]. It is therefore necessary to apply the following general actions:

- The development of measures against desertification, deforestation, and forest destruction: this should aim at the appropriate stabilization of the forest area and should even increase stabilization;
- The promotion of the total health of ecosystems: this action especially includes actions that counter the detrimental effects caused by, for example, contaminants;
- The development of measures to counter the degradation and unsustainable management of ecosystems as well as measures that increase the potential of forests to act as sinks of greenhouse gases (storage densities, biomass amount, etc.);
- The promotion of scientific research on forests as sources, sinks, and reservoirs of carbon as well as their sustainable management.

Carbon stored in forests is divided into different strata, generally distributed by aerial, root, and woody residues and humus biomass. The main factors defining the state of these strata are light, heat, water availability, and nutrients. These are the factors that can regulate forestry.

In the context of the carbon balance, productivity is defined as the percentage increase in this element in relation to forest biomass. By prioritizing species with high density and high growth, this productivity increases. An additional option may be species mixing, with the aim of optimizing the use of resources and thus achieving even greater fixation of carbon.

The large amounts of carbon fixed in humus and soil are also manageable through forestry. Continuous mulching is of great importance to ensure the permanence of organic matter in the soil, which is achieved with controlled regeneration systems directed at the productive goal.

Conflicts of interest may arise between carbon fixation and other forest functions. These may have different characteristics, and they have been previously described by several authors as follows [55,56]:

- Economic characteristics: short-term evaluation vs. long-term evaluation;
- Technological characteristics: the supply and demand balance of wood;
- Forest characteristics: forest stability vs. yield and harvesting costs;
- Ecological characteristics: biodiversity vs. carbon capture;
- Social characteristics: production safety vs. short-term utility.

Applying a management model that can balance these conflicts requires grounded knowledge of the reactions of forests to different forestry options. The further elimination of greenhouse gases from the atmosphere by increasing forests as sinks can be considered a short-term goal. On the other

hand, forest biomass can be used as a substitute for fossil fuels, as it reduces emissions from their use, generating C neutral energy [57].

5. Conclusions

Trees are generally species with longevity. Their cycles of growth, flowering, fruiting and, in general, their base metabolism are processes that respond to climate conditions, in particular, temperature, precipitation, and solar radiation. Thus, changes in these factors will influence growth rates and even species survival.

Given that climate change could alter forest yields and increase the biotic and abiotic risks in forest production in the medium term, current forest management might not be appropriate for the new conditions.

It is of great importance, then, to find the tools to enable native and planted forests to evolve with climate change. A critical phase in this regard is the regeneration or implementation phase of forests, as young plants are very susceptible to variations in radiation and water supply, and failure to establish them would compromise the stability of native forests and the creation of new planted forests.

Thus, the following forestry options should be presented to address climate change:

- Manage species to be as adapted as possible to the environment;
- Include pioneer species, which generally have a very wide environmental range;
- Reduce forest density from an early age to allow greater individual tree stability and less competition for water;
- Include non-native species with greater tolerance to changes in temperature and humidity;
- For natural forests, prioritize natural regeneration to maintain genetic variability. For artificial regeneration, prioritize high density planting or direct sowing, with improved regenerative material in both cases.

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