

## The Role of Monumental Trees in Carbon Storage

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**Abstract:** Forest ecosystems are an important component of the global carbon cycle. Changes in the forest carbon cycle were determined by considering the biological structures at the leaf and stand level. However, there is no consensus on the nature of productivity at the individual tree scale. The mass growth rate of trees, and thus carbon deposition, differs depending on the size and age of the trees. In this study, the role of old monumental trees, which provide a wide variety of ecological functions and environmental benefits, in carbon storage was investigated. Because nowadays, the importance of monumental trees in carbon sequestration and protection of biological diversity in forest management has been better understood and accordingly, monumental old trees have become a significant research subject. Although monumental trees make up a small proportion of the number of stems in a given stand or vegetation, they contribute greatly to carbon biomass and help reduce global warming. Monument trees have special structures that allow long-term carbon accumulation to be sustained. Features such as slow growth, stress tolerances, mosaic structure, phenotypic plasticity, and rejuvenation potential allow for sustained age-related increases in growth, allowing for long-term carbon accumulation. In addition, changes in available resources due to global warming may be an indicator of increases in the biomass of these trees. However, these issues are still under discussion. The slow but continuous growth abilities of these trees in order to achieve longevity contribute significantly to the total carbon stock and wood production. In addition, when these trees are evaluated at the stand scale, they also make a significant contribution in terms of annual carbon sequestration. Monument trees are not just aging carbon stores. They are unique beings that can hold large amounts of carbon compared to young trees. Depending on the growth and development status, the carbon sequestration capacities show a high increase, although disproportionately. In some forest types, the largest and oldest trees continue to accumulate large amounts of biomass even though they are at the end of their natural life stages. On the other hand, there are many different opinions. These views are generally based on an assumption that older individuals have reduced biomass accumulation. Therefore, it is argued that younger trees can sequester more carbon. In line with the same view, there is a widespread opinion that carbon accumulation obtained by photosynthesis is lost by respiration due to stand development in old forests. This situation suggested that old forests are negligible as carbon sinks. There are studies showing that old forests can continue to accumulate carbon contrary to the long held view that they are carbon neutral. Numerous hypotheses have been developed to explain age- and size-related changes in biomass. In this context, the change in biomass; It has been attributed to the changing balance between photosynthesis and respiration, increased hydraulic resistance, decreased nutrient supply, differences in the access rates of resources necessary for growth, and genetic changes due to meristem age. However, these hypotheses expressing the change in growth may not be consistent as they vary depending on the species, vegetation period and growing environment. This situation falls short of explaining the physiological basis of the changes in the biomass size of these trees. The fact that the ecological role of these trees, which are rare in the world and disappear for various reasons, cannot be fulfilled by any other living thing, requires increasing the studies on these trees. In this context, when the average annual increase in diameter of a 2 m-diameter Oriental beech (*Fagus orientalis*) tree is assumed to be 0.5 cm, its annual increase is calculated as 0.182 m<sup>3</sup>. The fact that this value is not to be underestimated shows that these trees can be considered as carbon storage areas. Therefore, the role of monumental trees in carbon storage should be re-evaluated.

**Keywords:** Monumental tree, Biomass, Carbon sequestration, Carbon storage, Growth.

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## 1. INTRODUCTION

Known as “living fossils”, large old trees play an important role in ecology, landscape, and culture and are an important part of ecosystems (Fu et al., 2022). Monumental trees are among the biggest and most long-lived organisms on earth (Lanner, 2002; Mattioni et al., 2020). The longevity, size, and spatial distribution of large old trees are dependent on evolutionary origins (Tng et al., 2012), long-term environmental changes (Phillips et al., 2008), and historical decay regimes (D'Amato & Orwig, 2008). Monumental trees have numerous ecological, physiological and evolutionary properties that provide many benefits at the ecosystem level due to their extremely long lifespan. Additionally, these trees are pioneers of change in a rapidly changing world and in the history of plant life, given their adaptations for stability and longevity, their specific environments and life histories. Centennial or millennial trees that can survive long-term are vital to maintaining the resilience and adaptive capacity of forests in an ever-changing environment. At the same time, monumental trees provide numerous ecological and environmental benefits for the development of all life forms and can preserve these benefits for a long time. Revealing the numerous benefits that monumental trees have developed depending on their different and superior features will be important for the protection of these trees and thus for the continuation of these benefits.

### 1.1. Ecological Roles of Monumental Trees

Monumental trees are critical organisms and ecological structures in forests, savannas, deserts, and agricultural and urban environments (Lindenmayer et al., 2012; Lindenmayer & Laurance, 2016). They are found individually or in small groups consisting of scattered trees in this ecosystem where they are found worldwide. Therefore, they are considered small natural features (Lindenmayer, 2017). Although they are limited in area, they play many ecological roles. At the same time, the ecological value of monumental trees increases with age. They play many important ecological roles, from storing large amounts of carbon to providing important habitat for wildlife. Besides; It is very important with its roles in ecosystem processes such as hydrological regimes, nutrient cycling, micro- and meso-climatic regimes, providing habitat and nutrients for various plant and animal species (Ligot et al., 2018). Therefore, they are biological legacies that represent the biological and ecological continuity of genetic resources and habitats for various organisms (Manning et al., 2009). They are in harmony with the ecosystem in which they live and have features that help control soil erosion, such as deep rooting or low water use. Monument trees are often reproductively dominant and contribute to the germination of disproportionate numbers of new plant communities in surrounding areas (Smith et al., 2013; Wenk & Falster, 2015). They are singled out by age, their small numbers and restricted distribution, regardless of the priority of its species, being confers as guarantors of the provision of seeds and vegetative material very suitable, with which contribute to natural forest regeneration.

Monument trees play critical roles in carbon storage and therefore in maintaining forest carbon stocks (Slik et al., 2013; Chen & Luo, 2015). Although monumental trees make up a small proportion of the number of stems in a given stand or vegetation, they contribute greatly to carbon biomass (Keith et al., 2009). In some forest types, monumental trees continue to accumulate large amounts of biomass even at the end of their natural life stages (Stephenson et al., 2011). Some of these roles cannot be replaced by other structures. Many of the ecological roles they play in their ecosystem cannot be fulfilled by other living things. Thus, large old trees play a key role (Tews et al., 2004), in terms of their disproportionate contribution to a wide range of ecological processes and their disproportionate value for biodiversity (Manning et al., 2006). They are considered essential components of forest ecosystems.

Monumental trees have a number of key characteristics in addition to extreme age, height, and environment. These features are unique to these trees and provide various benefits. Some important features of monumental trees, such as the presence of deep and widespread root networks, large cavities with large internal volumes, deeply cracked bark, large side branches, wide crown, and productive flowering, constitute their characteristic features (Ashton, 1975; Brokaw & Lent, 1999; Gibbons & Lindenmayer, 2002). Their unique structures provide nesting and sheltering cavities, create different microenvironments, and provide habitat and food for many animal species (Lindenmayer et al., 2012).

The importance of monument trees as habitat for animals and other plants is so great that they can act as 'biodiversity hotspots', supporting many more species than elsewhere in the surrounding landscape (Dean et al., 1999). Many animal

species occur in a given area solely due to the presence of large old trees (Kavanagh & Turner, 1994). Monumental trees can continue to have important ecological roles even when they occur as individual trees. For example, they have profound effects on local microclimate conditions, soil moisture, and soil nutrient levels (Dean et al., 1999; Voight et al., 2015).

## 1.2. Monumental Trees and Their Role in Carbon Storage

Forest ecosystems have frequently been subjected to significant environmental changes throughout geological and historical periods. In particular, the pace and complex nature of current global change seem particularly difficult to overcome (Valladares, 2017). Climate changes, especially global warming trends, cause irreversible consequences all over the world. Increasing greenhouse gas emissions (GHG) such as CO<sub>2</sub> are now recognized as the main cause of recent increases in global average temperature and changes in the global hydrological cycle. It has been revealed by the IPCC that warming over the last half century is mostly caused by human activities (>95% probability). Climate change and environmental degradation have reached alarming levels, bringing to the fore the ecological and sociocultural functions of forests as well as their economic functions. Because forests play an important role in reducing global climate change. They remove CO<sub>2</sub> from the atmosphere through photosynthesis and store carbon in their biomass. Forests play a key role in reducing greenhouse gas emissions that cause climate change by serving as carbon sinks. Understanding the magnitude and drivers of the rate of CO<sub>2</sub> exchange between forests and the atmosphere has been a focus of research, given concerns about the effects of increasing atmospheric carbon dioxide levels on climate change (IPCC, 2007).

Forests provide a wide range of ecological services and functions. It is known that carbon sequestration has an important place among the ecosystem services provided by forests and plays a critical role in the fight against climate change (Pukkala, 2016). For this purpose, the scope of forest management today mainly focuses on carbon sequestration and biodiversity. Forests both combat climate change by sequestering carbon and adapt by reducing the effects of climate change. Forest ecosystems are an important component of the global carbon cycle (Gray, 2015). Carbon; It is kept in the trunks, leaves, branches, roots of trees, litter and living cover and forest soil (Houghton, 1999; Goodale et al., 2002).

Changes in the forest carbon cycle were determined by considering the biological structures at the leaf and stand level (Stephenson et al., 2014). However, there is no consensus on the nature of productivity at the individual tree scale. The carbon storage and sequestration rate are directly related to factors such as the species, height, age and leaf biomass and healthy condition of each tree (Gül et al., 2021). CO<sub>2</sub> consumption of forests varies depending on their health, age and location. In this sense, the mass growth rate of trees and therefore their carbon accumulation may vary depending on the size and age of the trees. For this purpose, the role of monumental old trees, which provide a wide range of ecological functions and environmental benefits, in carbon storage was investigated. Because today, the importance of monumental trees in carbon sequestration and biodiversity protection in forest management is better understood, and accordingly, old monumental trees have become significant as a research subject.

The importance of monumental trees is increasing due to global warming and other environmental changes. Because monumental trees are the most important organisms that cope with the negativities caused by changing and developing climatic conditions and biotic and abiotic stress factors in the world. These trees have survived in many stages, from all kinds of climate changes to changes in the surrounding stand structure, in their growth environment for thousands of years (Oktan & Atar, 2021). Although monumental trees make up a small proportion of the number of stems in a given stand or vegetation, they contribute greatly to carbon biomass (Keith et al., 2009) and help reduce global warming. By reconstructing the past climate and environment, these trees have preserved and continue to exist even in long contrasting climatic phases (Medieval Warm Period, Little Ice Age, global warming) [Caetano-Andrade et al., 2020]. Monumental trees are natural and human-made systems against a climatic stimulus and its effects; They constitute the most important group of living beings that adapt to this bad situation by adjusting or changing themselves to reduce the effects of harm or benefit from the benefits.

Atmospheric carbon dioxide (CO<sub>2</sub>) has increased significantly during the current lifespan of these long-lived trees and old-growth forests. In the early twenty-first century, it was thought that a 500-year tree spent 70% of its life growing under pre-industrial CO<sub>2</sub> levels that were 30% lower than current levels. For this purpose, Phillips et al. (2008) investigated the question of whether old trees respond to the rapid CO<sub>2</sub> increase that has occurred in the last 150 years. Despite limited data, senescent trees have been shown to have a significant capacity for increased net growth following

post-maturity growth decline. Increases and changes in key environmental resources, including CO<sub>2</sub>, have been associated with growth and physiological functions in old trees. It was thought that this may indicate the potential for continued growth in old trees as a function of ongoing global climate change. In addition, there are opinions that CO<sub>2</sub>-induced stimulation of tree growth (Körner, 2009; van der Sleen et al., 2015) is not certain. For this reason, it is not clear whether changes in available resources due to global warming are indicators of increases in the biomass of trees.

There are synergistic relationships between the longevity of monumental trees and the benefits they provide to the ecosystem. Because the ecological value of these trees increases with age. The longevity of monumental trees results from a combination of mechanisms that serve both to prevent senescence (modularity, continuous growth, dormancy) and to tolerate aging (stress tolerance), creating tremendous potential and resilience in longevity (Munne-Bosch, 2020). Several mechanisms have evolved in individual trees to enable extreme longevity and deal with negative effects of ageing. Senescence implies a reduction in vigor. Therefore, continuous growth is the most effective mechanism in preventing aging (Cannon et al., 2022). The slow but continuous growth ability of these trees to achieve longevity makes a significant contribution to the total carbon stock and wood production. These mechanisms specific to monumental trees also allow the long-term carbon accumulation of monumental trees to be sustained.

Carbon stocks of forests are a result of both, carbon capture by biomass growth and the duration of carbon in biomass. It is stated that the carbon capital of forests is controlled by tree life rather than growth rate (Körner, 2017). Although carbon stock dynamics occur in quite large areas, they can be attributed to the dynamics of individual tree communities. Because monumental trees determine stand level dynamics (Newberry & Ridsdale, 2016), they play an important role in small-scale carbon accumulation and storage. Old trees simultaneously increase carbon capital with their long lifespan and continuous growth ability (Köhl et al., 2017). They store large amounts of carbon due to their high wood volume.

Although the ecological value of a monumental tree increases with age, its biological growth rate slows down with increasing age. So tree age and tree size are not necessarily related. The decrease in the growth rate, that is, the photosynthetic capacity, of monumental trees causes them to capture less carbon. However, it stores more carbon due to the increase in its biomass. Young trees have relatively low carbon accumulation. Young trees use the carbon they obtain through photosynthesis to convert it into growth energy rather than storing it. Young trees use biomass production to increase height rather than diameter growth until they reach the upper layer (Rozendaal & Zuidema, 2011; Newberry & Ridsdale, 2016).

Old trees store the majority of the carbon they obtain through photosynthesis. Old trees have low growth energy. Therefore, carbon accumulation is high. Young trees capture more carbon, while old trees store more carbon. In this context, when the average annual increase in diameter of a 2 m-diameter Oriental beech (*Fagus orientalis*) tree is assumed to be 0.5 cm, its annual increase is calculated as 0.182 m<sup>3</sup>. The fact that this value is not to be underestimated shows that these trees can be considered as carbon storage areas. Therefore, the role of monumental trees in carbon storage should be re-evaluated.

Tree growth and longevity; are the main factors that manage the diversity, functions and productivity of forests (Lorimer et al., 2001; Köhl et al., 2017). Research on the factors controlling these is essential to improve forest management (Worbes et al., 2003). Studies to be carried out are extremely important, especially in terms of the uncertainty of how long monumental trees, which are rare in the ecosystem, can maintain the numerous ecological and environmental benefits that cannot be provided by other trees or plants.

## 2. DISCUSSION AND RECOMMENDATIONS

The growth behavior of monumental trees is not well known. Revealing the growth behavior of trees provides insights into forest ecology and plant physiology. It can also improve our understanding of forest productivity, carbon storage, and dynamics (Clark & Clark, 1996; Slik et al., 2013). However, the physiological basis of the growth patterns of monumental trees has not been adequately documented.

There are limited studies on how the mass growth rate and therefore carbon accumulation changes as the size and age of monumental trees increases. With regard to carbon accumulation the growth pattern of old trees is of particular importance

(Lanner & Connor, 2001; Johnson & Abrams, 2009). Regarding the growth of large trees, contrasting results can be found in the literature (Sheil et al., 2017). Decreasing biomass accumulation in the oldest and largest trees has classically been assumed (Vanclay, 1994, Avery & Burkhart, 2015) but increasing biomass accumulation with tree size has recently been claimed (Sillett et al., 2010, 2015; Stephenson et al., 2014).

Post-maturity decline in wood production is a long-standing premise in forest ecology. A widely held assumption is that after an initial period of increasing growth, the mass growth rate of individual trees declines with increasing tree size (Phillips et al., 2008; Meinzer et al., 2011; Piper & Fajardo, 2011). Theoretically, this is a necessary consequence of the sigmoidal nature of organismal growth (Weiner & Thomas, 2001). This type of behavior has been determined for diameter and length increase, but it is not sufficient to explain biomass growth. Although the results of a few single-species studies have been consistent with this assumption, the bulk of evidence cited in support of declining growth is not based on measurements of individual tree mass growth. Studies document well-known age-related declines in net primary productivity of most even-aged forest stands. A large amount of scientific effort has been devoted to understanding the potential causes of the post-maturity decline in wood production. However, the distinction between factors acting at the tree and stand level is often unclear and further studies are needed at the individual tree scale (Sillett et al., 2010).

The decrease in tree growth over time can be caused by changes in the supply of necessary resources (light, nutrients, water), the changing balance between photosynthesis and respiratory, increasing hydraulic resistance, decreased nutrient supply, or genetic changes with meristem age. However, these hypotheses expressing the change in growth may not be consistent as they vary depending on the species, vegetation period and growing environment. Delzon et al. (2004) report a height-related decrease in above-ground annual biomass increment per unit leaf area. The hydraulic limitation hypothesis (Ryan & Yoder, 1997), which proposed a physiological mechanism whereby a tree's height growth declines with increasing height, is often invoked to explain the age-related decline in stand-level wood production. Yet, even though a tree's height growth may diminish with increasing height due to hydrostatic and hydrodynamic effects, wood production of the entire tree (or stand) does not necessarily diminish at the same rate (Ryan & Yoder, 1997), and diameter growth of old trees may continue long after height growth has slowed (Phillips et al., 2008). For example, leaf water stress occurs in redwoods, the tallest tree in the world, due to hydraulic and mechanical constraints. As a result, leaf expansion and photosynthesis are limited. It is difficult to reach above 130 m even if there is sufficient soil moisture (Koch et al., 2004; Niklas, 2007; Pandey et al., 2017). So they cannot grow taller indefinitely. However, although height growth does not continue indefinitely, diameter growth can continue as long as the individual lives. They have also developed strategies to prevent mortality from water stress when trees reach their maximum height. Recent studies highlight sustained or continuously increasing mass growth rates with increasing tree size and emphasize the significant role of old trees for carbon accumulation (Carey et al., 2001; Stephenson et al., 2014).

The metabolic theory of ecology predicts that, under demographic and resource steady-state assumptions, the growth rate of individuals increases continuously with body size. Therefore, this theory predicts that at the forest level, large trees should contribute to forest biomass accumulation as much as small trees (Enquist et al., 1999). Supporting this theory with empirical findings, Stephenson et al. (2014) analyzed 403 tropical and temperate tree species and revealed that the mass growth rate and tree size of most species showed a continuous increase together. Monumental trees don't just act as reservoirs of aging carbon. They actively fix large amounts of carbon compared to smaller trees. A single monumental tree can add as much carbon to a forest in a year as an entire medium-sized tree. Also found 'published equations for diameter growth rate in the absence of competition' for 41 temperate tree species and highlighted that 35 of these equations indicate increasing biomass growth with size even at the largest sizes. The authors concluded that biomass growth continuously increases with tree size (Stephenson et al., 2014).

Sillett et al. (2010) assessed two of the world's tallest tree species: *Sequoia sempervirens* and *Eucalyptus regnans*. From the measurements, they concluded that wood production was highest in the largest and oldest trees. A closely related study on *E. regnans* drew comparable conclusions from similar data (Sillett et al., 2015).

There are different reasons for continuous growth with increasing age. These are: competition for space, which predicts a constantly increasing mass productivity with tree size (Pretzsch, 2009), increasing the total leaf area of the tree with tree growth (Bloor & Grubb, 2003; R ger et al., 2011), or the process of adaptive reiteration which decreases the ratio of

respiration to photosynthesis, rejuvenates apical meristems, and improves the hydraulic conductance by newly developed leaves (Ishii et al., 2007).

To conclude, there is considerable theoretical and empirical uncertainty regarding how biomass growth might vary with stem size. Further research will be required to clarify these issues. Monumental trees alone are a carbon sink. Due to their high wood volume, they store large amounts of carbon and preserve it for a long time. The long-term importance of monumental trees for accumulating and storing large amounts of carbon requires a better understanding of their growth behavior, particularly to prevent them from being replaced by faster-growing younger trees. Once lost from an ecosystem, populations of these trees, along with their many associated ecological and cultural roles, are inherently difficult or even impossible to recover. At the same time, it may take centuries to recover the benefits provided by these trees. The fact that the ecological role of these trees, which are rare in the world and disappear for various reasons, cannot be fulfilled by any other living thing, requires increasing the studies on these trees.

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