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A synthesis of research on the sequestration of carbon in forests and the conservation of water

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ABSTRACT: Forests help solve environmental issues by sequestering carbon and conserving water. Forest management's ultimate goal is to optimize dual functions to reduce greenhouse gas emissions and maintain the water cycle. Increased forest production and ecosystem water balance have costs and benefits. This study reviews forest carbon sequestration and hydrological principles for future research. The interaction between forest carbon sequestration and water conservation revealed information gaps and research needs. Previous research has helped comprehend forest carbon fixing and hydrological regulation. Many equipment and methods can quantify and monitor forest carbon and hydrological issues at multiple geographical and temporal levels. Afforestation programs that improve carbon sequestration and water maintenance ecosystem services lack knowledge. Top-down scheduling of afforestation in locations with uncertain water supplies must address how much and where to plant assumed existing land, ecological implications, and local progress and income. Planting decisions dominate local management. Cooperative research is needed to build and manage planted forests for carbon sequestration, water management, and other societal purposes. This study's integrated paradigm for forest management considers carbon sequestration and water conservation can assist future research.

Uma síntese da pesquisa sobre a captura de carbono em florestas e a conservação da água

RESUMO: As florestas ajudam a resolver problemas ambientais, sequestrando carbono e conservando a água. O objetivo final do manejo florestal é otimizar as funções duplas para reduzir as emissões de gases de efeito estufa e manter o ciclo da água. O aumento da produção florestal e o equilíbrio hídrico do ecossistema têm custos e benefícios. Este estudo revisa o sequestro de carbono florestal e os princípios hidrológicos para pesquisas futuras. A interação entre o sequestro de carbono florestal e a conservação da água revelou lacunas de informação e necessidades de pesquisa. Pesquisas anteriores ajudaram a compreender a fixação de carbono florestal e a regulação hidrológica. Muitos equipamentos e métodos podem quantificar e monitorar o carbono florestal e as questões hidrológicas em vários níveis geográficos e temporais. Os programas de florestamento que melhoram o sequestro de carbono e os serviços ecossistêmicos de manutenção da água carecem de conhecimento. A programação de cima para baixo do reflorestamento em locais com abastecimento de água incerto deve abordar quanto e onde plantar assumindo a área de terra existente, implicações ecológicas e progresso e renda local. As decisões de plantio dominam a gestão local. A pesquisa cooperativa é necessária para construir e gerenciar florestas plantadas para sequestro de carbono, gestão de água e outros propósitos sociais. O paradigma integrado deste estudo para o manejo florestal considera o sequestro de carbono e a conservação da água pode auxiliar pesquisas futuras.

Introduction

Forests are widely appreciated for their function in providing ecosystem services (Raihan et al. 2018; 2019; 2023a). As a result of alarms about global climate change and the security of water reserves, carbon sequestration and conservation of water are the most significant factors in contemporary forest management (Raihan and Tuspekova 2022a; 2023). Formation of extensive plantation forests occupies tradeoffs for declined regional water accessibility and reduced streamflow (Doelman et al. 2020), despite the fact that increase of forests is preferred for increased terrestrial carbon sequestration and inclusive increases in the amount of ecosystem services provided worldwide (Zhang et al. 2017; Raihan 2024a). According to Schwarzel et al. (2020), such compromises are especially essential in regions where water is scarce and there is a history of drought. In regions where water is not a finite resource, however, forests regulate the local water cycle. They accomplish this by temporarily storing rainfall by either increasing water penetration in the soil or increasing water storing in the litter deposit, thus decreasing the quantity of water lost through immediate runoff (Wu et al. 2020).

To maximize socioeconomic values while curtailing or accelerating ecological influences, the scheduling and managing of plantation forestry demands an in-depth understanding of technological procedures. This is essential when considering both the natural obstacles to sustainability and the social demands (Raihan and Said 2022). Wood collection, new tree growth, and the preservation of extant forest cover are the three primary goals of traditional forest management (Raihan 2023a; 2023b; 2023c). Numerous forest management actions are being taken in uphold of these purposes, with intensive research attempts focusing on the deliverance of required forest goods serving as the driving force (Miah and Raihan 2017). Figure 1 illustrates the relationship between traditional forestry research and forest management. In modern forestry, the establishment and managing of plantation forests to produce non-timber goods and/or the provision of non-timber-related services is motivated by the understandings of the dynamic function woodlands play in ecological control and eco-safety (Haakana et al. 2020). Two of the most widely recognized and valued functions of forest ecosystems are the enhanced capacity for carbon sequestration and the efficient benefits of water conservation.

Over the course of several decades, several studies have been performed to determine the scope and regulations of forest carbon sequestration and to comprehend the monitoring functions that forests play in both regional and local water cycles (Raihan 2023d; 2023e; 2023f; 2023g; 2023h; 2023i; 2023j; 2023k). In this review, we examine some of the new information that has been acquired as well as some of the recent advancements in the field of forest carbon sequestration research and forest hydrological dynamics scrutiny. The purpose of this study is to recognize significant information gaps in the area of understanding the links between the sequestration of carbon in forests and the conservation of water in order to advance an outline for forthcoming forest research and managing that takes into account both carbon sequestration and water conservation.

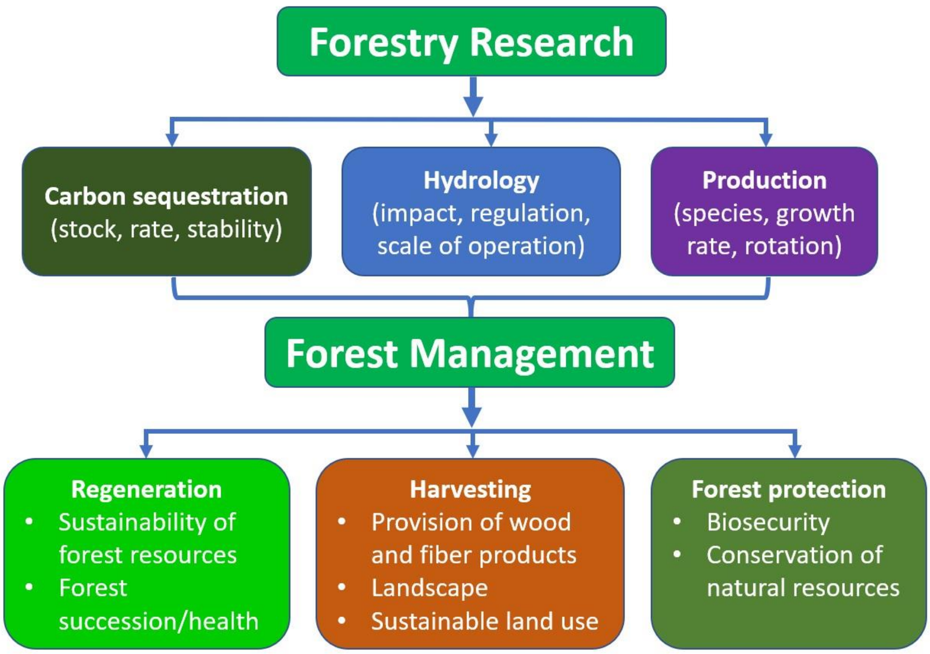

Figure 1. The connection between traditional forestry research and forest management.

Material and Methods

This study performed a systematic literature analysis to review the outcomes and debates on investigations that address the sequestration of carbon in forests and the conservation of water, with the goal of providing a comprehensive knowledge of the interconnections between the two. The study developed a set of keywords to conduct a thorough and representative search of the literature on the topic of forest carbon and water conservation in relation to climate change mitigation and environmental sustainability. Database classification terms have also been considered, along with synonyms, single and plural models, broader terms, alternative spellings, and more specific terms. The selected keywords used for searching documents for the review analysis are forest carbon, carbon sequestration, carbon emission, emission reduction, biomass carbon, ecosystem services, forest management, forest products, regeneration, harvesting, forest protection, forest hydrology, water conservation, water use, water quality, water conservation, hydrological processes, climate change, mitigation, and sustainability.

The initial search with the keywords led to 1872 documents. After scanning the documents based on the selection criteria and to remove possible duplication, 326 articles were selected for the next step of scanning. After screening those article's title and abstract, the comprehensive literature review encompassed a total of 56 distinct scholarly articles published between 1990 and 2022 were chosen for further analysis. The papers came from the academic aggregators Google Scholar, Scopus, and Web of Science (WOS). Figure 2 depicts the evolution of review criteria used to choose appropriate documents for analysis. To build a paradigm for future forest research and management that takes into account both carbon sequestration and water conservation, this paper provides an overview of the links between these two processes in forests. This study solely used research articles published in peer-reviewed journals to assure the quality of the results, which provide a foundation for future forest research and management taking into account carbon sequestration and water conservation. These papers were then reviewed to determine if their primary topic was similar to that of the current investigation.

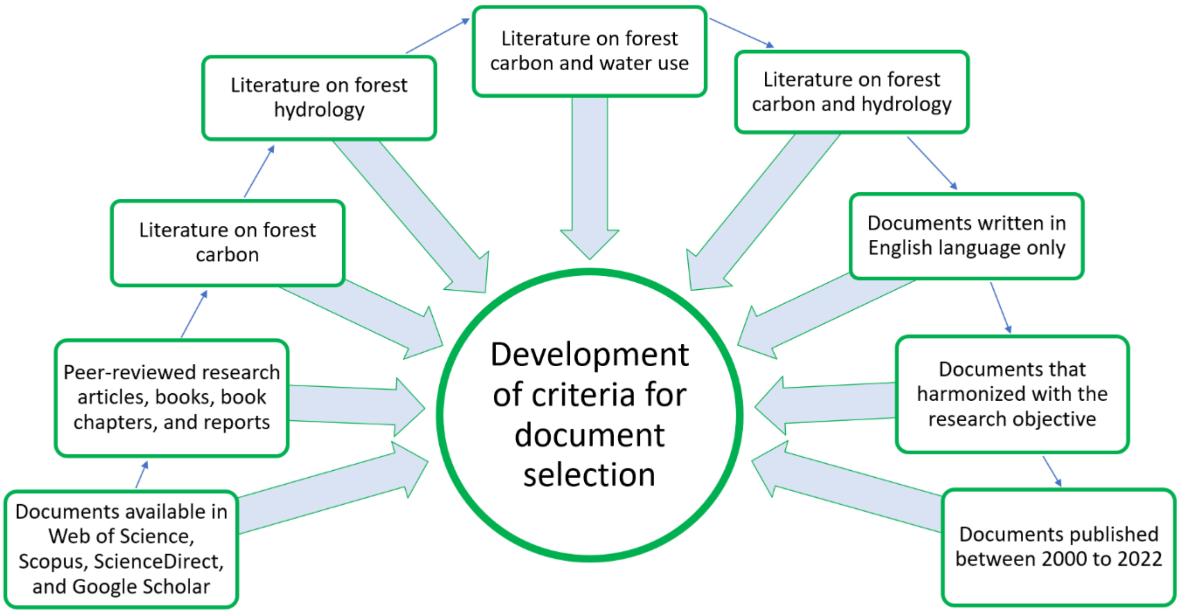

Figure 2. The development of criteria for document selection.

Forest carbon sequestration

Carbon may be sequestered by forest plants in a variety of locations, including biomass, wood debris, litter, and soils (Raihan and Tuspekova 2022b; 2022c). Quantifying forest carbon stocks and their partitioning into various carbon reservoirs, as well as determining spatial and temporal variations in forest carbon fixation and regulating mechanisms, were the primary foci of previous research on forest carbon stocks. Other research on forest carbon inventories has also centered on identifying the spatial and temporal variations in forest carbon fixation and regulating mechanisms (Raihan et al. 2021a; 2023b). Harvesting and modelling are two of the most common methods used to assess changes in the quantity of carbon stock in forests. Before cutting down a tree, it is essential to take precise measurements of its trunk, leaves, branches, and roots (Sun and Liu 2020; Raihan et al. 2024a). In order to acquire a more accurate image of the carbon stock in forest ecosystems, soil samples were also collected (Raihan 2023l; 2024b).

Traditional methods for measuring carbon stock are the most accurate, but they are also the most time-consuming, expensive, and challenging to implement in certain circumstances. Estimating the quantity of carbon stored in forests can be accomplished with allometric equations, a less labor-intensive method. The diameter of the bole, the height of the tree, the diameter of the crown, and the species of tree are used to construct a link between biomass and allometric equations for the purpose of biomass estimation (Raihan et al. 2021b; 2023c). Using data from forest inventories and biomass prediction equations for a variety of tree species, researchers are able to assess carbon stocks on a regional or national scale (Law et al. 2004). Carbon stock fluctuations (fluxes) in forests can also be measured, provided that periodic inventory data are accessible (Begum et al. 2020; Jaafar et al. 2020; Jubair et al. 2023).

The development and applications of remote sensing products of vegetation and ecosystem process modelling, coupled with site measurements and forest inventory data, have enabled large-scale, cost-effective studies of forest carbon budgeting and the underlying factors contributing to the spatiotemporal dynamics of forest carbon stocks. Now, these studies can investigate the factors that affect the spatial and temporal dynamics of forest carbon stocks. It is possible to divide remote sensing applications into two categories: those that measure changes in the carbon content of forests and those that measure the carbon content of forest biomass (fluxes). A number of studies have been conducted with the objective of extrapolating correlations between satellite-derived indices and ground-based biological measurements in order to obtain regional estimates of forest carbon stocks.

Using passive (multispectral and hyperspectral) and active (light detection and ranging [LiDAR] and radio detection and range [radar]) satellite remote sensing techniques, it is possible to acquire the data necessary for estimating the carbon stock of forest biomass. Passive remote sensing is applicable on dimensions ranging from the neighborhood to the entire planet because it relies on the reflection of solar radiation off the surface of the Earth (Timothy et al. 2016). However, because this method is more sensitive to the crown surface than to the characteristics below the canopy, it is less effective at capturing forest biomass in dense forests due to the saturation of reflected signals in these environments.

Active remote sensing is a technique for reconstructing forest biomass that accumulates data transmitted by flying devices. Active remote sensing systems, as opposed to weather-dependent passive methods, can provide information on the forest structure (such as tree height, canopy area, and trunk size) at any time of the year. When it comes to estimating carbon fluxes in forests, satellite-derived indices are a valuable tool. When constructing satellite-derived vegetation indices like CASA, VPM, and GIO-PEM, light usage efficiency models are frequently implemented. It assumes that there is a direct proportional relationship between the amount of carbon that vegetation absorbs, and the amount of photosynthetically active radiation absorbed. Due to the simplicity of the lighting efficacy model, it has the potential to be implemented in much larger areas, possibly even globally. Despite the fact that the remote sensing method excels at delineating large-scale vegetation activity, it is only capable of producing carbon fluxes and aboveground biomass carbon by employing simplistic empirical models. Using satellite observations to directly retrieve information about the carbon store and dynamics of subsurface soil was more problematic. Regional forest carbon inventories and balances can be accurately estimated by combining data from ecosystem models, remote sensing, and on-the-ground biological observations (Law et al. 2004).

Numerous variables influence the quantity of carbon stored in forests as well as its distribution (Raihan et al. 2022a; 2022b). Climate appears to be the most influential factor in determining the spatial patterns of forest carbon stocks at the continental and global scales. At the local and regional scales, the density and allocation of forest carbon varies with tree species, forest structure and types, stand development, management, and soil conditions; however, at the continental and global scales, climate appears to be the most influential factor (Zhou et al. 2019; Raihan et al. 2024b). On a regional and landscape scale, as well as in relation to forest types, development, and site conditions, the quantity of carbon stored in wild versus cultivated forests differs significantly (Law et al. 2004). Both accidental and deliberate human disturbances of forests have a negative impact on carbon stocks and the stability of forest ecosystems (Raihan and Tuspekova 2022d; 2022e).

In addition to the direct effects of wood harvesting and burning, protracted events such as insect infestations and droughts have the potential to influence the carbon fixation and cycling processes in forests in a variety of ways (Pregitzer and Euskirchen 2004). Increased decomposition rates at harvest time have a multiplicative effect on the carbon budget (Noormets et al. 2015). Destruction of trees by fire reduces the amount of carbon stored in the forest's biomass but can also alter the amount of carbon stored in the soil. Black carbon, being a byproduct of fire, modifies the organic carbon composition of soil in a manner that favors increased recalcitrance. Rapid urbanization in China has been shown to substantially increase forest soil carbon sequestration in urban areas (Lv et al. 2018), and the likely cause for this is the increased rate of soil fungal-related carbon and soil carbon turnover rate

(Wang et al. 2020). Changes to the current landscape plan could make the forest environment more stable, help trees grow, and store more carbon in tree biomass and soil (Yang et al. 2019).

Opening the proverbial "carbon black capsule" that is soil has become the primary focus of recent research on the carbon sequestration process in forests. The preponderance of forest stands only store about one-third of their total carbon as biomass. The remaining two-thirds of carbon exists in the soil as soil organic carbon and detritus (Law et al. 2004; Raihan and Tuspekova 2022f). Recent interest has increased in the methods by which carbon can be stored in the ground while retaining its inherent stability (Ali et al. 2022). A number of factors, including climate, management, and disturbance, influence the quantity of organic carbon that can be stored in soil as well as the rate at which it decomposes (Schuur et al. 2001). This helps determine the stability and long-term reserves of soil organic carbon because carbon molecules and complexation can be chemically resistant and physically protected (Wang et al. 2019).

Conditions favorable for organic carbon preservation include moist soils and low temperatures. Carbon sequestration in aboveground biomass is crucial to the process of reducing greenhouse gas emissions; however, converting farms into larch forests also increases the quantity of carbon in mineral soils by 100 g m2 per year (Wang et al. 2011). There was a considerable difference between plant species in terms of their capacity to store carbon and their utilization of soil nutrients, suggesting that selecting the right plant species could affect the total size of the carbon sink that a forest provides in its mineral soils (Wu et al. 2019). According to the findings of previous research on the ecosystem service of carbon sequestration provided by forests, measurements of forest carbon stocks and fluxes should be expanded beyond the stand level (Zhou et al. 2019; Raihan and Tuspekova 2022g).

Hydrological processes and forest water relations

There are growing concerns about the threat that large-scale afforestation poses to water security in arid nations, but expanding planted trees is viewed as a viable strategy for reducing carbon emissions and providing numerous ecosystem services (Raihan et al. 2022c; 2023d). Forests are well-known for their dependence on hydrological systems and their role in regulating these systems (Doelman et al. 2020). Our comprehension of forest water relations and hydrological processes is limited in comparison to our understanding of carbon sequestration, primarily as a result of technological limitations in observational studies. The dimensions of forest water relations and hydrological processes vary.

Numerous studies have been conducted to determine how a change in forest cover affects water resources, but the results have been inconsistent, making it difficult to draw definitive conclusions about the topic (Brown et al. 2007; Trabucco et al. 2008). The "bottom-up" methodology of conducting experiments at the watershed scale emphasizes the significance of forests for hydrological system management. Due to a paucity of data and the possibility of confounding influences, the complexities of smaller (1 000 km2) watersheds have received less attention than those of larger watersheds (e.g., climate variability, urbanization, dam construction). Top-down modelling is exemplified by techniques like energy-based equations and water-balance simulations (Zhou et al. 2015). In terms of their ability to simulate reality and their predictive potential, the extent to which these models are grounded in empirical data varies (Trabucco et al. 2008). Recent studies have indicated that comprehension of the characteristics of watersheds is essential to comprehending the effects of land cover changes on water supplies (Liu et al. 2016).

It is common knowledge that trees reduce catchment-level discharge, which has a knock-on effect of increasing water availability through increased precipitation (Alemayehu et al. 2009). The effects of reforestation and afforestation on water supplies are still a matter of debate. Nevertheless, it is well known that trees reduce drainage at the catchment level (Ellison et al. 2012). Determining the forest's "footprint" in terms of lowering runoff and competing for water resources with non-forest ecosystems beyond the forest boundary or enhancing precipitation for the benefit of increased local ecosystem productivity remains a topic of considerable interest. Both of these subjects pertain to the influence of the forest on the availability of water resources. Recent research has shown that different regions of China have experienced substantially different hydrological responses to massive reforestation and vegetation greening, which has led to severe water shortages in the Southwest region of the country (Li et al. 2018). It has been recommended that the Loess Plateau in China not be reforested without first considering the region's water supply constraints (Feng et al. 2016). Recent studies indicate that the afforestation of poplars in China's Songnen Plain has resulted in a shortage of soil water, especially when compared to the regions that border it (Wu et al. 2019).

The vast majority of studies on forest water relations examine the distributions of precipitation in relation to forest type and structure, as well as evapotranspiration at the stand or regional scale. Due to the uneven distribution of forests in relation to terrain characteristics and the complexity of water flow movement and distribution, it is practically impossible to evaluate the effects of various forest stands on catchment and watershed hydrological processes. Assumption-based parameterization is needed to help describe forest hydrological processes at the stand level and then scale them up to the watershed level.

Carbon sequestration and water conservation: a new direction for forestry research

Although extensive literature surveys reveal abundant information on understanding the process of forest carbon sequestration at various scales, from local to global, the understanding of hydrological management of forests and the impact of afforestation on regional water resources is insufficient. Thus, these themes are not sufficiently comprehended as they ought to be. Most of the current studies on forest carbon sequestration and hydrological regulations are conducted at different spatial and temporal dimensions, using various approaches and tactics. Therefore, assessing the comparative advantages of forest carbon sequestration and water conservation as conflicting objectives is a highly difficult task that is hindered by a considerable degree of uncertainty. Carbon sequestration and water conservation are often overlooked when it comes to creating afforestation programs or developing management plans for protecting natural forests. However, it is noteworthy that both ecological services hold significant importance. The unresolved issue is to the optimal management of forests to maximize their commercial carbon worth while also keeping their regional water management function. Thus, it is crucial to optimize the economic worth of forests by capitalizing on their carbon content. Forest management should aim to limit human impact on the environment to the greatest extent possible.

During the stages of reestablishment and early development, reducing the number of trees that are present in an area on a regular basis and in accordance with the protocols that have been established for the planning and management of forests significantly reduces the risk that local water supplies will become depleted. Complete forest preservation and additional planting are required to meet the current demand for services related to the sequestration of carbon and the protection of biodiversity; however, this places an increased strain on water supplies that are already being used for a variety of other natural and social purposes. While developing an afforestation program, it would be beneficial to take into account the distribution of water resources in addition to the availability of land for afforestation across a variety of land uses. This would result in an improved program design.

There are still many questions, all of which need answers that were derived from extensive investigation before they can be considered answered. A planning approach that starts at the top and works its way down for afforestation in areas where it is predicted that access to water would be difficult brings up questions of how many trees should be planted, where those trees should be put, and what impacts this will have on the ecology as well as the capacity of people to make a living in the region if it is allowed to continue. When it comes to the management of afforestation/reforestation activities, "what trees to plant" and "how to grow them" are the most significant issues to take into account. It is necessary to take into account socioeconomic preferences, a mechanism of eco-compensation or payment for ecosystem services (PESs), the selection and preparation of a site, the self-sustainability of established forests, the tending and end uses of trees that have been planted, and other similar considerations in order to find a workable solution to the issues that are at hand. Studies and information that are currently available have very restricted scopes and purposes, which prevents them from adequately addressing the complexities of the problems and topics that are currently being discussed. Figure 3 provides a visual representation of the integrated study paradigm that has been developed.

This framework on forest carbon sequestration and water conservation presented in Figure 3 considers the current trend as well as the perspective of society on forests. Also, it considers the capacity of the forest to store carbon as well as its capacity to retain water. The scientific partnership between the fields of forest regeneration, harvesting, and protection is the foundation on which the framework is formed. This can be accomplished by employing a uniform experimental design and establishing a worldwide or regional forest research network. Both steps are necessary to get the desired result. The establishment of planted forests for the benefit of society and the protection of biosecurity is the primary objective of the framework, which is designed to facilitate this process. The framework's primary focus is on ensuring the delivery of carbon sequestration, water conservation, and other ecosystem services from forested areas in a sustainable manner. It will be feasible to obtain a better knowledge of the scales at which climate and geography may imperil ecosystem services such as carbon sequestration and water conservation if an effort of this kind is undertaken.

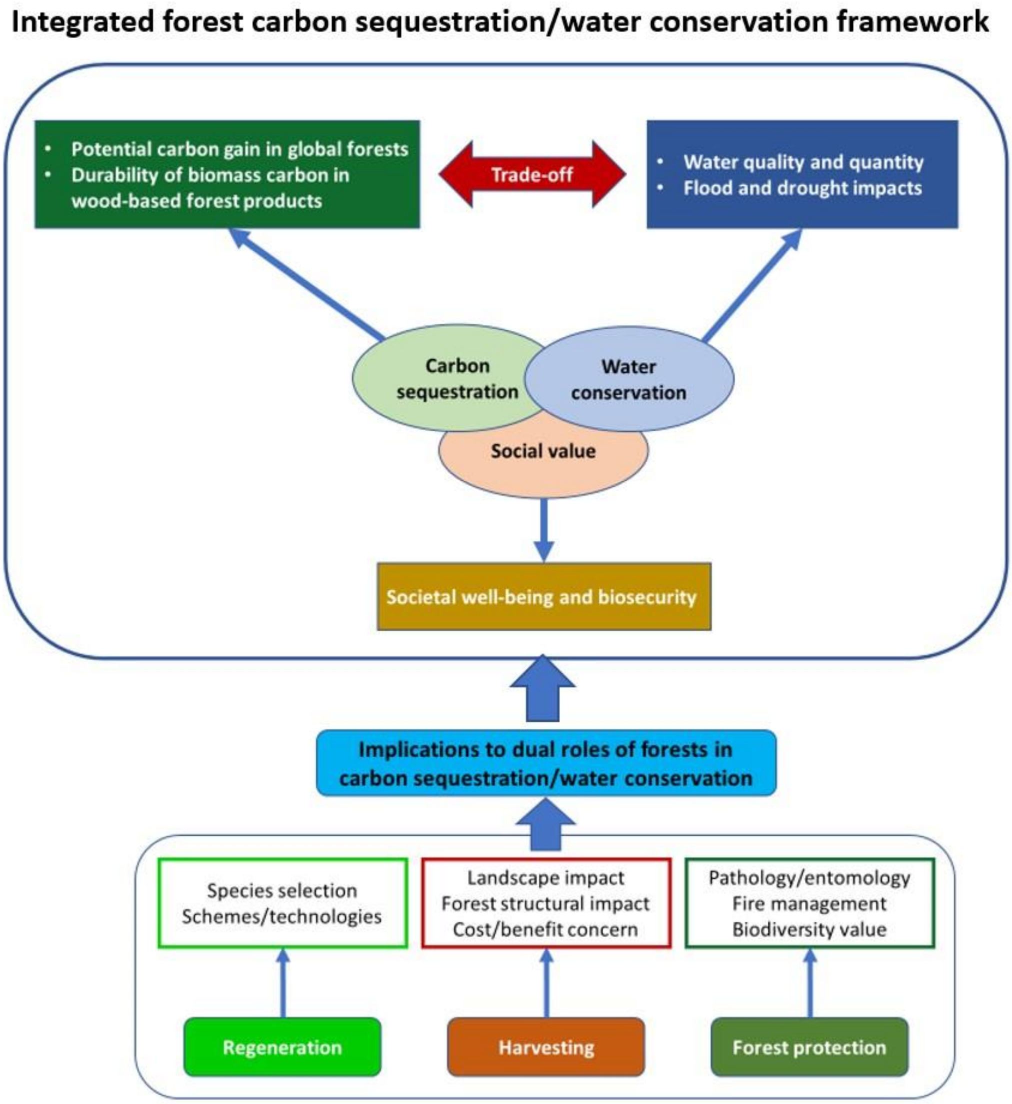

Figure 3. Research horizons that may help build an integrated framework for forest carbon sequestration and water conservation.

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