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The Role of Mangroves Forests in Decarbonizing the Atmosphere

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Abstract

Mangrove forests occupy approximately not more than 1% of the world's forested land, according to experts. These important ecosystems are currently being lost at an alarming rate. Aquaculture, urban development, agriculture, and industrial development have been observed to be the major causes of these mangrove losses. Mangroves are an important source of ecosystem goods and services, among which are carbon sequestration, providing breeding and nursery grounds for several species of flora and fauna, materials, medicines, and climate change impact protection. Carbon dioxide capturing and sequestration is a system of man-made processes to reduce carbon dioxide emissions from utilities which use coal and gas. Mangroves can actually do this as natural carbon capture and sequestration (CCS) agents for mankind.

Keywords: mangroves, ecosystems, capture, sequestration

1. Introduction

The term mangrove (Rhizophoraceae) refers to various plant species (trees and shrubs) which are tolerant to salty waters and normally grow in the intertidal zones of coastlines belonging to tropical and subtropical sheltered coastlines [1]. The term is applied to both individual plants and entire ecosystems occupied by mangroves. The area covered by mangroves is referred to as the mangal. Mangroves cover less than 1% of tropical forests worldwide [1]. Mangroves are a well-adapted plant species that grow in fresh, brackish, and salty water wetlands. They occur dominantly in brackish and salty water wetlands since this tends to eliminate competition from plants and shrubs which are adapted to freshwater wetlands. The mangroves' adaptation mechanisms include salt coping mechanisms which enable them to filter out more than 90% of the salt in seawater, water hoarding mechanism which enables them to hoard water in thick succulent leaves, and breathing in a variety of ways using snorkel-like parts [2].

According to [3], the *Rhizophora* species are the red mangroves. The red mangroves develop better within brackish or marine water bodies, while the other species known as *Avicennia* are the black mangroves which develop better near the land side of the estuaries. Both of these species are found in areas which receive flooding and which are shallow during high tide. For a proper development they require average coldest monthly temperatures of more than 20° C and seasonal temperature variations not exceeding 5° C. In addition, they also require fine grained growing media and strong wave and tidal current-free shores. Salty water and large tidal range are also required for the development of mangroves.

2. Geographical distribution of mangroves

Mangrove forests are confined to regions 30° north and 30° south of the equator. The total area occupied by mangrove forests in the world is 18.1 million ha. South and Southeast Asia has a total of 7.5173 million ha of mangrove forest area. This is equal to 41.5% of the world's total mangrove forest area [4]. The region where mangroves are found is known to be sheltered and receives high amounts of rainfall. In terms of expanse, the largest areas of mangroves are in Asia, which tops the list in terms of size, Asia is followed by Africa, and the last on the list comes South America. At country level, there are four countries whose mangrove areas amount to 41% of the total area of mangroves in the world. These countries are Indonesia, Brazil, Nigeria, and Australia [5].

Mangroves have been restricted to tropics and subtropics because these special trees are very sensitive to the cold. They are predominantly found in two regions within the tropics and subtropics; these two regions are, namely, the Indo-West Pacific which has 58 species and the Atlantic-East Pacific which has 12 species [6].

3. Ecology of mangroves

True mangroves have been observed to occur in nature as 54–75 species. Mangroves which are healthy are very important to healthy marine ecology. This is so due to the detritus which originates from the fallen leaves and branches from mangroves. This detritus provides support to a lot of sea creatures [7].

Additionally, mangroves form valuable ecosystems. These ecosystems play many important roles apart from providing detritus. They are habitats to several species of plants and animals alike. The competition from other plants is reduced to almost zero. This means that there are very few plants which are able to survive in mangrove ecosystems. However, there are quite a number of animal species which are able to thrive in mangrove forests. The ecosystems therefore act as breeding grounds for birds, reptiles, crustaceans, fish, and insects. They are also home to the juveniles as well as entire communities of these creatures [7].

4. Biology of mangroves

The biology of mangroves is very interesting. They have various adaptations that enable them to survive. Of the 110 species which are known as mangroves, only 54–72 species in 10 genera are known to be true mangroves [8]. These 54–72 species belong to 16 families as well, and they seldom occur outside mangrove habitat [5].

4.1 Adaptation for support in soft waterlogged sediments

Mangroves have a wide variety of adaptations, one of which is the dense root system which gives them ability to stand upright in soft, waterlogged coastal sediment [5]. The sediment is so fine and soft. This is also another way of excluding other plants from being able to develop where they grow, and therefore this eliminates competition for the rarely available nutrients and oxygen (**Figure 1**).

4.2 Adaptation for reproduction and survival of offspring

The mangroves' adaptation in terms of reproduction appears in several forms. Mangroves are viviparous. The occurrence of viviparity in mangroves means

that the seeds break their dormancy while still on the parent plant. Another way reproduction and survival of offspring is ensured is seed dispersal by the flowing currents and varying tides of the water which tend to throw the germinating seeds far and wide [5].

The aforementioned adaptation ways including buoyant or floating seeds which are able to float horizontally and later switch to a vertical position securing anchor-age in the fine and soft substrate for growth tend to ensure survival of the offspring (Figure 2).

4.3 Adaptation to low quantities of oxygen

The mangroves' various adaptations depend on the species. The red mangroves have lenticels which are propped above the water to absorb oxygen through the bark of the tree, while black mangroves have pneumatophores. The pneumatophores are root-like structures which are specialized and stick out of the saline water to enable



Figure 1.
The figure is showing the way mangroves are adapted to survive in the waterlogged soft substrate for growth by having widely spaced and dense root system. Photo credit: Beatrice Njeri Obegi, Research Scientist, Kenya Marine and Fisheries Research Institute.



Figure 2.
The figure is showing the way mangroves are adapted to increase offspring survival. In the foreground some offspring can be seen germinating on the parent and have quick growth rate. Photo credit: Beatrice Njeri Obegi, Research Scientist, Kenya Marine and Fisheries Research Institute.

breathing by the plant. They are also covered with lenticels. The pneumatophores can reach up to 30 cm in height. Mangroves have four types of breathing tubes, namely, stilt or prop type, snorkel or peg type, knee type, and ribbon type [8]. These are so well adapted as to enable mangroves to breath depending on the type of environmental survival requirements.

4.4 Adaptation for efficient nutrient uptake

One of the major requirements for plant growth is need for enough nutrients. Mangroves have developed processes which enable them to take up and utilize nutrients efficiently from the soil which have low nutrient content. They have also developed nutrient conserving processes which include evergreenness, reabsorption of nutrients, immobilization of nutrients, and high root/shoot ratio [9]. Mangroves are also opportunistic in utilizing nutrients (**Figure 3**).



Figure 3.
The figure is showing the way mangroves are adapted to survive by efficient nutrient uptake and use. This figure is clearly showing the large root/shoot ratio. Photo credit: Beatrice Njeri Obegi, Research Scientist, Kenya Marine and Fisheries Research Institute.



Figure 4.
The figure is showing the way mangroves are adapted to lessen internal water loss. The shiny and succulent leaves can be seen on the left side of the photo. Photo credit: Beatrice Njeri Obegi, Research Scientist, Kenya Marine and Fisheries Research Institute.

4.5 Adaptation to the saline environment

Mangroves have evolved many ways of adapting to saltwater. The major ways they have are that they filter out the salt from the water and take up only the almost pure water. Mangroves are able to filter out more than 90 percent of the salt in saline water as it enters the roots. The other way they have adapted to the saline condition is by excreting the salt from the leaves.

4.6 Adaptation to limit internal water loss

Mangroves hoard water in a variety of ways. They store water in their thick succulent leaves. The leaves of some mangrove species have a waxy coating to seal in water, and evaporation is reduced to a minimum. Yet some other species have tiny hairs to deflect wind and sunlight (**Figure 4**). In addition they also have openings on the underside of their leaves away from the sunlight [10].

5. Carbon capture and storage technologies: the state of the art and future prospects

Currently there are many technologies available to achieve the decarbonization of the atmosphere to maintain the temperature of the atmosphere at a value or range of values which are not exceeding the 2°C threshold. According to [11], carbon capture and sequestration (CCS) is a set of technologies which have been articulated widely by several authors as having potential for reducing the concentrations of carbon dioxide in the atmosphere. The hardworking writers agree that these technologies have the potential of playing a pivotal role in helping mankind to meet the climate change targets. Additionally, [11] reports that carbon capture and sequestration (CCS) has the capability to deliver low carbon heat and power and can also help in decarbonizing industries (especially the steel and coal industries) with further applications to facilitate in reducing the net removal of CO₂ from the atmosphere.

The technologies of carbon capture and sequestration, according to [12], should include the storage of CO₂ for several hundreds of years for climate change mitigation to be meaningful to human beings. Further, [12] reports that carbon capture and storage involves three stages, namely, (i) capture of CO₂, (ii) transport of CO₂, and (iii) storage of CO₂ (or injection of CO₂). However, Herzog [13] adds a fourth stage which is the stage of monitoring of the CO₂ stored.

5.1 Capture of CO₂

The capture of CO₂ is the first step in carbon capture and storage. This step according to [13, 14] is essentially to ensure that the CO₂ is transported and stored successfully and economically. IPCC [15] reports that carbon dioxide capture is the process of reducing carbon dioxide emission from carbon dioxide-producing activities. The main CO₂-producing processes have been identified as industrial- and energy production-related processes.

The capture of CO₂ has aroused a lot of interest among many climate change experts. There are 10 pathways of carbon dioxide capture and sequestration. According to Alden and Hepturn [16] the 10 pathways of CCS and the estimates of the amounts of carbon dioxide each method can remove and the costs associated with each pathway are as follows: (i) CO₂ chemicals—Splitting CO₂ into its

constituents, this pathway will take out 0.3–0.6 Gigatonnes of CO₂/year in 2050 and will cost from USD 80 to USD 300/tonne of CO₂. (ii) CO₂ fuels—Combining hydrogen and carbon dioxide to form hydrocarbon fuels like methanol, among many others, this pathway will take out 1.0–4.2 Gigatonnes of CO₂/year in 2050 and will cost as much as USD 670/tonne of CO₂. (iii) CO₂ fixation using micro-algae—Algae can be used to fix CO₂, and the resulting biomass is processed into products like fuels and carbon-based chemicals, and this pathway will take out 0.2–0.9 Gigatonnes of CO₂/year in 2050 and will cost from USD 230 to USD 920/tonne of CO₂. (iv) CO₂ use in concrete building materials—This involves using CO₂ to cure concrete works, and this pathway will take out 0.1–1.4 Gigatonnes of CO₂/year in 2050 and will cost from USD 30 to USD 70/tonne of CO₂. (v) CO₂-enhanced oil recovery (EOR)—This involves the injection of CO₂ into oil wells to increase oil production, and this pathway will take out 0.1–1.8 Gigatonnes of CO₂/year in 2050 and will cost from USD 40 to USD 60/tonne of CO₂. (vi) CO₂ capture in bioenergy with carbon capture and storage (BECCS)—This involves splitting CO₂ into its constituents, and this pathway will take out 0.3–0.6 Gigatonnes of CO₂/year in 2050 and will cost from USD 80 to USD 160/tonne of CO₂. (vii) CO₂-assisted weathering—This involves crushing rocks and spreading them over land to accelerate the formation of stable carbonates from CO₂ in the atmosphere, and there are no estimates for this pathway yet. (viii) CO₂ storage by forests—This pathway will take out up to 1.5 Gigatonnes of CO₂/year in 2050 and will cost from USD 10 to USD 40/tonne of CO₂. (ix) CO₂ sequestration by soil—This involves land management for soil carbon management, and this pathway will take out 0.9–1.9 Gigatonnes of CO₂/year in 2050 and will cost from USD 20 to USD 40/tonne of CO₂. (x) CO₂ utilization in agriculture through biochar—This involves utilizing biochar in agriculture, and this pathway will take out 0.2–1.0 Gigatonnes of CO₂/year in 2050 and will cost up to USD 60/tonne of CO₂.

5.2 Transportation of CO₂

A number of researchers have given details on the methods of transport of CO₂. Some reports by [17–19] provide three options for transportation of CO₂ for storage. The options are as follows: (i) CO₂ transportation using pipelines—This transportation option is widely used. Using this method, CO₂ is transported by means of pipelines just like oil and gas. The pipeline can transport CO₂ over very long distances on land. (ii) CO₂ transportation by means of marine tankers—This option of transportation is used after the CO₂ is liquefied. This method is used whenever the distances through which the liquefied CO₂ should be transported far exceed the distances which pipelines can cover. (iii) CO₂ transportation by means of tankers and trucks—This method is used to transport liquefied CO₂ by means of trucks and tankers. However, this option is not very attractive [17].

5.3 Storage of CO₂

World Resources Institute [14] and Lal [20], in their studies and subsequent reports, have classified carbon dioxide storage into two broad categories of storage methods. The first method mentioned is the abiotic method. This method does not involve living organisms. Under this method, World Resources Institute [14] and Lal [20] list three categories of procedures as follows: (i) CO₂ storage in oceanic injection—This involves injection of CO₂ streams into the ocean depths. The injection into the ocean depths maybe done by injecting CO₂ below 1000m, injecting CO₂ at 500–1000 m depth as a denser CO₂/seawater mixture, injecting CO₂ as a discharge from a pipe fixed to a ship, or injecting CO₂ by pumping it into the bottom of

the sea forming a CO₂ lake. [13] adds onto this by confirming that, actually, oceanic injection of liquid CO₂ at depths of 3000 m and more is known to keep the liquid CO₂ in a stable state for long periods of time. (ii) CO₂ storage by geologic injection—This follows the steps of capture, liquefaction, transportation, and injection of CO₂ into the geologic rocks found in the earth's crust. In this procedure, CO₂ may be injected into coal seams, old oil wells (this increases yield of the oil wells), stable rock formations, or saline aquifers. (iii) Scrubbing and mineral carbonation—This involves transforming industrial CO₂ into CaCO₃, MgCO₃, and other minerals of similar chemical makeup.

The second method of storage is the biotic method. World Resources Institute [14] and Lal [20] state that this is a method which is based on the managed and/or unmanaged (i.e., natural) intervention in CO₂ storage of plants high up in the plant kingdom (e.g., mangroves) as well as microorganisms (e.g., phytoplankton of the sea and soil among many habitats). World Research Institute [14] and Lal [20] further provide two categories of biotic CO₂ storage as follows: (i) CO₂ sequestration by oceanic organisms—There are a number of biological processes which lead to CO₂ sequestration in the ocean. One such process is the photosynthetic processes carried out by phytoplankton. (ii) CO₂ sequestration by terrestrial processes—This is the transfer of carbon into biotic and pedologic (i.e., soil ecosystems) carbon pools. This is achieved by the action of forest ecosystems (including mangrove forests), wetlands, and the associated soils or histosols.

5.4 Monitoring, measuring, and verification of the impact of the stored carbon dioxide on the environment

The capture, transport, and storage (sequestration) of the carbon should be coupled with monitoring, measuring, and verification (MMV). World Resources Institute [14] accordingly reports that some of the parameters which should be measured, monitored, and verified are (i) the footprint of the project at depth to gather information on CO₂ levels and location and pressure geometry, (ii) pressure and temperature of the reservoirs to gather information on wells' and confining units' integrity, (iii) structural stresses to gather information on the wells' and confining units' integrity, (iv) performance and integrity of the wells to gather information on the wells' integrity evaluation and CO₂ monitoring, and (v) CO₂ concentrations and fluxes to gather information on accidental leakages, accident planning, and early warning systems.

6. Carbon sequestration capabilities of mangroves forests

Greenhouse gases (GHGs) are gases which cause global warming and in turn lead to climate change. Carbon dioxide is the most commonly produced greenhouse gas. The process of carbon sequestration is the process of capturing carbon dioxide from the atmosphere and storing it. The main types carbon sequestration are geologic and biologic [1]. Mangroves play a great role in biologic carbon sequestration. They form ecosystems which scientists refer to as "blue carbon ecosystems" as opposed to "green carbon ecosystems" which are found on the land.

Mangrove forests are able to store three to four times more carbon than the forests which are found on land. Mangroves are able to store and stock pile carbon from the atmosphere during their growing period from 50 metric tons to as much as 220 metric tons per acre. For the whole world, mangroves are therefore able to sequester more than 24 million metric tons of carbon per year [21]. Further, there are other studies showing and confirming that mangroves have great potential in

CO₂ sequestration. One of the supporting studies by Brown et al. [22] reports that geomorphological and biophysical qualities of locations of mangals are important in site selection for maximization of mangrove forest carbon sequestration. On the other hand, Cameron et al. [23] claims that there is not enough scientific evidence due to the small number of studies on the matter. However, despite this, Cameron et al. [23] in their study concluded that aquaculture pond (one of the reasons for mangrove forest destruction) restoration back to mangrove forest ecosystems has great potential for increasing carbon sequestration. Additionally, Spalding et al. [24] reports that if fully restored mangroves forests have the potential to sequester 69,000,000 tonnes of CO₂ which is released into the atmosphere equivalent to a yearly CO₂ atmospheric input by 25 million homes in the United States and save 296,000,000 tonnes of soil carbon stock in avoided emissions which is equivalent to a yearly CO₂ atmospheric input by 117 million homes in the United States.

7. Mangrove destruction

Mangroves have been degraded over time. According to Spalding et al. [24], between the years 1996 and 2016, which is a period of slightly over a decade, total global mangrove forest area had been reduced from 1.42795×10^7 ha to 1.36714×10^7 ha which is equal to a net loss of more than 6.0×10^5 ha. In another study, Muhammed and Koike [25] classified the cases of these losses mentioned by Spalding et al. [24] as either overexploitation or destructive actions caused by activities which do not have any bearing on sustainable exploitation of mangroves.

8. Effects of the destruction of mangrove forests

Mangroves account for 1% of the total biological carbon sequestration. However, they contribute a total of 14% of carbon sequestration by the oceans. This is a huge amount, and it means that if these blue carbon ecosystems are disturbed, the world atmospheric gas system will be upset along with huge amounts of climate change causing carbon dioxide being left in the atmosphere [21].

9. Conclusions

In conclusion, mangroves are plants which occur mostly in the intertidal zone of saline waters. They are special trees which have developed special adaptations to survive the harsh saline environments where they occur. They have huge capabilities for carbon sequestration. This means that these mangrove habitats should be protected as destruction will upset the atmospheric gas balance to a huge extent.

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Conflict of interest

The author wishes to declare that there is no conflict of interest.

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